

Power demand of a flail mower during pineapple field demolition

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Abstract

J.S. Pérez de Corcho Fuentes, F. Garbati Pegna, C. Iglesias Coronel, F. García Reina, and P. Spugnoli. 2009. Power demand of flail mower during field demolition of pineapple fields. Cien. Inv. Agr. 36(1): 59-68. The power demand for the demolition of pineapple (*Ananas comosus*) fields at the end of their productive cycle with a flail mower has been determined using strain gage measures, the trials were conducted at three different angular velocities of the cutting apparatus and three translation velocities, using two different sets of knives. The results of the investigation show the influence of the knife type and cinematic regime of the cutting apparatus in the energy demand; furthermore they allow the validation of flail mower power demand models.

Key words: Agricultural engineering, agricultural machinery, *Ananas comosus*, energy mechanization.

Introduction

The speed of the cutting blades is one of the main factors that allow cutting without a counter edge and this depends on the diameter of the trajectory, the inertia, the stem's resistance to flexion and on the maximum cutting force of the apparatus. The energy and the cutting power of mowers and shredders also depend on the knives speed, on the feed speed, on the crop properties, on the knives' cutting width and on the number of blades cutting simultaneously (Fernández and Martínez, 1988; Moore Almeida and Benez, 1997).

The most important factor in the power requirements of the shredder is the flow of the material, which depends linearly on the shredder's advancement speed. With the increase of speed (and flow), the energy demand grows in the tractor power take off (PTO) (Kühlborn, 1968; Persson, 1987).

The speed of the cutting blades has a considerable effect on the energy of the conveyance of the material, which depends mainly on the flow of feeding but also on the energy losses due to friction and to air resistance during circulation. In flail shredders, as the speed of the blades grows, the height and the distance to which the residues are thrown increases and so do the friction with the air and the demand for power (Kühlborn, 1968; Persson, 1987; Moore Almeida and Benez, 1997).

The previously proposed equations (Fernández and Martínez, 1988) and the analysis of the dynamics of the cutting apparatus of a flail shredder (Pérez de Corcho Fuentes, 2006) allow proposing a model for determining the power demand expressed in kW at the PTO:

$$N_{ATP} = \frac{0.0625 \cdot n \cdot \rho \cdot F_a \cdot C_x \cdot (R+r)^3 \cdot \omega^3 + Y \cdot B \cdot V \cdot (R \cdot \omega)^2 + (M_f + n_s \cdot \varepsilon \cdot b_c \cdot k \cdot R_h) \omega}{\eta_{ATP} \cdot 1000} \quad (1)$$

where, n is the total number of cutting blades, ρ the air density ($\rho = 1,225 \text{ kg}\cdot\text{m}^{-3}$), F_a the surface facing the air during the movement of the cutting blades (m^2), C_x the non-dimensional coefficient of air resistance that includes the effects of the cutting blade shape ($C_x = 0,1 \dots 1$), R the radius of the extreme edge of the cutting blades (m), r the radius of the shaft of the cutting apparatus of the shredder (m), ω the angular speed of the cutting apparatus ($\text{rad}\cdot\text{s}^{-1}$), Y the mass of residues in humid base ($\text{kg}\cdot\text{m}^{-2}$), B the shredder's working width (m), V the shredder's working speed ($\text{m}\cdot\text{s}^{-1}$), M_f : the moment of the friction force in the supports (Nm), n_s the number of cutting blades cutting the stems simultaneously, ε the work consumed for cutting per area unit ($\text{J}\cdot\text{m}^{-2}$), b_c the projection in the horizontal plane of the cut width of a cutting blade (m), k the relationship between the actual cutting area and the working area, R_h the distance from the rotor's axle to the center of the blade's cutting zone (m), and η_{PTO} PTO the efficiency of the transmission from the tractor's PTO to the cutting mechanism of the shredder.

The equation (1) that determines the power needed to overcome the opposing forces during the idle-running (air resistance and friction in the supports of the cutting apparatus) and the power needed to carry out the technological process (cutting and spreading of the shredded material) can be stated as:

$$N_{PTO} = \frac{a \cdot \omega^3 + c \cdot \omega^2 + (b+d) \cdot \omega}{\eta_{ATP} \cdot 1000} \quad (2)$$

where a , c , b and d are coefficients related to power losses due to air resistance, spreading of shredded material, moment of the friction force in the supports and cutting, respectively.

The objective of this investigation was to determine the power demand of a flail shredder during the clearing of pineapple fields and to investigate the influence of the type of the cutting blade and the cinematic regimen of the shredder cutting mechanism on the power.

Materials and methods

Test field

The investigations were conducted in the Empresa de la Piña de Ciego de Avila, Cuba, in plain areas where red ferralitic soils are predominant, on pineapple (*Ananas comosus* (L.) Merrill) plants at the end of their productive cycle. The soil humidity was 25.11% with an apparent density of $1.27 \text{ g}\cdot\text{cm}^{-3}$, raised beds 0.13 m high. The volume of cutoff stems obtained was $75.10 \text{ t}\cdot\text{ha}^{-1}$ and with an average of more than 78.5% humidity.

Machinery

A Nobili BNU-160 flail shredder (Nobili S.p.A., Italy) was used, coupled to a Valtra Valmet 985 tractor (Valtra, Brasil) was used. The characterization of the natural and agrotechnical conditions was carried out according to the standard NC 34-47/1987 (*Oficina Nacional de Normalización*, Cuba), adapted to the characteristics of the pineapple fields where the trials were conducted. The energy study of the cutting apparatus of the shredder was made according to the standard NC 34-48/1987 and previous on the field works carried with tensometric means (Moore Almeida and Benez, 1997; Moraes da Silveira, 2001; Moraes da Silveira and Gonçalves, 2004).

Experimental design and statistical analysis

The experiments were conducted at random with a factorial design of $3 \times 3 \times 2$ (three cut speeds, three work speeds, using two types of cutting blades) and with three repetitions. The torque and the rotation frequency of the PTO

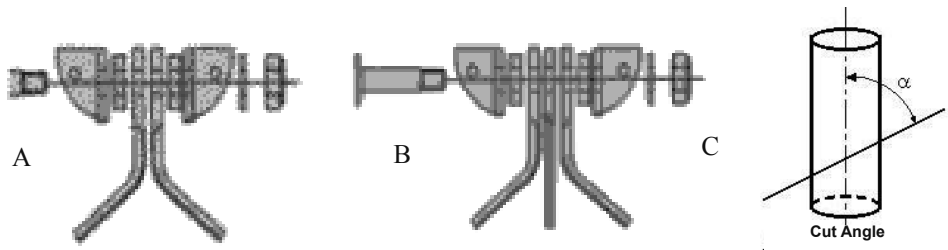


Figure 1. Cutting blades for shredding trials of pineapple plants (*Ananas comosus*) under field laboratory conditions. A. Universal cutting blade, B. Universal compound cutting blade and C. Cut angle of the cutting blades with respect to the stem axel.

and the shredder’s advancement speed were measured simultaneously. The frequency of data acquisition was 50 Hz, with at least 2,700 measurements for each variable in experimental plots of 3.6 x 10 m. Two types of cutting blades were used (Figure 1) with an edge angle of 20° and a cutting angle of 60°.

The speeds considered for the trials were 95, 140, and 184 rad·s⁻¹ for the angular speed of the rotor and 1.0, 1.4, and 1.8 m·s⁻¹ for the advancement speed of the combined equipment.

A torsionmeter was mounted on the PTO (Figure 2) and connected to a data acquisition system constituted of an EL-525 electronic card (DS Europe slr, Italy), which feeds the resistive bridge used to measure the torque in the tractor power take off and executes the bridge’s output signal conditioning.

The signals obtained were transmitted by low-noise coaxial conductors to the datalogger (Pico

ADC-11/10, Pico Technology, UK), which was connected to the parallel port of a portable computer (Texas Instruments Extensa 450). The data were obtained using the software PicoScope (Pico Technology, UK) in Windows environment.

The angular speed of the ATP was determined with a photoelectric sensor and electronic circuit pulse counter, obtaining signals with a frequency proportional to the speed. The work speed was determined with a fifth-wheel system, using a photoelectric sensor and a circuit similar to the ATP circuit.

For determining the demand of run-idle power, the cutting mechanism of the shredder was started, without load, at a minimum of four different angular speeds with the two types of cutting blades. The torque M_{iv-PTO} and the rotation frequency of the tractor PTO ω_{PTO} were measured to determine the power for the idle running N_v :

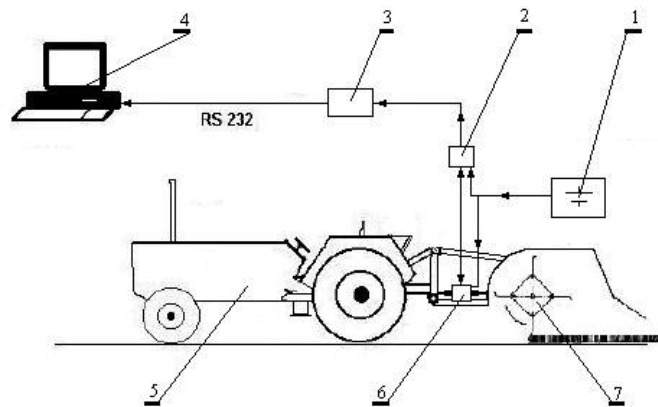


Figure 2. Scheme of the data acquisition system: 1. Battery, 2. Feeding and signal conditioning card EL-525, 3. Datalogger Pico ADC-11/10, 4. Portable computer (Texas Instruments Extensa 450), 5. Tractor, 6. Torsionmeter, and 7. Flail shredder apparatus.

$$N_v = 0.001 \cdot M_{n-PTO} \cdot \omega_{PTO} \quad (3)$$

For determining the power consumption during the field tests with load, the torsor moment M_{ic-PTO} and the rotation frequency ω_{PTO} were measured for the different speed levels defined for the experiment. The power N_{PTO} can be described by the following equation:

$$N_{PTO} = 0.001 \cdot M_{ic-PTO} \cdot \omega_{PTO} \quad (4)$$

The analysis of the multiple regression for N_v and N_{PTO} based on ω allowed for the determination of the coefficients for equation (2), from which $n \cdot F_a \cdot C_x$ and M_f were also determined for the idle running.

The computer program Statgraphics 5.1 was used (Statistical Graphics Corp., Herndon, VA, EUA) to obtain the regression equations for the power demand in run-idle and working conditions while Excel was used for graphics and calculations.

Results and discussion

Determination of run-idle power demand

The regression equations for the demand of power, according to equation (2), have a linear term and a cubic term. The equations obtained are as follows:

Universal cutting blade:

$$N_v = 9.93 \cdot 10^{-7} \cdot \omega^3 + 1.16 \cdot 10^{-2} \cdot \omega \quad (5)$$

Universal compound cutting blade:

$$N_v = 1.19 \cdot 10^{-6} \cdot \omega^3 + 1.29 \cdot 10^{-2} \cdot \omega \quad (6)$$

The models developed explained more than 99% of the variability of the power demand based on ω , and these results correspond with the values proposed by Fernández and Martínez (1988). The coefficients a and b obtained from adjusting the linear and cubic terms, respectively, were estimated with an error lower than

3%. The coefficient a was 11% higher for the universal compound cutting blade compared to the universal cutting blade, while the b was 20% higher for the universal compound cutting blade than for the universal cutting blade.

With the a and b coefficients of (2) it is possible to calculate the product of the air thrust area ($n \cdot F_a$) with the air resistance coefficient (C_x) in order to estimate the loss of power due to the air resistance and to the moment of the friction force in the supports M_f , according to the equation (1). The product $n \cdot F_a \cdot C_x$ for the cutting apparatus with the universal cutting blade was 0.267 and for the universal compound cutting blade was 0.319, which is 20% higher due to a larger area of air thrust. The moment M_f was 11.9 Nm for the first blade and 12.9 Nm for the second, which is 11% higher because as the number of cutting blades increases, the mass of the cutting apparatus grows.

The run-idle power demand of the flail shredder (Figure 3) increased with ω and was found from 14% to 18% higher for the universal compound cutting blade than for the universal cutting blade.

The representation of the linear and cubic terms of the equations of the run-idle power demand, due to the friction resistance in the supports and to the air thrust of the cutting apparatus, intersect in the range of angular speeds between 100 and 110 $\text{rad} \cdot \text{s}^{-1}$. For lower values of ω the losses due to friction in the supports are higher than those due to air resistance, while over 110 $\text{rad} \cdot \text{s}^{-1}$, the losses due to air resistance are higher growing more rapidly with the increase of ω .

The increase in the losses of power when running idle with the universal compound cutting blade was higher than with the universal cutting blade being higher the area of air impulsion, the mass of the apparatus and the friction in the supports. When the angular speed of the cutting mechanism was higher than 110 $\text{rad} \cdot \text{s}^{-1}$, the power losses increased significantly due to the air resistance. When ω increased from 110 to 185 $\text{rad} \cdot \text{s}^{-1}$ (68%), the idle running power losses grew more than three times.

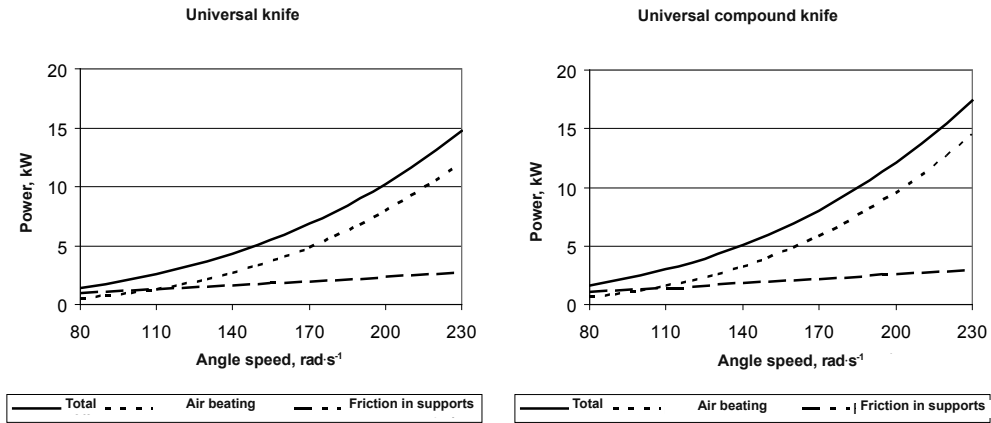


Figure 3. Idle running power demand of the shredder.

Determination of the power demand of the technological process

According to the results, the power demand for pineapple fields shredding increases with the feed speed and the cutting apparatus angular velocities, as previously reported (Fernández and Martínez, 1988; Kühlborn, 1968; Persson, 1987; Moore Almeida and Benez, 1997).

The regression equations for the power demand of the technological processes during the shredding are consistent with the linear term of the equation model (2), which is related to the cutting of the residues, and with the other quadratic term, which is associated with the throwing of the shredded material. The models obtained explain more than 95% of the variability of the power demand for the technological process related to ω .

The coefficients of equation (2), which are related to the power demand of the technological process (Table 1), suggest that the difference between the maximum and the average values of the coefficient d (related to the cutting) for the different working speeds was lower than 2% for both types of cutting blades, since the advancement speed did not significantly influence the power demand of the cutting process. The mean value of d was 42% higher for the universal com-

pound cutting blade compared to the universal cutting blade, which is consistent with a higher energy expense for cutting with the first type of blade, due to the higher number of blades and consequent cutting effort were higher.

Concerning the c coefficient, which is related to the throwing of the shredded material, the difference between the average value and those of the higher and lower feeding speed respectively, is of about 35%. Considering the ratio c/V this difference was lower than 7.5% for both kinds of blades. This shows that the power demand for the throwing of the shredded material increases with the feeding speed and that the quantities of residues are similar in the different experimental plots.

In addition the difference between the average values of c and c/V for the two types of cutting blades was lower than 5%, which shows that the characteristics of the experimental plots for both types of blades are similar and that there is no significant influence of the blade type on the power demand for throwing that depends on the flow of material processed and on ω .

The power demand of the cutting mechanism of the shredder (Figures 4 and 5) increases when V and ω increase. For the universal cutting blade, the linear term was between 40 to 60% of the power demand of the technological process, for

Table 1. Coefficients estimated for the regression equations used to estimate the power requirements of the residue grinding process ($N_{pt} = c \cdot \omega^2 + d \cdot \omega$) of pineapple (*Ananas comosus*) residues.

Working speed (V) $m \cdot s^{-1}$	c	d	c/V
Universal blade			
1.06	$5.44 \cdot 10^{-4}$	$6.58 \cdot 10^{-2}$	$5.13 \cdot 10^{-4}$
1.42	$7.96 \cdot 10^{-4}$	$6.52 \cdot 10^{-2}$	$5.61 \cdot 10^{-4}$
1.83	$1.09 \cdot 10^{-3}$	$6.40 \cdot 10^{-2}$	$5.95 \cdot 10^{-4}$
Mean	$8.10 \cdot 10^{-4}$	$6.50 \cdot 10^{-2}$	$5.56 \cdot 10^{-4}$
Mean maximum difference, %	34.60	1.23	7.01
Compound universal blade			
1.01	$5.35 \cdot 10^{-4}$	$9.06 \cdot 10^{-2}$	$5.30 \cdot 10^{-4}$
1.41	$8.13 \cdot 10^{-4}$	$9.34 \cdot 10^{-2}$	$5.77 \cdot 10^{-4}$
1.78	$1.10 \cdot 10^{-3}$	$9.36 \cdot 10^{-2}$	$6.18 \cdot 10^{-4}$
Mean	$8.16 \cdot 10^{-4}$	$9.25 \cdot 10^{-2}$	$5.75 \cdot 10^{-4}$
Mean maximum difference, %	34.80	1.19	7.48

a low ω , and from 24 to 39% for high ω values, so for the universal compound cutting blade, this proportion was from 48% to 65% and from 31% to 47%, respectively.

For the universal compound cutting blade, the proportion of the cutting power is 10% to 30% higher than for the universal cutting blade. As ω increases, the power demand for throwing grows more rapidly than for cutting as confirmed by the decrease of power demand for cutting at high ω values.

The relationship between the power demand for cutting and for throwing varies with ω . For the universal cutting blade (Figure 4) with a speed $V = 1.06 \text{ m} \cdot \text{s}^{-1}$ and $\omega = 121 \text{ rad} \cdot \text{s}^{-1}$, the linear and quadratic terms (cutting and throwing, respectively) have similar values. From this value of ω onwards the energy expense for throwing is

higher than that for cutting, and the relationship reverses when ω decreases. Similar behavior is observed with the universal compound cutting blade (Figure 5) when working with $V = 1.40 \text{ m} \cdot \text{s}^{-1}$ and $\omega = 115 \text{ rad} \cdot \text{s}^{-1}$ and with $V = 1.01 \text{ m} \cdot \text{s}^{-1}$ and $\omega = 171 \text{ rad} \cdot \text{s}^{-1}$.

By summing the equations for determining the power need for the idle running and for the technological process, it is possible to obtain the total power demand at the tractor's PTO (Table 2). The run-idle power demand is between 10% and 16% of the total power demand for the process at higher feeding speed and up to 14%-23% for lower ones (Figure 6) being these proportions for both types of blades. The proportion of the run-idle component on the total power demand decreases when V grows due to the major need of power for throwing of the shredded material increases.

Table 2. Equations to determine the demand of tractor power take off (PTO) during pineapple fields demolition using flail mower.

Knife type	Advancement speed, $m \cdot s^{-1}$	Equation
Universal	1.83	$N_{PTO} = 9,93 \cdot 10^{-7} \cdot \omega^3 + 1,09 \cdot 10^{-3} \cdot \omega^2 + 7,56 \cdot 10^{-2} \cdot \omega$
	1.42	$N_{PTO} = 9,93 \cdot 10^{-7} \cdot \omega^3 + 7,96 \cdot 10^{-4} \cdot \omega^2 + 7,68 \cdot 10^{-2} \cdot \omega$
	1.06	$N_{PTO} = 9,93 \cdot 10^{-7} \cdot \omega^3 + 5,44 \cdot 10^{-4} \cdot \omega^2 + 7,74 \cdot 10^{-2} \cdot \omega$
Universal compound	1.78	$N_{PTO} = 1,19 \cdot 10^{-6} \cdot \omega^3 + 1,10 \cdot 10^{-3} \cdot \omega^2 + 10,65 \cdot 10^{-2} \cdot \omega$
	1.41	$N_{PTO} = 1,19 \cdot 10^{-6} \cdot \omega^3 + 8,13 \cdot 10^{-4} \cdot \omega^2 + 10,63 \cdot 10^{-2} \cdot \omega$
	1.01	$N_{PTO} = 1,19 \cdot 10^{-6} \cdot \omega^3 + 5,35 \cdot 10^{-4} \cdot \omega^2 + 10,35 \cdot 10^{-2} \cdot \omega$

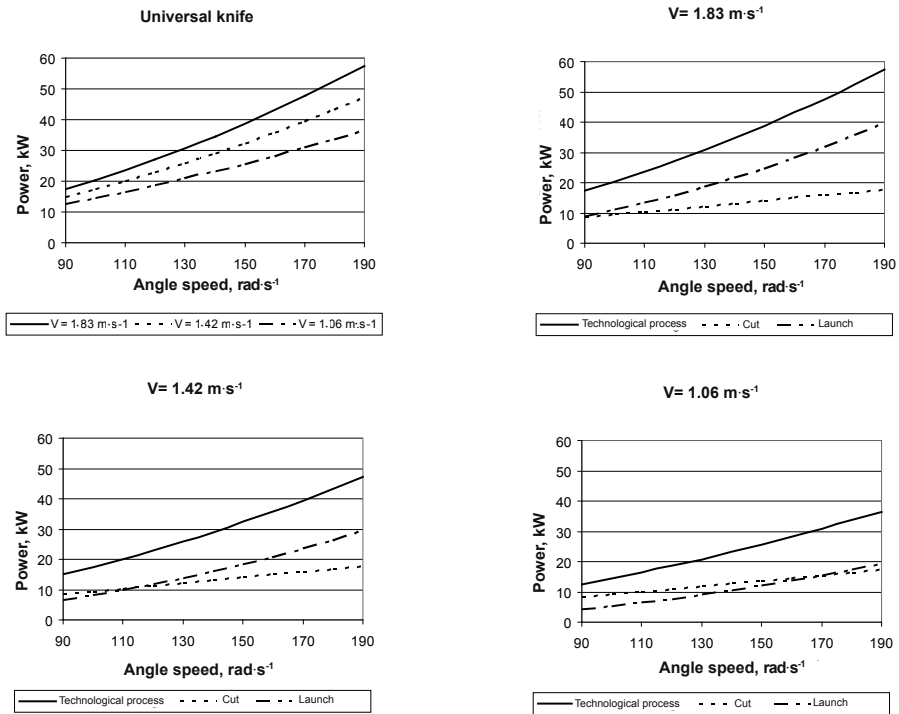


Figure 4. Power demand during the grinding process of the residues of a pineapple (*Ananas comosus*) field, using a residue grinder equipped with a universal blade.

The lower demand for power is obtained when the angular speed of the cutting mechanism is 95 rad·s⁻¹. With this rotation frequency, the shredded residuals are longer than the length allowed by the agrotechnical demands. This affects the quality of the process, so it becomes inadequate.

The increase of the power demand when the work speed increases is due to the larger feeding flow to the machine and a higher power demand for the spread of the shredded vegetal material. On the other hand, the increase of the angular speed produces an increase in the cutting power demand and the spreading power demand, because the speed with which the cutting blade hits the vegetal mass increases, and the shredded residuals are spread at higher speeds.

The energy demand during the work of the cutting mechanism with the universal compound cutting blade is 12 to 21% higher than with the universal cutting blade, due to the demand of the vacuum power and the cut being higher for

the first blade. Therefore, the universal cutting blade should be used, in spite of the increase of the mean length of the remnants by around 8%.

The results obtained in this investigation, the analysis of the linear and cubic components for the demand of the vacuum power and the linear and quadratic components for the power of the technological process, as well as the influence of the angular speed of the cutting mechanism with respect to those components (Figures 3, 4 and 5) have not been reported in the literature so far.

According to the results obtained, the type of the cutting blade and the kinematical regimen of the cutting mechanism of the flail shredder influence the energy demand of pineapple residues demolition. The cut power for the universal compound cutting blade is 15 to 21% higher than for the universal cutting blade, while the spread power is independent of the type of cutting blade. The work speed significantly influences the spread power without affecting the

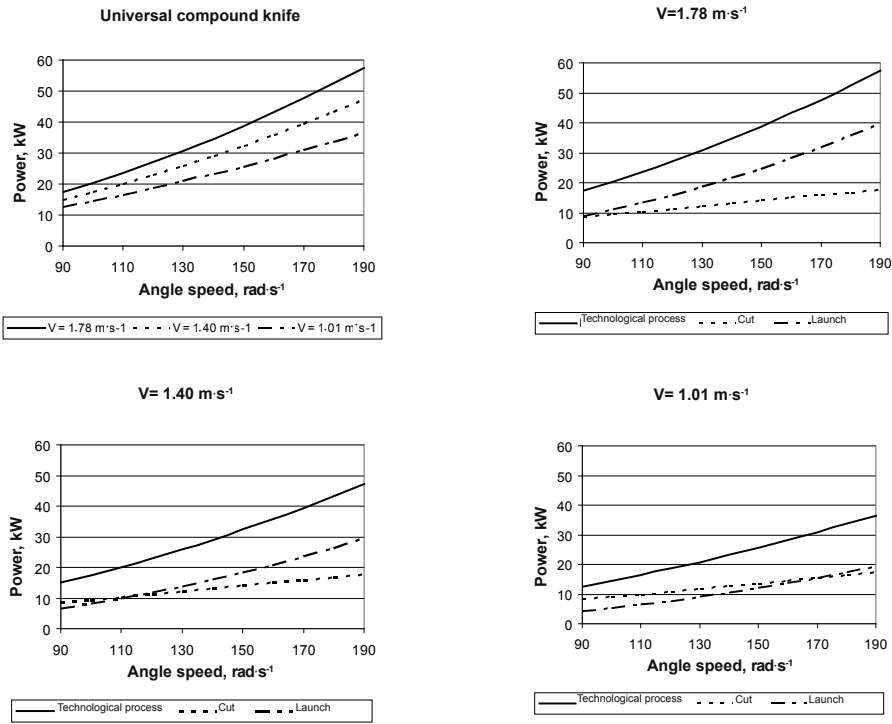


Figure 5. Power demand during the grinding process of the residues of a pineapple (*Ananas comosus*) field, using a residue grinder provided with the composed universal blade.

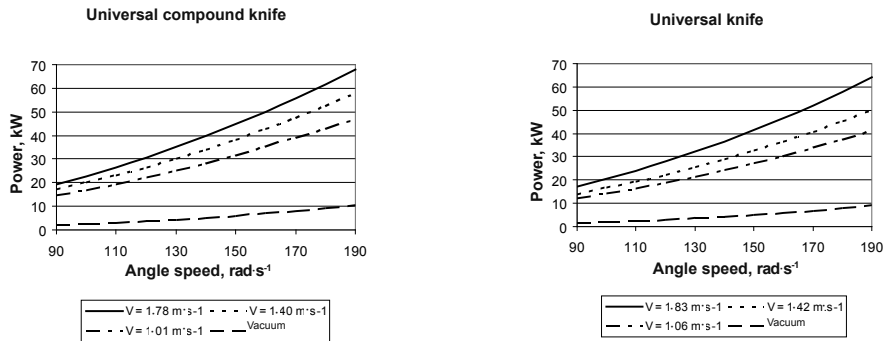


Figure 6. Power demand during the grinding process in the tractor ATP during grinding of pineapple (*Ananas comosus*) residues while working at different speeds (V). Power demand for the activation of the vacuum device with two types of cutting blades.

cut power. As the work speed and the angular speed of the cutting mechanism increase, the total demand for power increases. The results of the experimental investigations and the re-

gression analysis allowed for the validation of the model for the power demand of the flail shredder.

Resumen

J.S. Pérez de Corcho Fuentes, F. Garbati Pegna, C. Iglesias Coronel, F. García Reina y P. Spugnoli. 2009. Demanda de potencia de una trituradora de mayales durante la demolición de campos de piña. Cien. Inv. Agr. 36(1): 59-68. Se determinó la demanda de potencia de la demolición de campos de piña (*Ananas comosus*) que terminan su ciclo de producción con una trituradora de mayales, con dos tipos de cuchillas, tres velocidades angulares del órgano de corte y tres velocidades del conjunto, utilizando mediciones tensométricas. Los resultados de las investigaciones demuestran la influencia del tipo de cuchilla y el régimen cinemático del órgano de corte en la demanda de energía en la demolición de rastrojos de piña, y permitieron validar los modelos para la demanda de potencia de la trituradora.

Palabras clave: Ananá, *Ananas comosus*, energía, maquinaria agrícola, mecanización, ingeniería agrícola.

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