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Research Paper

Optimisation and finite element simulation of the chopping process for chopper sugarcane harvesting

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High levels of mechanical damage are a major obstacle for the mechanical harvesting of sugarcane. A chopping system for use in a sugarcane harvester was developed and tested. The three influencing factors studied were the rotational speed of chopping drums (*RS*), the overlapping length of upper and lower chopping blades (*OL*) and the bevel angle (*BA*). The quality of chopping included the percentage of undamaged billets (*PUB*) and the standard deviation of chopping length (*SDCL*), and together with the average maximum chopping power consumption (*PC*) these were regarded as outputs. A Box-Behnken design was employed to conduct the experiments and build regression models. The optimised results indicated that when *RS* increased from 200 to 250 rpm on the condition that *OL* and *BA* were set as 2 mm and 21.8°, respectively, *PUB* decreased from 97.0% to 95.6%, with *PC* increasing from 515 to 625 W and *SDCL* increasing from 1.24 to 1.36 mm. Based on these optimised parameters, a finite element model was established to simulate the chopping process. The chopping resistance of blades, stress distribution of sugarcane and blades in the chopping process were then analysed. Results showed that the maximum Von Mises stress of sugarcane, upper and lower chopping blades in the chopping process were about 16.87, 106.08 and 115.72 MPa, respectively.

1. Introduction

Harvesting is a critical step of a sugarcane production system. Mechanical harvesting has been widely used for sugarcane production in the world since 1960s, which has substantially improved the efficiency of harvesting (Ma et al., 2017). However, stalk damage such as cracks and splits, and juice loss from mechanical harvesting remains a problem compared to manual harvesting. Therefore, it is vitally important to study the major factors causing the increase of cane damage in the mechanical harvesting process to find the most effective methods for reducing harvesting loss.

Mechanical sugarcane harvesting operations are typically performed using either whole stalk harvesters or chopper

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Nomenclature

Symbols

d	Diameter of feeding roller, m
E	Young's modulus, Pa
G	Shear modulus, Pa
K	Correction factor of diameter
k	The number of independent parameters
L	Chopping length of sugarcane, m
M	Number of total billets in a set of experiments
m	Number of undamaged billets in a set of experiments
n_1	Rotational speed of chopping drums, rpm
n_2	Rotational speed of feeding rollers, rpm
R^2	Determination coefficient
s	Overlapping length of upper and lower chopping blades, mm
t	Time, ms
X_0	Natural value of X_i at the centre point
x_i	Dimensionless value of the independent variable X_i
X_i	Natural value of an independent variable
ΔX_i	Step change value of variable X_i
Y	Response value
Z	Number of chopping blades on each chopping drum
α	Significance level
β_0	Model intercept coefficient
β_i	Regression coefficient of linear term
β_{ii}	Regression coefficient of quadratic term
β_{ij}	Regression coefficient of interaction term
ε	Error
μ	Poisson's ratio
ρ	Density, kg m^{-3}

Abbreviations

ANOVA	Analysis of variance
BA	Bevel angle, °
BBD	Box-Behnken design
DAQ	Data acquisition card
DTS	Dynamic torque sensor
FEM	Finite element method
OL	Overlapping length of upper and lower chopping blades, mm
PC	Average maximum chopping power consumption, W
PUB	Percentage of undamaged billets, %
RS	Rotational speed of chopping drums, rpm
SDCL	Standard deviation of chopping length, mm

harvesters (Ma, Karkee, Scharf, & Zhang, 2014). In the last few decades, chopper harvesters have been widely used for sugarcane harvesting in many areas of the world because of their reliability and suitability for high yielding sugarcane varieties (Salassi & Champagne, 1998). In southern China, the small- and medium-sized single-row chopper harvesters are recommended since around 80% of total sugarcane planting area is located in mountainous and hilly areas (Ou et al., 2013). In normal harvesting operations, the chopper harvester firstly prepares the cane row by removing the tops of the stalks with topper, separating the rows with crop-lifting spirals, and inclining the stalks away from the oncoming harvester using a knockdown roller. Two counter rotating disc base-cutters with multiple blades produce an impact cut at ground level, then the feeding rollers capture the ends of the stalks and convey the entire stalks rearward into the chopping system. The stalks are then chopped into 300–400 mm lengths before passing through a series of trash extractors and falling into a collection bin below the elevator (Kroes & Harris, 1995). The objective of the harvesting system is to deliver the maximum quantity of cane with the highest sugar quality using the most efficient method (Richard, Jackson, & Waguespack, 1996). While chopper harvesters are often utilised to maximise cane stalk recovery rate without regard to quality, chopping systems with up to six chopping blades per drum have recently been installed for the purpose of cutting shorter billets in order to increase loading quantity (Barnes, Loughran, Whiteing, & Lamb, 2009). Unfortunately, this modification had a detrimental effect on harvesting quality due to increasing sugar juice loss and billet damage.

Chopping quality and energy consumption are the two most important assessment criteria for sugarcane chopper harvesters. The design and operating parameters of chopping components are the main factors that influence the performance of chopping system, such as the number and shape of chopping blades installed on the chopping drums, centre distance of upper and lower drums, clearance between the upper and lower chopping blades and the speeds of feeding rollers and chopping drums. The evaluation criteria of chopping quality mainly consist of the billet quality and uniformity of chopping lengths (Mathanker et al., 2015). A clearance between the chopping blades of 2 mm is a commonly recommended installation parameter. An appropriate overlapping length of upper and lower chopping blades can help reduce the appearance of cracks, splits and chips to improve chopping quality. The billet quality also highly depends on the operating parameters. Adopting appropriate feeding speed and then maintaining constant conveying speed could improve chopping quality. The sugarcane chopping energy depends on the size, maturity, moisture content and other material characteristics of the cane, as well as the working condition and operational parameters of chopping system.

Despite the rapid development of mechanical sugarcane harvesting, little detailed research has been undertaken to understand and quantify the performance of sugarcane harvester chopping systems, as well as the mechanical damage of stalks during chopping process. Mechanical damage has a significant influence on the quality of sugarcane stalk, resulting in a decrease in quality through biological degradation which occurs through juice deterioration and stalk rot, both of which reduce sugar yield and increase production cost (Burrows & Shlomowitz, 1992). As a result, the sugar quality of newly cut canes harvested by a chopper harvester is usually maintained for only one day, which means that harvested billets must be milled quickly. Predicting the damage level and stress distribution of sugarcane stalk under different chopping condition is therefore helpful in terms of improving