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Design and Implementation of Optimized Cutter for Agricutural Residues

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ABSTRACT: This paper presents a mechanical design approach, fabrication and experimental validation of a cutting blade using in agricultural residues. It is required that the approach angle between the cutting edge and the residue stalk must be constant along the cutting edge. The results showed that applying the logarithmic profile for the cutters would well satisfy the requirement. The cutting forces induced at different positions along the fabricated cutting edge were found to be unchanged. The results are promising to apply in design chopping machines to save energy consumption in practice.

KEYWORDS: Agricultural residues; cutting; design; experiments; optimization.

I. INTRODUCTION

Agricultural residues have been considered as the most important biomass resource, however most of them are abandoned or burned [1, 2]. It is extremely important to serve for making animal feed and biomass energy by shortening agricultural residues into smaller sizes. Typically, the cutters used to shorten agricultural residues are rotary straight knives and scissors or saws [2]. Several investigations have been done to minimize the cutting energy for chopping agricultural residues [3-9]. In previous studies, the authors of this paper found that several major cutting parameters, including approach angle, feed angle, have significant effects on the cutting force and consumption power. Applying the response surface methodology (RSM) [10] and Taguchi techniques [11], the optimal setting can reduce cutting force and power consumption respectively by 2.3 times and 4 times, compared to typical conditions in commercial choppers, where these angles are usually set to be 0°. The isues should be further addressed is how to keep the approach angle and feed angle to be contant along the cutter length. In fact, the feed angle can be easily set during operation. However, the feed angle can vary along the cutting edge length if it is a straight blade. Therefore, it is necessary to design an appropriate tool profile to ensure a constant tool contact angle. In order to realize those promising results for practical applications, this paper presents the design and experimentally implementation and validation of the optimized cutters. Corn stalk was selected for experimental tests.

II. DESIGN OF THE OPTIMIZED CUTTER

A. Geometric Design

A typical schema of the agricultural chopping process is shown in Figure 1.

In Figure 1, the approach angle is assigned as α, and the feed angle is β. These two angles are required to be the optimized values, as found as certain and fixed numbers. As can be seen in Figure 1, the feed angle β can be easily set before cutting processes. However, the approach angle, α would be varied along the cutter edge if the cutter is in a straight form, as shown in Figure 2.

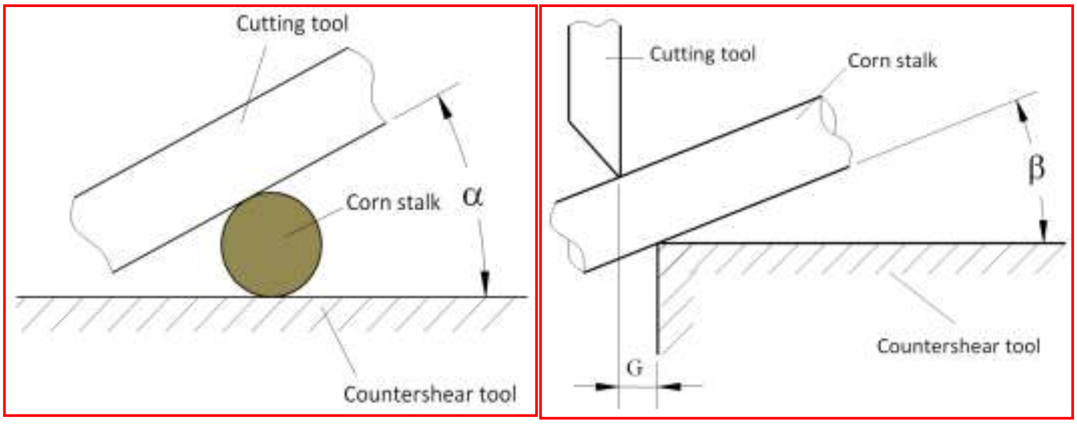

Figure 1. Schema of the cutting angles

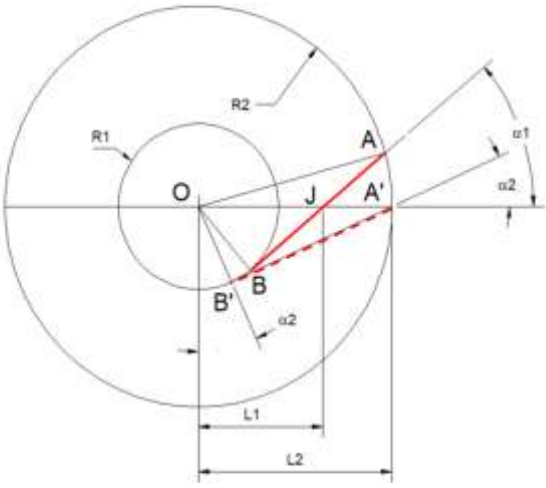

Figure 2. Variation of the approach angle on straight cutter edge

In Figure 1, a straight tool with blade length AB rotates around center O. The minimum and maximum radii of the tool are R1 and R2 respectively. Considering the cutting position J is a distance L1 from the tool's center of rotation, when the cutting edge AB is intersecting the tool holder OA', the angle α can be determined by the following expression:

$$\sin\alpha_1 = \frac{OB}{OJ} = \frac{R_1}{L_1} \qquad (1)$$

If the tool continues to rotate to the furthest cutting position, the cutting edge intersects the cutter at point A', then the angle α is determined as:

$$\sin\alpha_2 = \frac{OB'}{OA'} = \frac{R_1}{L_2} \qquad (2)$$

Thus, the angle α changes as a function of two parameters: the minimum radius R1 and the distance L from the cutting position to the center of rotation of the tool according to the relationship:

$$\sin\alpha = \frac{R}{L} \qquad (3)$$

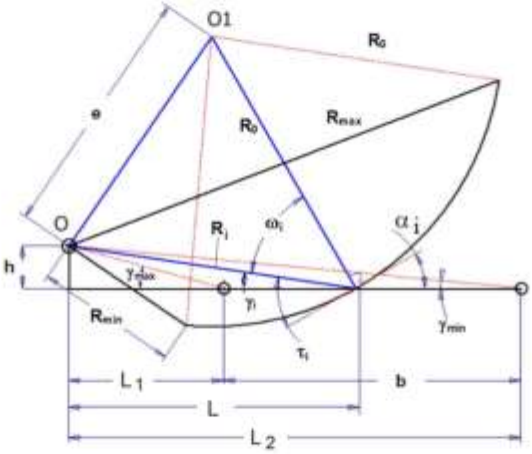

Figure 3. Variation of the approach angle on a cutter edge with arc form

In case the tool profile is in the form of an arc with center O1, radius R0 as shown in Figure 3, the tool rotates around the center O, a distance e from the center O1. At the moment shown, the cutting point has a radius Ri from the center of rotation, corresponding to the horizontal distance L. Assume that the tool lies as a fixed distance h below the center of rotation. The turning radius Ri of the cutter at the cutting point can be calculated as follows:

$$R_i = h\sin(\gamma_i) \tag{4}$$

Where, γi is the angle between the radius Ri and the horizontal. It is possible to determine the angle ω by two rays connecting the cutting point with the center of rotation and the center of curvature of the tool according to the relationship:

$$\cos(\omega_i) = \left(\frac{R_0^2 + R_i^2 - e^2}{2R_0 R_i} \right) \tag{5}$$

The relationship of angles in the figure has:

$$\tau_i = 90 - \gamma_i \tag{6}$$

From there it is obtained:

$$\alpha_i = 90 - \tau_i - \gamma_i \tag{7}$$

It is easily to observe that the values of α will vary along the cutter edge.

From the analysis above, either the a straight or circle arc profiles seemed to not provide a constant value of the approach angle along the cutting edge. Hence, when chopping a bundle of the residues, it is not able to satisfy a certain value of the angle which was optimized. To address this issue, a new profile of the cutting edge, using a logarithmic curve is proposed and analyzed as depicted in Figure 4.

As can be seen in Figure 4, a logarithmic spiral always has a tangent to the radius vector corresponding to a constant angle α. The curve has also been well known as the Equiangular Spiral. The equation of the spiral in the polar coordinate system has the following form:

$$r = ae^{m\theta} \tag{8}$$

Where r is the distance from the center (origin) to the points on the curve, a and m are the parameters, θ is the sweep angle of the radius ray. The relationship of the parameters a, m and angle α is described by the equation below:

$$\tan\alpha = \frac{\rho}{\rho'} = \frac{ae^{m\theta}}{ame^{m\theta}} = \frac{1}{m} \qquad (9)$$

Through equation (9), it can be seen that the equation for determining angle α does not depend on radius of curvature ρ or extreme angle θ.

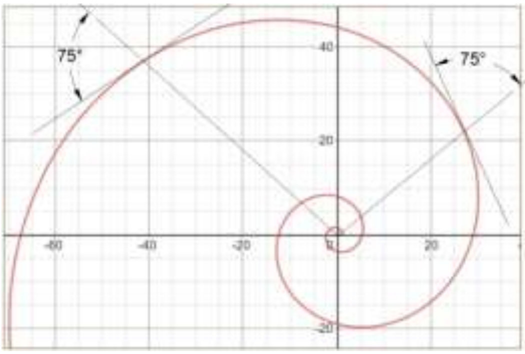

Figure 4. A logarithm spiral

This property of a logarithmic spiral is well suited to the requirement of maintaining a constant feed angle at all points along the cutting edge. Figure 5 illustrates the idea of using a logarithmic spiral with an angle α=30°.

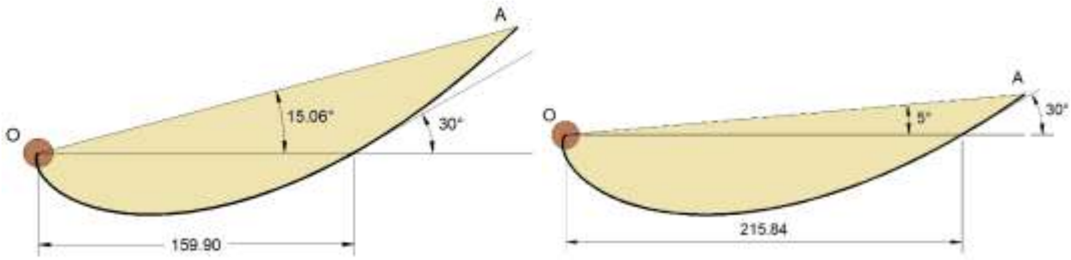

Figure 5. An example of the constant tangent angle of logarithmic curve

As can be seen in Figure 5, the angle between the tangent to the radius joining the center of the spiral is constant. Suppose the cutter OA has a logarithmic profile whose center of rotation O coincides with the center of the helix. At the first position when radius OA joins an angle of 15.06° to the horizontal, the angle between the tangent of the blade and the horizontal radius is 30°. When the ray OA is rotated by an angle of 10.06° clockwise to its new position (by an angle of 5° with the horizontal), the angle between the tangent of the blade and the horizontal radius remains 30°.

To summary, the logarithm profile satisfied well the requirement of keeping the approach angle as constant along the cutting edge. Hence, the proposed cutter will be designed using this profile, as shown in the next section.

B. Practical Design

Consider the equation describing the logarithmic curve in polar coordinates:

$$r = ae^{m\theta} \qquad (10)$$

The angle between the tangent of the curve and the radius of rotation, can be determined by:

$$m = \frac{1}{\tan\alpha} \qquad (11)$$

Thus, if the angle α, is predetermined, it is possible to determine m and from there construct a logarithmic curve with the desired tangent angle. Some important features for tool profile design are as follows: The radius r0 at angle θ = 0 is determined by substituting θ = 0 into equation (10):

$$r_0 = ae^0 = a \tag{12}$$

Similarly, the radius r1 at angle θ = π is determined:

$$r_1 = ae^{m\pi} \tag{13}$$

Formula (13) is used to determine the parameter a value according to the radius r1, ie according to the given tool diameter as follows:

$$a = \frac{r_1}{e^{m\pi}} \tag{14}$$

Assuming the found optimal feed angle is α, we need to construct the blade profile curve according to different sizes of rotary tool diameters, depending on the actual chopper design requirements.
The realized drawing of the cutter is shown in Figure 6.

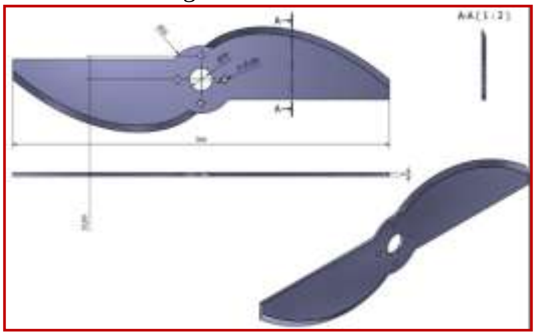

Figure 6. The proposed cutter in 3D design step

III. EXPERIMENTAL VALIDATION

The cutter designed was then assemblied on a typical chopping available on the market. An experimental test was done to check if the cutting force is kept constant at different cutting points. The experimental setup is depicted in Figure 7.

Figure 7. Experimental setup to validate the cutter in-situ

In the feeding hub, 5 positions were marked to place the corn stalk. The position of the corn stalk to-be-cut was gradually moved from afar to the center of rotation of the knife. The value of shear force measured when cutting the stalk at each position was collected and compared. In this experiment, all other parameters were kept the same, except for the position of corn plants when cutting was controlled. The results obtained is shown in Figure 8.

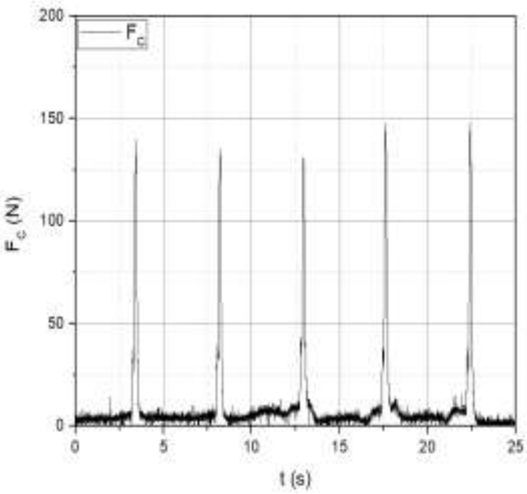

Figure 8. The unchanged cutting force at different points along the edge

As can be seen in Figure 8, the cutting force values at 5 different cutting positions,located at different distance from the rotary center along the cutting edge appeared as approximate the same. In other words, the cutter profile proposed provides a well satisfication of the constant approach angle, resulted in unchanged cutting force.

IV. CONCLUSION

A cutter profile in the logarithmic form was proposed, analyzed, designed and validated. The following remaks can be noted:

- It is required that an optimized value of the approach angle between the cutter edge and the stalk to-be-cut must be kept constant along the cutting edge;
- Cutter edge either in straight or circle curve is not able to keep such angle constant;
- Applying the logarithmic profile in design and realization of the cutting blade provide unchanged cutting forces at different positions along the cutting edge;

The results obtained are promising to apply in design chopping machines to save energy consumption in practice.

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Ethical statement: The authors declare that we have followed ethical responsibilities.

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