Experimental research on affecting factors of the cutting quality of sugarcane harvesters under complicated excitations

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Abstract: The sugarcane field excitation, cutting forces and the engine excitation constitute complicated excitations acting on sugarcane harvesters. In this study, the sugarcane cutting mechanism under complicated excitations was analyzed. The dynamics and the mathematical models of sugarcane harvesters were established and simulated. Based on theoretical analysis, sugarcane cutting experiments were done on a self-built sugarcane harvester test platform (SHTP), designed as single-factor and the orthogonal experiments. Effects of the sugarcane field excitation characterized by the sugarcane field excitation device (SFED) output frequency, the engine excitation characterized by the actuating engine output frequency, the cutter rotating speed, the sugarcane harvester travelling speed simulated through the sugarcane transporting speed of the SHTP and the cutter inclination angle on the cutting quality of sugarcane harvesters were studied. Effects of the axial cutter vibration on three-directional cutting forces and the sugarcane cutting quality (SCQ) as well as effects of three-directional cutting forces on the SCQ were further studied. It is shown that the sugarcane field excitation, the axial cutter vibration amplitude and frequency as well as the three-directional cutting forces have significantly negative monotonic correlated effects on the SCQ while the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle have significantly positive monotonic correlated effects on the SCQ. Significance levels of effects on three-directional cutting forces and the SCQ form high to low are as follow, the axial cutter vibration, the sugarcane field excitation, the cutter rotating speed, the engine excitation, the cutter inclination angle, the sugarcane harvester travelling speed. The theoretical analysis results were verified through experiment and an optimal combination was obtained with the cutter rotating speed of 700 r/min, sugarcane harvester travelling speed of 0.6 m/s and cutter inclination angle of 8º. This study can provide a reference for setting cutting parameters of sugarcane harvesters with a good SCQ.

Keywords: sugarcane harvester, cutting quality, complicated excitations, experimental research, theoretical analysis
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1 Introduction

Valued achievements on improving the cutting quality of sugarcane harvesters have been obtained. Thanomputra et al.[1] improved the cutting efficiency of sugarcane harvesters through abrasive-sand-added high-pressure water cutting. Mello et al.[2,3] used different cutters to do sugarcane cutting experiments and found the one with the best cutting quality. Silva et al.[4] evaluated the sugarcane ratoon damage degree caused by the cutting height through statistical experiment data. Ripoli et al.[5] designed a cutter with an automatic in-soil-cutting-depth-controlling system dependent on sugarcane field roughness. Johnson et al.[6,7] studied effects of the cutting speed and the cutting-edge angle on the cutting energy of sugarcane harvesters. Kroes et al.[8] established a kinematic double-cutter model to study the cutter trajectory and calculate the maximum ratio between the sugarcane harvester travelling speed and the cutter rotating speed for the purpose to improve the sugarcane cutting quality (SCQ) theoretically. Liu et al.[9] obtained the shear modulus and the tensile strength of sugarcanes through tension and compression experiments. Taghijarah et al.[10] obtained the bending strength of sugarcanes through measuring cutting forces. Lai et al.[11,12] found the sugarcane field excitation has a bad effect on the cutting system of sugarcane harvesters, causing the axial cutter vibration, which leads to a poor SCQ. Wang et al.[13] established a cutter vibration model to study the effect of the bearing clearance on the cutting system vibration. Huang et al.[14] simulated the sugarcane cutting process through infinite element analysis to study relationships among cutting forces, the cutter inclination angle and the sugarcane cutting speed. Liu et al.[15] studied relationships among the sliding cutting angle, the cutter inclination angle, the sugarcane cutting speed and cutting forces. Xu et al.[16] established a cutting system model to obtain curves of cutting force changing with time and cloud pictures of the cutting system vibration displacement in the sugarcane cutting

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process. Yang et al.[17,18] studied effects of the cutter rotating speed and the sugarcane harvester travelling speed on the cutting quality of sugarcane harvesters.

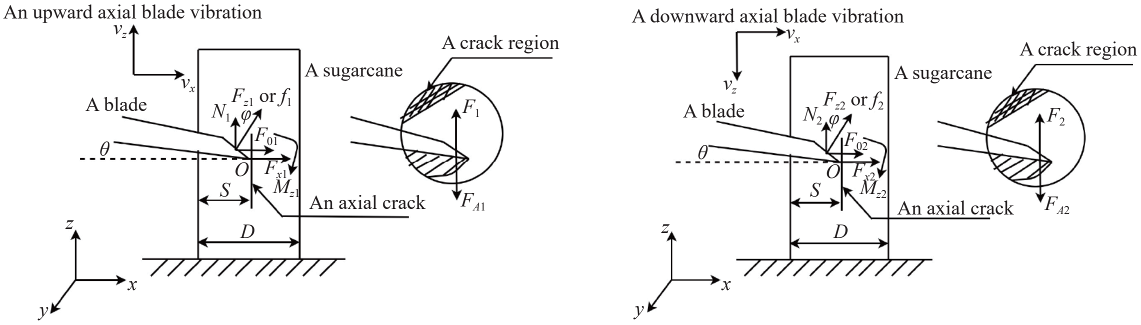
Research above was about mechanics characteristics of sugarcanes, effects of the sugarcane cutting form, design parameters of the cutters, the cutting system vibration, the sugarcane harvester travelling speed and the cutter rotating speed on the cutting quality of sugarcane harvesters and cutting forces. It is shown that the sugarcane field excitation has a bad effect on the cutting quality of sugarcane harvesters in that it causes vibrations of sugarcane harvesters leading to vibrations of the cutters.

As is mentioned above, the axial cutter vibration has a bad effect on the cutting quality of sugarcane harvesters. The sugarcane field excitation, cutting forces and the engine excitation constitute complicated excitations acting on sugarcane harvesters. However, none of the research above was focused on effects of the sugarcane field excitation, the engine excitation, the cutter rotating speed, the cutter inclination angle, the sugarcane harvester travelling speed on the cutting quality of sugarcane harvesters, the axial cutter vibration and cutting forces comprehensively under actual complicated excitations in sugarcane fields.

In this study, a self-built sugarcane harvester test platform (SHTP) with complicated excitations simulated through two sugarcane field excitation devices (SFED) and an actuating engine was developed to study effects of these influence factors on the axial cutter vibration, three-directional cutting forces and the cutting quality of sugarcane harvesters. That is, experiments in sugarcane fields can be simulated in labs, which is never achieved in previous study. This study provided a reference for setting such cutting parameters as the cutter rotating speed, the cutter inclination angle and the travelling speed of sugarcane harvesters with a good SCQ.

2 Sugarcane cutting mechanism under complicated excitations

Simplified as a planar problem, the force diagram of a sugarcane cut by a blade is shown in Figure 1[19,20]. The x axis points to the direction of the sugarcane harvester travelling speed. The z axis along the cutter axes points to the upward vertical direction. Forces and motions along the y axis are not considered, so gravities and the supporting force generated by the ground acting on the sugarcane are not considered[19,20].



a. Effect of the upward axial blade vibration on the sugarcane b. Effect of the downward axial blade vibration on the sugarcane

Figure 1 Force diagram of a sugarcane

According to Figure 1a and Figure 1b, when an upward axial or a downward axial vibration of the cutters appears, the blade will generate an upward pressure F_{z_1} or a downward pressure F_{z_2} acting on the sugarcane and the upper or the lower surface of the cutter will also generate a friction force, f_1 or f_2 acting on the upper or the lower surface of the sugarcane. F_{z_1} and F_{z_2} are vertical to the wedge surface of the blade. F_{z_1}, F_{z_2}, f_1 and f_2 are along the same action line at the contact point O. The sugarcane harvester travelling speed is v_x. Therefore, the cutter will generate a pressure F_x along the x axis acting on the sugarcane at the point O. When stresses generated by F_x exceeded the lateral bending strength of the sugarcane, axial cracks of the sugarcane will appear and the sugarcane ratoon may be broken. F_{z_1} and F_{z_2} can be decomposed into the horizontal cutting force F_0, and the vertical compression N. The relationship between these two component forces is shown in Equation (1).

$$N = \frac{F_0}{\tan\varphi} \tag{1}$$

F_0 is calculated through the Experience Equation (2)[15].

$$F_0 = \frac{D}{2}\theta + S v_x - \xi\varphi + C \tag{2}$$

where, v_x is the sugarcane harvester travelling speed, m/s; D is the diameter of the sugarcane, m; S is the cut-in depth, m; θ is the cutter inclination angle, rad; φ is the cutting-edge angle, rad; ξ and C are constant dependent on mechanics characteristics of the sugarcane.

According to the classical friction law, when the upward axial cutter vibration appears, the friction force f_1 is calculated through Equation (3a). When the downward axial cutter vibration appears, the friction force f_2 is calculated through Equation (3b).

$$\begin{cases} f_1 = \left(F_{z_1} + \dfrac{N_1}{\cos\theta_1}\right)\mu & \text{(a)} \\ f_2 = \left(F_{z_2} + \dfrac{N_2}{\cos\theta_2}\right)\mu & \text{(b)} \end{cases} \tag{3}$$

Equation (1) and Equation (3) are combined to obtain Equation (4) used to calculate the resultant force, F_1 or F_2 are generated by the cutter along the tangential line of its circular motion.

$$\vec{F} = \vec{F}_0 + \vec{f} - \vec{F}_A \tag{4}$$

$$F_A = m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} \tag{5}$$

where, F_A is the inertia force keeping the rest state of the sugarcane when the axial cutter vibration shock acts on it, N; m is the equivalent mass of the sugarcane, kg.

Axial cutter vibration frequency components are complicated, which can be regarded as a combination of several simple axial harmonic vibrations shown in Equation (6a). According to force analysis of Figure 1, when the upward axial cutter vibration appears, F_{z_1} will generate a bending moment M_{z_1} acting at the point O. According to the second Newton Law, F_{z_1} and F_{z_2} are calculated through Equation (6b). When the downward axial cutter vibration appears, F_{z_2} will generate a bending moment F_{z_2} acting at the point O. M_{z_1} and M_{z_2} are calculated through Equation (6c).

$$\begin{cases} z = \sum_{i=1}^{N} A_i \sin(\omega_i t + \varphi_i) & \text{(a)} \\ F_z = m\dfrac{d^2 z}{dt^2} & \text{(b)} \\ M_z = F_z \dfrac{S}{2\cos\theta} & \text{(c)} \end{cases} \tag{6}$$

where, A_i is the axial cutter vibration amplitude of the sine series, m; ω_i is the axial cutter vibration angular frequency, rad/s; φ_i is the initial phase, rad.

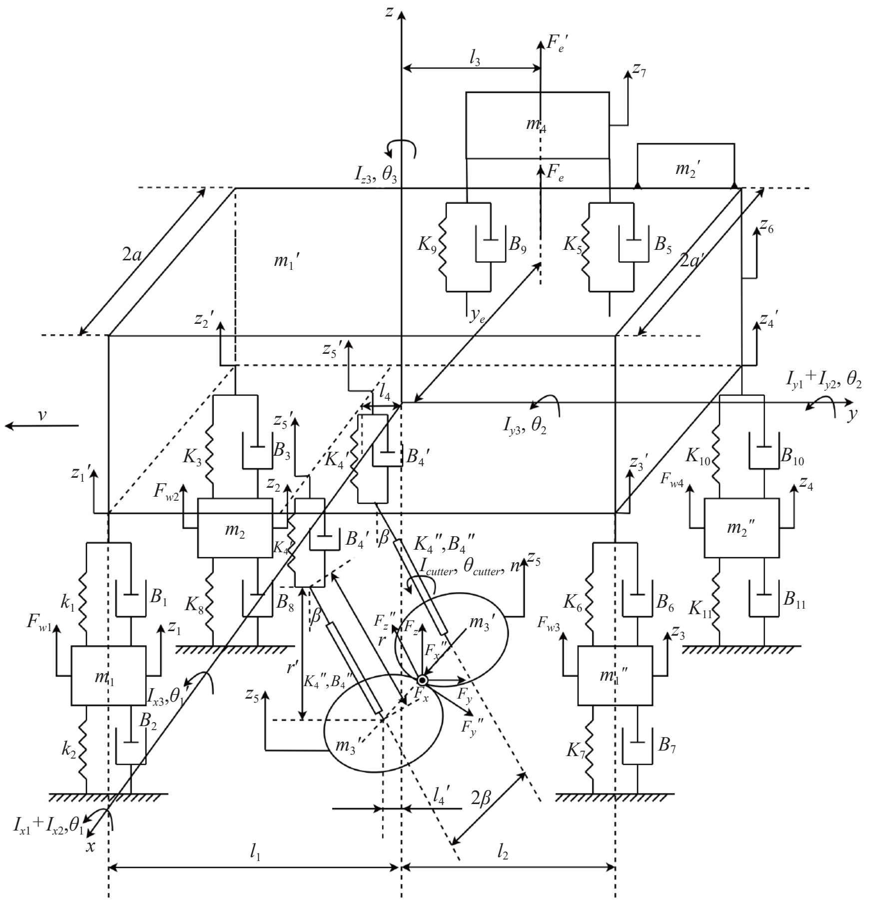
The tensile strength along the axial direction of the sugarcane is much greater than that along the lateral direction. If a sugarcane is not cut off at once along the lateral direction, cracks will be extended along the axial direction. Therefore, if a sugarcane is cut for several times, when the upward axial cutter vibration appears, under the combined action of M_{z_1} and the moment generated by F_x, M_x is calculated through Equation (7), the axial tearing cracks of the sugarcane will be easy to appear. When the downward axial cutter vibration appears, the sugarcane ratoon will be broken if F_{z_2} is greater than the compressive strength of the sugarcane.

$$M_x = F_x \frac{S}{2\sin\theta} \tag{7}$$

According to Equation (6), there is a positive correlated relationship between M_z and the axial cutter vibration amplitude A_i and frequency ω_i, the cut-in depth S while there is a negative correlated relationship between M_z and the cutter inclination angle θ. Therefore, the greater the axial cutter vibration amplitude and frequency as well as the cut-in depth are, the greater F_z and M_z will be, then the much more easily axial cracks of the sugarcane will appear, the poorer the SCQ will be, matching the conclusion of the previous research[11,12] that the axial cutter vibration has a bad effects on the cutting quality of sugarcane harvesters, which was further verified through experiments in this study. The greater the cutter inclination angle is, the smaller F_z and M_z will be, then the less easily axial cracks of the sugarcane will appear, the better the SCQ will be, also verified through experiments in this study.

3 Dynamics and mathematical models of sugarcane harvesters

The dynamics model of a sugarcane harvester is simplified as a multi-freedom-degree spring-damping-mass system shown in Figure 2[19]. Four wheels, two cutters, the body frame, the logistics frame and the engine of the sugarcane harvester are simplified as mass blocks. Connections of four wheels and the body frame as well as the sugarcane field, the cutting system and the body frame, the engine and the body frame are simplified as spring dampers.



Note: m_1, m_2, m_1'', m_2'', m_3'', m_1', m_2', m_4' are masses of two front wheels, two rear wheels, one cutter, the body frame, the logistics frame and the engine, kg; I_{cutter}, I_{x3}, I_{y3}, I_{z3}, I_{x1}, I_{y1}, I_{x2}, I_{y2} are rotational inertias of a cutter around x, y and z axes, the body frame and the logistics frame around x and y axes, kg·m^2; K_1, B_1, K_3, B_3 are stiffness and damping coefficients between two front wheels and the body frame, N/m, N/(m/s); K_2, B_2, K_8, B_8 are stiffness and damping coefficients between two front wheels and the sugarcane field, N/m, N/(m/s); K_6, B_6, K_{10}, B_{10} are stiffness and damping coefficients between two rear wheels and the body frame, N/m, N/(m/s); K_7, B_7, K_{11}, B_{11} are stiffness and damping coefficients between two rear wheels and the sugarcane field, N/m, N/(m/s); K_4', B_4' are the stiffness and the damping coefficients between the cutting system and the body frame, N/m, N/(m/s); K_4'', B_4'' are the stiffness and the damping coefficients between two cutter axes and the cutter frame, N/m, N/(m/s); K_9, B_9, K_5, B_5 are stiffness and damping coefficients of the front and the rear anti-vibration pads of the engine, N/m, N/(m/s).

Figure 2 Dynamics model of a sugarcane harvester

The mass center of the body frame is set as the coordinate origin. The z axis points to the upward vertical direction. The x axis along radiuses of two cutters points to the left of the sugarcane harvester. The y axis along the sugarcane harvester travelling speed points to the back of the sugarcane harvester.

F_{w1}, F_{w2}, F_{w3}, and F_{w4} are sugarcane field excitations acting on the four wheels, calculated through Equation (8)[21,22].

$$F_{w_i}(t) = K_i\xi(t) + B_i\dot{\xi}(t),\ \ i = 2, 8, 7, 11 \tag{8}$$

where, $\xi(t)$ is the piecewise fitting equation of sugarcane field roughness every 20 s, m, shown in Equation (9)[21,22].

$$\xi(t) = \sum_{i=1}^{8} a_i \sin(\omega_i t + \varphi_i) = \sum_{i=1}^{8} a_i \sin(2\pi f_i t + \varphi_i) \tag{9}$$

where, a_i is the amplitude, m; ω_i is the angular frequency, rad/s; f_i is the frequency, Hz; φ_i is the initial phase, rad.

F_e and F'_e are periodical forces acting on the body frame by the engine and the engine by its internal structures, calculated through Equation (10).

$$\begin{aligned} F_e(t) &= 55.17\sin(2\pi\times 40.021t) \\ F'_e(t) &= 2493\cos(2\times 2\pi\times 29.18t) \end{aligned} \tag{10}$$

where, F_x, F_y, and F_z are cutting forces along the x, the y, and the z axes, N, calculated through Equation (11).

$$\begin{aligned} F_x(t) &= 517.2\sin\left(2\pi\times 19.067t\right) \\ F_y(t) &= 414.2\sin\left(2\pi\times 19.067t\right) \\ F_z(t) &= 373.2\sin\left(2\pi\times 19.067t\right) \end{aligned} \tag{11}$$

where, F''_x, F''_y, and F''_z are the radial, the tangential and the axial cutting forces, N, calculated through Equation (12).

$$\begin{aligned} F''_x(t) &= 517.167\sin\left(2\pi\times 19.067t\right) \\ F''_y(t) &= 462.108\sin\left(2\pi\times 19.067t\right) \\ F''_z(t) &= 383.903\sin\left(2\pi\times 19.067t\right) \end{aligned} \tag{12}$$

where, a, a', and R are halves of the front wheel distance, the rear wheel distance and the centre distance of two cutters, a=0.68 m, a'= 0.605 m, R=0.27 m; l_1 and l_2 are distances between the mass centre of the body frame and the front axle, the mass centre of the body frame and the rear axle, l_1=1.8 m, l_2=1.2 m; l_4 and l'_4 are distances between the mass centre of the cutter frame and the z axis when the cutter inclination angle is 0°, the mass center of a cutter and the z axis in the sugarcane cutting process, l_4=0.9 m, l'_4=0.83 m; β and v are the cutter inclination angle and the sugarcane harvester travelling speed, β=8°, v=0.6 m/s; l_3 and y_e are distances between the mass centre of the body frame and the action line of F_e along the x axis and the y axis, l_3=0.1 m, y_e=0.303 m; r and r' are the length of a cutter axis and the distance between the mass centre of a cutter and the y axis in the sugarcane cutting process, r=0.5 m, r'= 0.495 m.

z'_1, z'_2, z'_3, z'_4 are vertical displacements of connection points of four wheels and the body frame; z'_5 is the vertical displacement of connection points of the cutting system and the body frame. They are calculated through Equation (13)[21,22].

$$\begin{aligned} z'_1 &= z_6 - \frac{a}{2}\theta_2 + r'\theta_2 - l'_4\theta_1 \\ z'_2 &= z_6 + \frac{a}{2}\theta_2 + r'\theta_2 - l'_4\theta_1 \\ z'_3 &= z_6 - \frac{a'}{2}\theta_2 - r'\theta_2 + l'_4\theta_1 \\ z'_4 &= z_6 + \frac{a'}{2}\theta_2 - r'\theta_2 + l'_4\theta_1 \\ z'_5 &= z_6 + r'\theta_2 - l'_4\theta_1 \end{aligned} \tag{13}$$

where, z_1, z_2, z_3, z_4, z_5, z_6, and z_7 are vertical displacements of four wheels, a cutter, the body frame and the engine, m; θ_{cutter}, θ'_1, θ'_2, and θ_3 are cutter rotating angles around its axis, the x, the y, and the z axes, rad. θ_1 and θ_2 are body frame rotating angles around the x and the y axes, rad; They are calculated through given values of parameters above.

According to the D'Alembert principle, the mathematical model of Figure 2 is written as Equation (14) in a matrix form[21-24].

$$M\ddot{Z} + B\dot{Z} + KZ = F \tag{14}$$

where, M, Z, B, K, and F are the generalized mass matrix, the generalized displacement column vector, the generalized damping coefficient matrix, the generalized stiffness coefficient matrix and the generalized external force column vector. M, B, and K are 13×13 square matrixes while Z and F are 13-dimentional column vectors. B and K depend on the force condition of Figure 2. All masses and rotational inertias are on the positive diagonal of M in the order of the left and the right front wheels, the left and the right rear wheels, the cutter, the body frame and the engine. The equivalent mass and rotational inertias of the body frame are $m'_1 + m'_2$, I_{x1}+I_{x2}, and I_{y1}+I_{y2}. Z and F are shown in Equation (15) and Equation (16).

$$\mathbf{Z} = [z_1\ z_2\ z_3\ z_4\ z_5\ z_6\ z_7\ \theta_{\text{cutter}}\ \theta_3\ \theta'_1\ \theta'_2\ \theta_1\ \theta_2]^{\mathrm{T}} \tag{15}$$

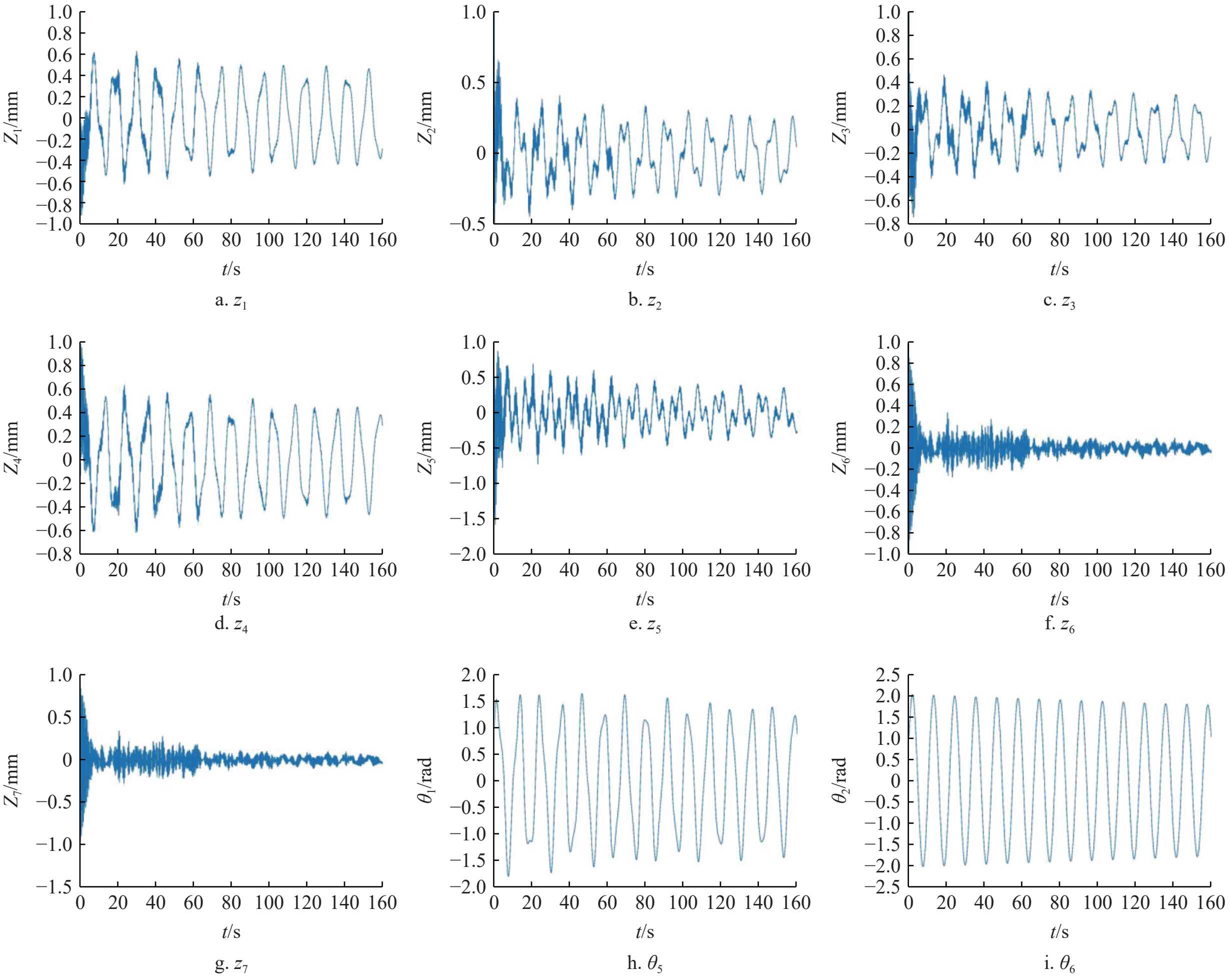
$$F = \begin{bmatrix} K_2\xi + B_2\dot{\xi} \\ K_8\xi + B_8\dot{\xi} \\ K_7\xi + B_7\dot{\xi} \\ K_{11}\xi + B_{11}\dot{\xi} \\ F''_z\cos\beta + F''_y\sin\beta - F''_x\sin\beta \\ F_e \\ F'_e \\ -F''_y R \\ F''_x l'_4\cos\beta \\ F''_x l'_4\sin\beta + F''_y r'\cos\beta - F''_y l'_4\sin\beta - F''_z l'_4\cos\beta - F''_z r'\sin\beta \\ -F''_x r'\cos\beta \\ F_e l_3 \\ F_e y_e \end{bmatrix} \tag{16}$$

Relationship curves of z_1, z_2, z_3, z_4, z_5, z_6, z_7, θ_1, and θ_2 changing with time drawn through MATLAB according to Equation (14) are shown in Figures 3a-3i.

As shown in Figures 3 that z_1-z_7, θ_1 and θ_2 change with time in periodical damping variation laws with gradually decreasing amplitudes in that F_w, F_e, and F'_e are periodical excitations. θ_{cutter}, θ'_1, θ'_2, and θ_3 become greater and greater along with time in that two cutters keep rotating around their axes, the x, the y, and the z axes in the sugarcane cutting process, so their relationship curves changing with time are simple monotonically-increasing lines neglected here. Therefore, the dynamics and the mathematical models of sugarcane harvesters are reasonable. Besides, according to Equation (14), there are 13 dependent variables in the mathematical model of sugarcane harvesters, so the dynamics model of sugarcane harvesters is a multi-input and multi-output second-order underdamped linear time-invariant discrete dynamics systems with 13 degrees of freedom.

Relationship curves of z_5 changing with a_i, f_i, n, v and β drawn through MATLAB according to Equation (14) are shown in Figures 4a-4e.

As is shown in Figure 4, the greater a_i and f_i are, the greater z_5 is, showing the more obvious the sugarcane field excitation is, that

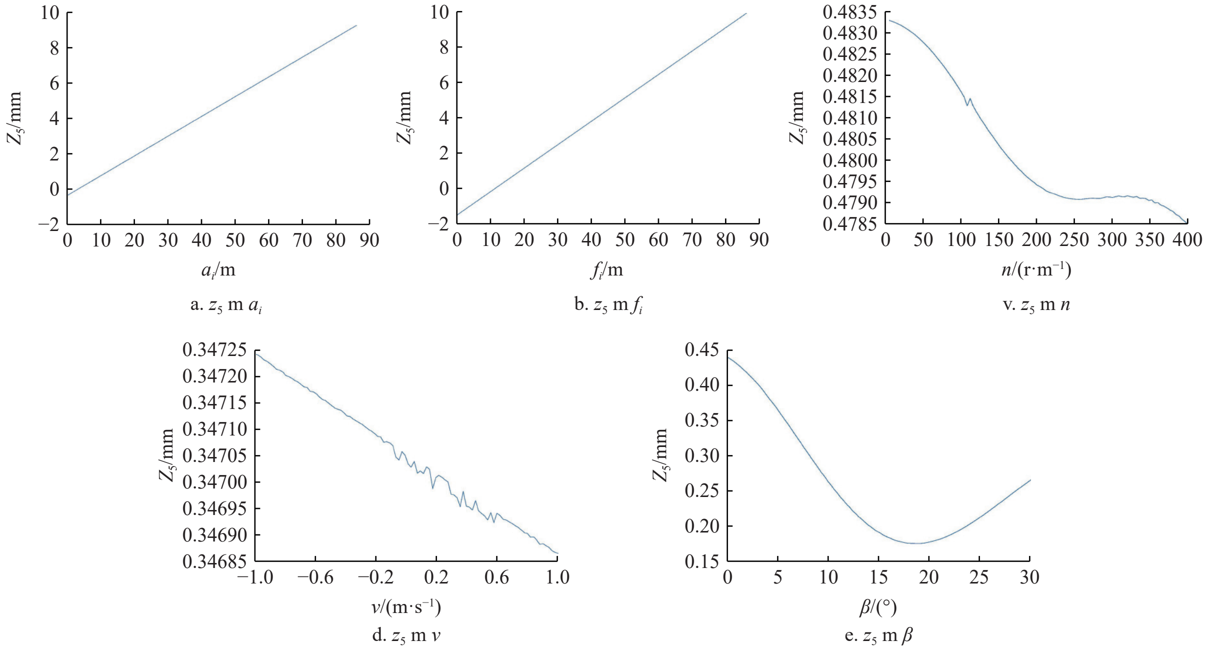


a. z_1 b. z_2 c. z_3

d. z_4 e. z_5 f. z_6

g. z_7 h. θ_5 i. θ_6

Figure 3 Relationship curves between different dependent variables and time



a. z_5 m a_i b. z_5 m f_i v. z_5 m n

d. z_5 m v e. z_5 m β

Figure 4 Relationship curves between z_5 and different parameters

is, the hillier a sugarcane field is, the more severe the axial cutter vibration will be, then the poorer the SCQ will be according to sugarcane cutting mechanism analysis, matching the conclusion of research above[11,12] that the sugarcane field excitation and the axial cutter vibration have bad effects on the cutting quality of sugarcane harvesters, further verified through experiments.

Additionally, according to Figures 4c-4e, the greater n, v and β are, the smaller z_5 is, showing the greater the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle are, the weaker the axial cutter vibration will be, then the better the SCQ will be according to the sugarcane cutting mechanism, further verified through experiments.

4 Materials and methods

4.1 Experiment materials

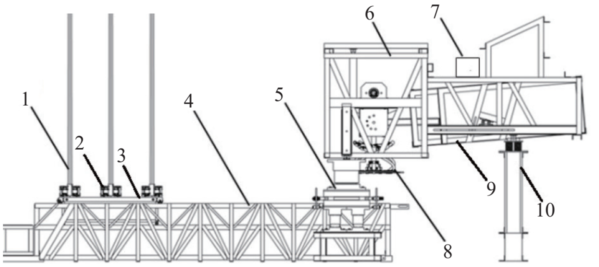
Fresh No.42 Guitang sugarcanes were used to do sugarcane cutting experiments. Sugarcanes are laterally isotropic[25]. That is, there are no differences in mechanics characteristics along their lateral direction. Significant differences exist in mechanics characteristics along their fiber direction and the vertical direction. Elasticity moduli along and vertical to the fiber direction of No.42 Guitang sugarcanes are 813.0 MPa and 152.5 MPa. Their Poisson ratios are 0.530, 0.105, and 0.265. Their shear moduli of the isotropic and the anisotropic planes are 17.75 MPa and 1.14 MPa. Bodies of these sugarcanes were straight and their leaves as well as burrs were wiped off. Their average diameter was (28±3) mm.

4.2 Experiment equipment

The manufactured SHTP and its structural diagram are shown in Figure 5. It is mainly made up of the sugarcane transporting pathway (STP), the sugarcane-holding device, the sugarcane-transporting vehicle, two SFEDs, two vibration absorbers, the actuating engine, the cutting system, the body frame and the logistics frame. On the SHTP, the sugarcane field excitation is simulated through two SFEDs and the engine excitation is simulated through the actuating engine. The manufactured SFED and its three-dimensional model are shown in Figure 6[21,22,26]. It was developed based on characteristics of sugarcane field roughness signals collected in a flat and a hilly sugarcane fields[21,22,26].

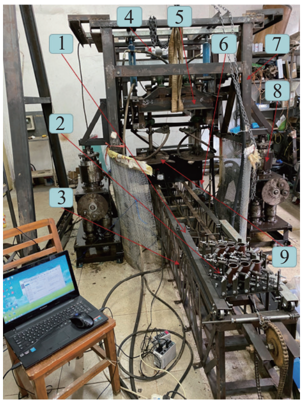
Sugarcanes were inserted into nine sleeves of the sugarcane-holding device. The distance between every group of three sugarcanes is 300 mm. Two cutters with four blades were used. The cutting-edge angle is 30º. The x axis points to the direction of the sugarcane transporting speed of the sugarcane-transporting vehicle. The sugarcane harvester travelling speed is simulated through the sugarcane transporting speed. The z axis points to the upward vertical direction. The y axis is vertical to the plane formed by the x and the z axes.

The experiment equipment is as follow: two digital frequency convertors, a piezoelectric three-directional force-measuring instrument, a digital angle-measuring instrument, a laser speed-measuring instrument, an LK-G150 laser displacement sensor, a high-speed camera and a hydraulic system. Digital frequency convertors were used to control output frequencies and amplitudes of two SFEDs and the actuating engine. The main experiment equipment is shown in Figure 7.



1. Sugarcane 2. Sugarcane-holding device 3. Sugarcane-transporting vehicle 4. STP 5. SFED 6. Body frame 7. Actuating engine 8. Cutting system 9. Logistics frame 10. Vibration absorber

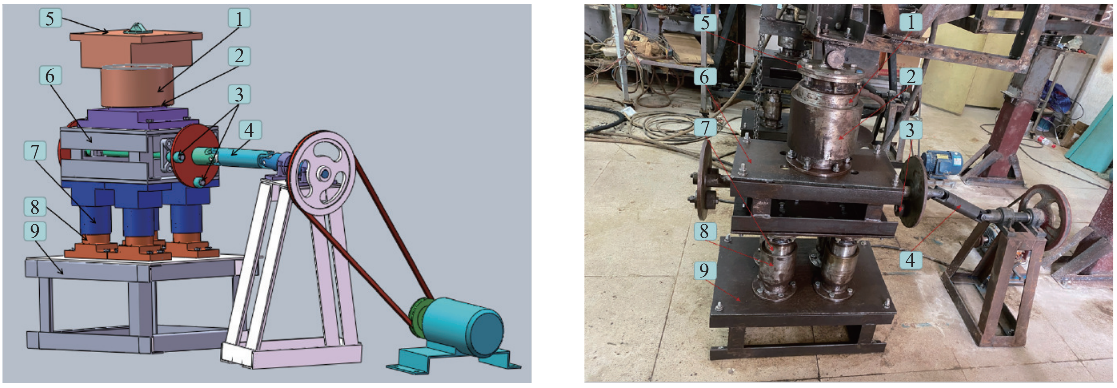
a. Structural diagram of SHTP



1. Sugarcane-transporting vehicle 2. Sugarcane-holding device 3. STP 4. Actuating engine 5. Cutter frame 6. Vibration absorber 7. Body frame 8. SFED 9. Cutter

b. Prototype of SHTP

Figure 5 Structural diagram and prototype of SHTP



1, 2. External and the internal sleeves of the upper spring 3. Eccentric mass blocks 4. Axis coupler 5, 6, 9. Upper, middle and lower support platforms 7, 8. External and the internal sleeves of a lower spring

a. Three-dimensional model of SFED

1, 2. External and the internal sleeves of the upper spring 3. Eccentric mass blocks 4. Axis coupler 5, 6, 9. Upper, middle and lower support platforms 7, 8. External and the internal sleeves of a lower spring

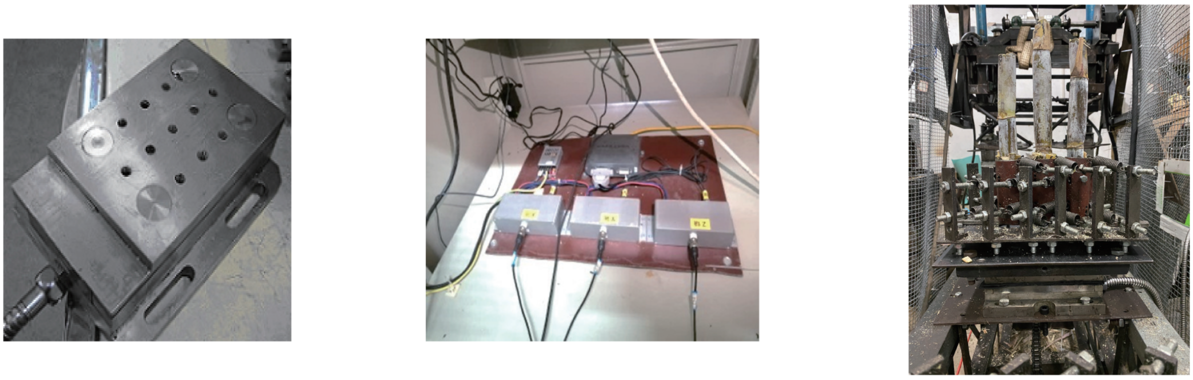
b. Prototype of SFED

Figure 6 Three-dimensional model and prototype of SFED

Three-directional cutting forces were measured through the force-measuring system. According to the high-speed photographing result in the sugarcane cutting process, there are wave crests, showing in the sugarcane cutting process of sugarcane harvesters, a sugarcane is cut off in more than one time of cutting. Three column vectors corresponding to three-directional cutting forces were obtained through the common milling force-measuring system in every group of experiments. In every column vector, the number of absolute values much greater than others is equal to the number of wave crests got by high-speed photographing. The average value of these greater absolute values was calculated as the value of the cutting force along this direction.

a. The laser of the LK-G150 laser displacement sensor falling on the cutter along the *z* axis to measure the axial cutter vibration amplitude

b. The digital angle-measuring instrument put on the cutter to measure the cutter inclination angle



c. Piezoelectric three-directional force measuring instrument

d. Three channels of the piezoelectric three -directional forcemeasuring instrument corresponding to the *x*, the *y* and the *z* axes

e. Piezoelectric three-directional force measuring instrument installed under the sugarcane-holding device

Figure 7 Main experiment equipment

4.3 Sugarcane cutting quality evaluating indexes

Sugarcane cutting quality evaluating indexes were the number of sugarcanes whose ratoon were broken, the axial crack number, the axial crack depth and the axial crack length[19,20,27,28]. The sugarcane cutting quality evaluating value (SCQEV) was calculated with these four indexes through the improved entropy method[19,20,27,28] shown in Equation (17).

$$\begin{cases} x'_{ij} = \dfrac{x_{ij} - x_{j\min}}{x_{j\max} - x_{j\min}}, \quad p_{ij} = x'_{ij} \Big/ \sum\limits_{i=1}^{m} x'_{ij} \\ k = 1/\ln m, \quad e_j = -k \sum\limits_{i=1}^{m} p_{ij} \ln p_{ij} \\ g_j = 1 - e_j, \quad w_j = g_j \Big/ \sum\limits_{j=1}^{4} g_j \\ Q_i = \sum\limits_{j=1}^{4} x'_{ij} w_j, \quad Q = \sum\limits_{i=1}^{m} Q_i \Big/ m \end{cases} \tag{17}$$

where, x'_{ij}, x_{ij} are the membership degree and the value of j-th index in i-th repeated experiment under the same condition, j=1, 2, 3, 4, respectively, the number of sugarcanes whose ratoons were broken, the axial crack number, the axial crack depth and the axial crack length, i=1, 2, 3, …, m, Every group of experiments in this study were done for five times, so m=5; $x_{j\max}$ and $x_{j\min}$ are the maximum and the minimum values of j-th index; p_{ij} is the proportion of j-th index in i-th experiment; e_j, g_j, and w_j are the entropy value, the difference coefficient and the weight of j-th index; Q_i is the SCQEV of i-th experiment; Q is the average value of Q_i, as the SCQEV of this experiment condition. The greater the SCQEV is, the poorer the SCQ is.

4.4 Experiment design

4.4.1 Single-factor experiment design

Single-factor experiments were done under simulated complicated excitations, that is, the combined action of two SFEDs, the actuating engine and cutting forces. Experimental factors were the SFED output frequency, the cutter rotating speed, the cutter inclination angle and the sugarcane transporting speed. Experimental indexes were the axial cutter vibration amplitude, three-directional cutting forces and the SCQEV. These experiments were aimed at studying effects of the axial cutter vibration amplitude and frequency, the cutter rotating speed, the cutter inclination angle and the sugarcane harvester travelling speed on three-directional cutting forces and the SCQ.

In order to avoid the resonance of the SHTP, constant levels of the SFED output frequency and the actuating engine output frequency were set as 4 Hz and 30 Hz[25]. According to previous research results, constant levels of the cutter rotating speed, the sugarcane transporting speed and the cutter inclination angle were set as 650 r/min, 0.6 m/s and 15°[29]. Levels of these experimental factors are listed in Table 1.

Table 1 Levels of experimental factors

Experimental factor	Constant level	Range	Step length
Cutter rotating speed/r·min^{-1}	650	450-750	50
Cutter inclination angle/(°)	15	0-20	2
Sugarcane transporting speed/m·s^{-1}	0.6	0.1-0.8	0.1
SFED output frequency/Hz	4	1-9	1
Actuating engine output frequency/Hz	30		

4.4.2 Orthogonal experiment design

Experimental factors of this orthogonal experiment were output frequencies of the SSFE and the actuating engine, the cutter rotating speed, the sugarcane transporting speed, the cutter inclination angle. Their levels are listed in Table 2. Experimental indexes were the axial cutter vibration displacement, three-directional cutting forces and the SCQEV. This orthogonal experiment was aimed at studying significance levels of effects of the sugarcane field excitation, the engine excitation, the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle on the axial cutter vibration, three-directional cutting forces and the SCQ. Effects of the axial cutter vibration on three-directional cutting forces and the SCQ as well as effects of three-directional cutting forces on the SCQ were further studied. The $L_{25}(5^6)$ orthogonal table was chosen. The experiment arrangement is listed in Table 3.

Table 2 Levels of the five experimental factors

Experiment factor	Level				
	1	2	3	4	5
SFED output frequency *A*/Hz	8	11	17	20	25
Actuating engine output frequency *B*/Hz	19	22	26	28	30
Cutter rotating speed *C*/r·min^{-1}	450	500	650	700	750
Sugarcane transporting speed *D*/m·s^{-1}	0.4	0.5	0.6	0.7	0.8
Cutter inclination angle *E*/(°)	4	8	16	18	20

Table 3 Experiment arrangement of the orthogonal experiment cutting sugarcanes under simulated complicated excitations

Group	Experimental factor					
	A	*B*	*C*	*D*	*E*	Blank column
1	1	1	1	1	1	1
2	1	2	2	2	2	2
3	1	3	3	3	3	3
4	1	4	4	4	4	4
5	1	5	5	5	5	5
6	2	1	2	3	4	5
7	2	2	3	4	5	1
8	2	3	4	5	1	2
9	2	4	5	1	2	3
10	2	5	1	2	3	4
11	3	1	3	5	2	4
12	3	2	4	1	3	5
13	3	3	5	2	4	1
14	3	4	1	3	5	2
15	3	5	2	4	1	3
16	4	1	4	2	5	3
17	4	2	5	3	1	4
18	4	3	1	4	2	5
19	4	4	2	5	3	1
20	4	5	3	1	4	2
21	5	1	5	4	3	2
22	5	2	1	5	4	3
23	5	3	2	1	5	4
24	5	4	3	2	1	5
25	5	5	4	3	2	1

5 Results

5.1 Single-factor experiment result analysis

5.1.1 Effects of the sugarcane field excitation on the axial cutter vibration and cutting forces

The sugarcane field excitation has a bad effect on the cutting quality of sugarcane harvesters in that it causes vibrations of sugarcane harvesters, leading to vibrations of the cutters and the axial cutter vibration has a bad effect on the cutting quality of sugarcane harvesters[11,12]. Therefore, change laws of the axial cutter vibration amplitude and three-directional cutting forces with the SFED output frequency were studied.

A three-directional cutting force signal under a 4 Hz output frequency of the SFED and a 700 r/min cutter rotating speed is shown in Figure 8. The total number of blades is 8 and the blades distribute uniformly around the cutters, so the shortest cutting time interval of the cutters is 0.0106 s. There are two wave crests in Figure 8, that is, the sugarcane was cut by the cutters twice and the sugarcane was cut off after two times of cutting according to what was captured by the high-speed camera in Figure 9, so in the sugarcane cutting process of sugarcane harvesters, a sugarcane is cut off by more than one time of cutting. Moreover, in Figure 9, these two cut-in points were different, that is, there was a height difference between them, so when the sugarcane was cut for the second time, the cutters pressed the sugarcane and the axial cutter vibration might make the sugarcane ratoon broken. Therefore, the axial cutter vibration amplitude and frequency directly affect the SCQ. Three-directional cutting forces were measured through a common milling force-measuring system.

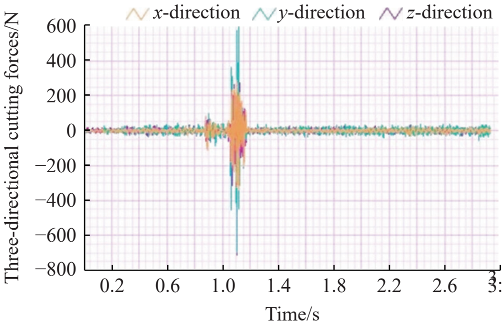


Figure 8 Three-directional cutting force signal

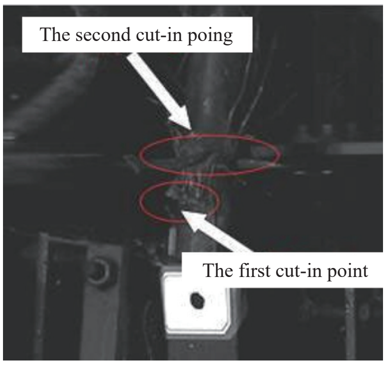
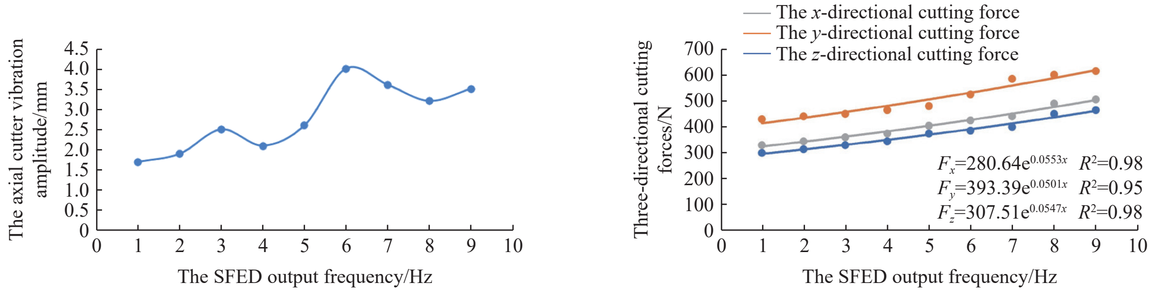


Figure 9 High-speed photograph in the sugarcane cutting process

The average value of results of five times of experiments under the same condition was chosen as the final result of this group of experiments.

Relationship curves of the axial cutter vibration amplitude and three-directional cutting forces changing with the SFED output frequency are shown in Figure 10.

According to Figure 10a, the greater the SFED output frequency was, the greater the axial cutter vibration amplitude was. According to Figure 10b, determination coefficients of these fitting curves and their fitting equations are greater than 0.95, so they have high accuracies. There are obviously positive monotonic correlated relationships between three-directional cutting forces and the SFED output frequency. That is, the greater the SFED output frequency was, the greater three-directional cutting forces were. Monotonic correlation and single-factor variance analysis results with the SFED output frequency as the independent variable got though SPSS are listed in Tables 4 and 5.



a. Axial cutter vibration amplitude and SFED output frequency b. Three-directional cutting forces and SFED output frequency

Figure 10 Relationship curves of the axial cutter vibration amplitude and three-directional cutting forces changing with the SFED output frequency

Table 4 Monotonic correlation analysis results of the axial cutter vibration amplitude and three-directional cutting forces changing with the SFED output frequency

Experimental index	Monotonic correlation coefficient	*p*-value
Axial cuter vibration amplitude	0.957	0.000
x-directional cutting force	0.065	0.040
y-directional cutting force	0.043	0.045
z-directional cutting force	0.190	0.039

It is listed in Table 4 that p values are smaller than 0.05, so there are significant monotonic correlated relationships between the axial cutter vibration amplitude and the SFED output frequency, three-directional cutting forces and the SFED output frequency. Moreover, monotonic correlation coefficients are greater than 0, so there are significantly positive monotonic correlated relationships between the axial cutter vibration amplitude and the SFED output frequency, three-directional cutting forces and the SFED output frequency, matching what are found through Figure 10. Therefore, the more obvious the sugarcane field excitation is, that is, the hillier a sugarcane field is, the more severe the axial cutter vibration and the greater three-directional cutting forces will be. The more severe the axial cutter vibration is, the greater the axial cutter vibration amplitude and frequency will be, so the more obvious the sugarcane field excitation is, that is, the hillier a sugarcane field is, the greater the axial cutter vibration amplitude and frequency will be, matching what are found through Figures 4a and 4b.

Table 5 Single-factor variance analysis results with the SFED output frequency as the independent variable

Experimental index	Axial cutter vibration amplitude					*x*-directional cutting force				
Source	Quadratic sum	Freedom degree	Mean square value	*F* value	*p* value	Quadratic sum	Freedom degree	Mean square value	*F* value	*p* value
Inter-group	458.398	17	26.965	302.562	0.000	2 865 071.943	17	168 533.644	3.27	0.001
Intra-group	3.208	36	0.089			1 855 500.245	36	51 541.673		
Total value	461.606	53				4 720 572.188	53			
Experimental index	*y*-directional cutting force					*z*-directional cutting force				
Source	Quadratic sum	Freedom degree	Mean square value	*F* value	*p* value	Quadratic sum	Freedom degree	Mean square value	*F* value	*p* value
Inter-group	7 628 341.311	17	448 725.959	3.247	0.001	4 769 919.277	17	280 583.487	9.029	0.000
Intra-group	4 974 733.432	36	138 187.040			1 118 757.555	36	31 076.599		
Total value	12 603 074.743	53				5 888 676.831	53			

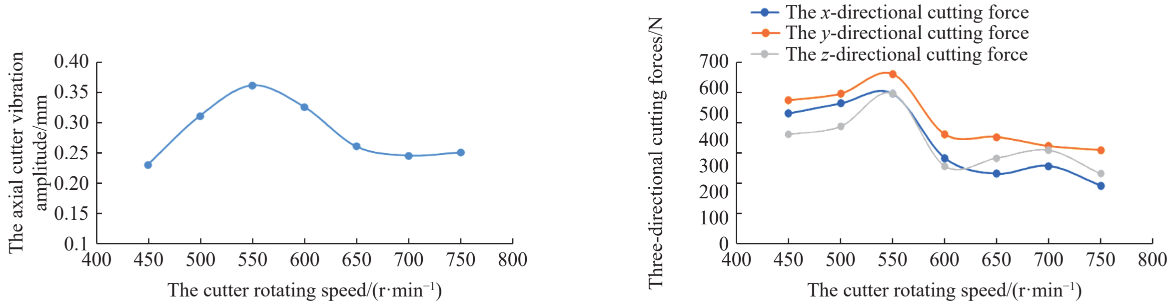
Besides, as shown in Table 5 that p values are smaller than 0.05, so the SFED output frequency has significant effects on the axial cutter vibration amplitude and three-directional cutting forces. Therefore, the sugarcane field excitation has significantly positive monotonic correlated effects on the axial cutter vibration and three-directional cutting forces.

On the other hand, according to Figure 10a, when the SFED output frequency was 6 Hz, the axial cutter vibration amplitude increased to 4.03 mm, the maximum value. According to LMS modal test results of the SHTP got previously by our research group[21,22], there is an inherent frequency of the SHTP near 6 Hz. In order to avoid the resonance of the SHTP, the SFED output frequency should be far away from 6 Hz. According to Figure 10b, the resonance of the SHTP made three-directional cutting forces increase significantly. Therefore, the greater the SFED output frequency and the axial cutter vibration amplitude are, making the compressive frequency and the pressure of the cutters acting on the sugarcane greater, then causing three-directional cutting forces to increase. That is, the more obvious the sugarcane field excitation and the more severe the axial cutter vibration are, that is, the hillier a sugarcane field is and the greater the axial cutter vibration amplitude and frequency are, the greater three-directional cutting forces will be.

5.1.2 Effects of the cutter rotating speed on the axial cutter vibration and three-directional cutting forces

Relationship curves of the axial cutter vibration amplitude and three-directional cutting forces changing with the cutter rotating speed are shown in Figure 11.

According to Figure 11a, the axial cutter vibration amplitude increased along with the cutter rotating speed increasing at the beginning. When the cutter rotating speed was 550 r/min, the axial cutter vibration amplitude reached the maximum value, 0.36 mm. Then the axial cutter vibration amplitude decreased along with the cutter rotating speed increasing and it kept being 0.24 mm. Therefore, there should be a resonance point of the SHTP near 9.2 Hz, the output frequency of 550 r/min, matching results of the LMS modal test of the SHTP got previously by our research group that there is an inherent frequency of the SHTP near 10 Hz[21,22]. According to Figure 11b, along with the cutter rotating speed increasing, three-directional cutting forces increased firstly and then decreased. When the cutter rotating speed was 550 r/min, three-directional cutting forces increased significantly. Change laws of three-directional cutting forces with the cutter rotating speed are similar to that of the axial cutter vibration amplitude.



a. Axial cutter vibration amplitude and the cutter rotating speed b. Three-directional cutting forces and the cutter rotating speed

Figure 11 Relationship curves of the axial cutter vibration amplitude and three-directional cutting forces changing with the cutter rotating speed

Monotonic correlation and single-factor variance analysis results with the cutter rotating speed as the independent variable got though SPSS are listed in Tables 6 and 7.

As is listed in Table 6, p values are smaller than 0.05, so there are significant monotonic correlated relationships between the axial cutter vibration amplitude and the cutter rotating speed, three-directional cutting forces and the cutter rotating speed. Moreover, monotonic correlation coefficients are smaller than 0, so there are significantly negative monotonic correlated relationships between the axial cutter vibration amplitude and the cutter rotating speed, three-directional cutting forces and the cutter rotating speed. Therefore, the greater the cutter rotating speed is, the more severe the axial cutter vibration and the greater three-directional cutting forces will be, so the greater the cutter rotating speed is, the greater the axial cutter vibration amplitude and frequency will be, matching what is found through Figure 4c.

Table 6 Monotonic correlation analysis results of the axial cutter vibration amplitude and three-directional cutting forces changing with the cutter rotating speed.

Experimental index	Monotonic correlation coefficient	p-value
Axial cuter vibration amplitude	–0.025	0.044
x-directional cutting force	–0.043	0.040
y-directional cutting force	–0.023	0.045
z-directional cutting force	–0.120	0.044

Table 7 Single-factor variance analysis results with the cutter rotating speed as the independent variable

Experimental index	The axial cutter vibration amplitude					x-directional cutting force				
Source	Quadratic sum	Freedom degree	Mean square value	F value	p value	Quadratic sum	Freedom degree	Mean square value	F value	p value
Inter-group	39.466	11	3.588	108.757	0.000	244 532.067	11	22 230.188	4.574	0.001
Intra-group	0.792	24	0.033			116 652.457	24	4860.519		
Total value	40.258	35				361 184.524	35			
Experimental index	**y-directional cutting force**					**z-directional cutting force**				
Source	Quadratic sum	Freedom degree	Mean square value	F value	p value	Quadratic sum	Freedom degree	Mean square value	F value	p value
Inter-group	934 882.281	11	84 989.298	4.342	0.001	628 898.261	11	57 172.569	10.044	0.000
Intra-group	469 822.212	24	19 575.926			136 610.341	24	5692.098		
Total value	1 404 704.493	35				765 508.602	35			

Moreover, it is shown in Table 7 that p values are smaller than 0.05, so the cutter rotating speed has significantly negative monotonic correlated effects on the axial cutter vibration and three-directional cutting forces.

5.1.3 Effects of the sugarcane harvester travelling speed and the cutter inclination angle on three-directional cutting forces

Relationship curves of three-directional cutting forces changing with the sugarcane transporting speed and the cutter inclination angle are shown in Figures 12 and 13.

Determination coefficients of these fitting curves and their fitting equations are greater than 0.96, so they have high accuracies. There are obviously positive monotonic correlated relationships between three-directional cutting forces and the sugarcane transporting speed, three-directional cutting forces, and the cutter inclination angle. That is, the greater the sugarcane transporting speed and the cutter inclination angle were, the greater three-directional cutting forces were. Monotonic correlation and single-factor variance analysis results with the sugarcane transporting speed and the cutter inclination angle as independent variables got though SPSS are listed in Tables 8-11.

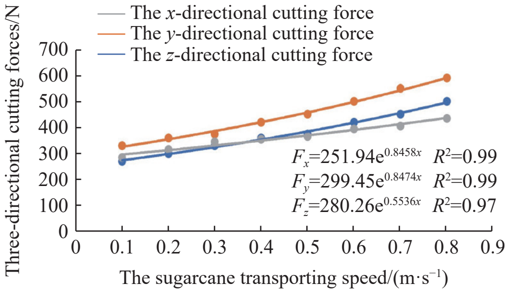


Figure 12 Relationship curves between three-directional cutting forces and the sugarcane transporting speed

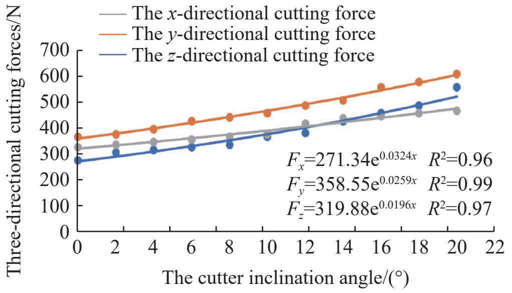


Figure 13 Relationship curves between three-directional cutting forces and the cutter inclination angle

Table 8 Monotonic correlation analysis results of three-directional cutting forces and the sugarcane transporting speed

Experimental index	Monotonic correlation coefficient	p value
The x-directional cutting force	0.688	0.000
The y-directional cutting force	0.665	0.000
The z-directional cutting force	0.867	0.000

Table 9 Monotonic correlation analysis results of three-directional cutting forces and the cutter inclination angle

Experimental index	Monotonic correlation coefficient	p value
x-directional cutting force	0.154	0.042
y-directional cutting force	0.144	0.044
z-directional cutting force	0.194	0.049

Table 10 Single-factor variance analysis results with the sugarcane transporting speed as the independent variable

Experimental index	x-directional cutting force					y-directional cutting force					z-directional cutting force				
Source	Quadratic sum	Freedom degree	Mean square value	F value	p value	Quadratic sum	Freedom degree	Mean square value	F value	p value	Quadratic sum	Freedom degree	Mean square value	F value	p value
Inter-group	144 558.591	7	20 651.227	3.060	0.030	552 587.222	7	78 941.032	3.636	0.015	370 760.430	7	52 965.776	12.010	0.000
Intra-group	107 987.836	16	6749.240			347 384.372	16	21 711.523			70 564.646	16	4410.290		
Total value	252 546.428	23				899 971.594	23				441 325.076	23			

Table 11 Single-factor variance analysis results with the cutter inclination angle as the independent variable

Experimental index	x-directional cutting force					y-directional cutting force					z-directional cutting force				
Source	Quadratic sum	Freedom degree	Mean square value	F value	p value	Quadratic sum	Freedom degree	Mean square value	F value	p value	Quadratic sum	Freedom degree	Mean square value	F value	p value
Inter-group	106 469.987	10	10 646.999	1.955	0.041	406 990.367	10	40 699.037	2.323	0.048	273 071.685	10	27 307.169	7.673	0.000
Intra-group	119 810.773	22	5445.944			385 417.389	22	17 518.972			78 290.343	22	3558.652		
Total value	226 280.760	32				792 407.756	32				351 362.028	32			

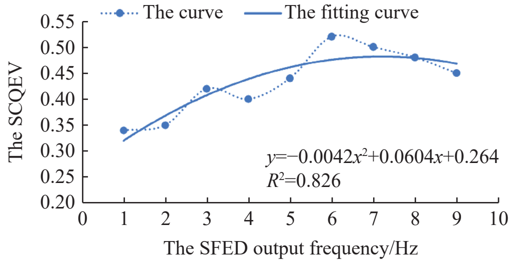
It is listed in Tables 8 and 9 that p values are smaller than 0.05, so there are significant monotonic correlated relationships between three-directional cutting forces and the sugarcane transporting speed, three-directional cutting forces and the cutter inclination angle. Moreover, monotonic correlation coefficients are greater than 0, so there are significantly positive monotonic correlated relationships between three-directional cutting forces and the sugarcane transporting speed, three-directional cutting forces and the cutter inclination angle, matching what are found through Figure 12 and Figure 13. Therefore, the greater the sugarcane harvester travelling speed and the cutter inclination angle are, the greater three-directional cutting forces will be.

Meanwhile, according to Tables 10 and 11, p values are smaller than 0.05, so the sugarcane transporting speed and the cutter inclination angle have significant effects on three-directional cutting forces. Therefore, the sugarcane harvester travelling speed and the cutter inclination angle have significantly positive monotonic correlated effects on three-directional cutting forces.

5.1.4 Effects of field excitation, cutter rotating speed, harvester travelling speed and cutter inclination angle on the SCQ

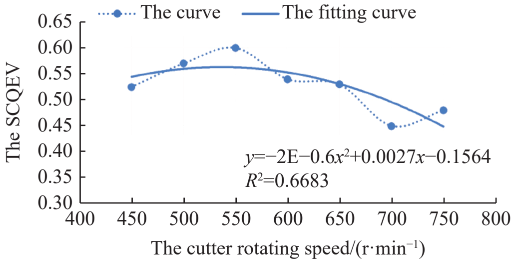
Relationship curves of the SCQEV changing with the SFED output frequency, the cutter rotating speed, the sugarcane transporting speed and the cutter inclination angle are shown in Figures 14-17.

Determination coefficients of these fitting curves and their fitting equations are greater than 0.65, so they have high accuracies. According to Figure 14, when the SFED output frequency increased, the SCQEV increased with a poorer SCQ. When the SFED output frequency was 6 Hz, the SCQEV reached the maximum value, 0.53 with the poorest SCQ. According to Figure 15, the SCQ can be improved when the cutter rotating speed increases. The optimal cutter rotating speed is 700 r/min. When the cutter rotating speed was 550 r/min with the output frequency of 9.2 Hz, the SCQ was the poorest in that the resonance of the SHTP appeared, causing the greatest axial cutter vibration amplitude according to Figure 10a. According to Figure 16, along with the sugarcane transporting speed increasing, the SCQEV decreased firstly with a better SCQ and then it increased with a poorer SCQ. The optimal sugarcane transporting speed is 0.6 m/s with the best SCQ, that is, the optimal sugarcane harvester travelling speed is 0.6 m/s. According to Figure 17, the SCQ will be poorer when the cutter inclination angle increases. The optimal cutter inclination angle is 8° with the best SCQ.



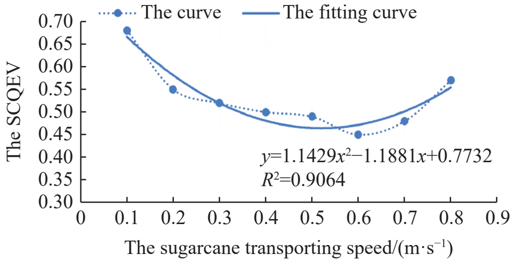
y=−0.0042x^2+0.0604x+0.264
R^2=0.826

Figure 14 Relationship between SCQEV and SFED output frequency



y=−2E−0.6x^2+0.0027x−0.1564
R^2=0.6683

Figure 15 Relationship between SCQEV and cutter rotating speed



y=1.1429x^2−1.1881x+0.7732
R^2=0.9064

Figure 16 Relationship between SCQEV and sugarcane transporting speed

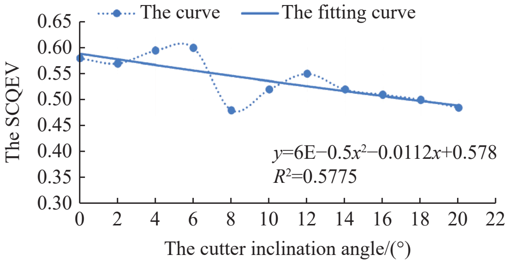


Figure 17 Relationship between SCQEV and cutter inclination angle

Based on analysis above, optimal level combination of the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle is 700 r/min, 0.6 m/s and 8° for sugarcane harvesters with a good SCQ.

Monotonic correlation and single-factor variance analysis results with the SFED output frequency, the cutter rotating speed, the sugarcane transporting speed and the cutter inclination angle as independent variables and the SCQEV as the dependent variable got though SPSS are listed in Tables 12 and 13.

Table 12 Monotonic correlation analysis results of the SCQEV changing with SFED output frequency, cutter rotating speed, sugarcane transporting speed and the cutter inclination angle

Experimental factor	Monotonic correlation coefficient	p-value
SFED output frequency	0.106	0.046
Cutter rotating speed	–0.012	0.045
Sugarcane transporting speed	–0.664	0.000
Cutter inclination angle	–0.167	0.044

Table 13 Single-factor variance analysis results with SFED output frequency, cutter rotating speed, sugarcane transporting speed and cutter inclination angle as independent variables and SCQEV as the dependent variable

Experimental factor	Source	Quadratic sum	Freedom degree	Mean square value	F-value	p-value
SFED output frequency	Inter-group	41.001	17	2.412	1.207	0.048
	Intra-group	71.942	36	1.998		
	Total value	112.943	53			
Cutter rotating speed	Inter-group	0.276	11	0.025	0.159	0.049
	Intra-group	3.801	24	0.158		
	Total value	4.077	35			
Sugarcane transporting speed	Inter-group	0.161	7	0.023	1.424	0.043
	Intra-group	0.259	16	0.016		
	Total value	0.420	23			
Cutter inclination angle	Inter-group	0.119	10	0.012	1.096	0.046
	Intra-group	0.238	22	0.011		
	Total value	0.357	32			

According to Table 12, p values are smaller than 0.05, so there are significant monotonic correlated relationships between the SCQEV and the SFED output frequency, the SCQEV and the cutter rotating speed, the SCQEV and the sugarcane transporting speed, the SCQEV and the cutter inclination angle. Moreover, the monotonic correlation coefficient between the SCQEV and the SFED output frequency is greater than 0, so there is a significantly positive monotonic correlated relationship between the SCQEV and the SFED output frequency, matching what is found through Figure 14. Therefore, the more obvious the sugarcane field excitation is, that is, the hillier a sugarcane field is, the poorer the SCQ will be, matching what are found through Figures 4a and 4b. Monotonic correlation coefficients between the SCQEV and the cutter rotating speed, the SCQEV and the sugarcane transporting speed, the SCQEV and the cutter inclination angle are smaller than 0, so there are significantly negative monotonic correlated relationships between the SCQEV and the cutter rotating speed, the SCQEV and the sugarcane transporting speed, the SCQEV and the cutter inclination angle, matching what are found through Figures 15-17. Therefore, the greater the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle are, the better the SCQ will be, matching the sugarcane cutting mechanism and what are found through Figures 4c-4e.

Furthermore, it is listed in Table 13 that p values are smaller than 0.05, so the SFED output frequency, the cutter rotating speed, the sugarcane transporting speed and the cutter inclination angle have significant effects on the SCQEV. Therefore, the sugarcane field excitation has a significantly positive monotonic correlated effects on the SCQ while the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle have significantly negative monotonic correlated effects on the SCQ.

5.2 Orthogonal experiment result analysis

Main effect analysis results obtained through multi-factor variance analysis of SPSS are listed in Tables 14-16.

Table 14 Main effect analysis result of the axial cutter vibration displacement in the sugarcane cutting process as the dependent variable

Source	Dependent variable: axial cutter vibration displacement in the sugarcane cutting process G					
	III-type quadratic sum	Freedom degree	Mean square value	F-value	p-value	Partial eta square
The corrected model	260.423ª	20	13.021	141.663	0.000	0.981
The intercept	2754.351	1	2754.351	29 965.851	0.000	0.998
The SFED output frequency A	247.260	4	61.815	672.513	0.000	0.980
The actuating engine output frequency B	2.577	4	0.644	7.009	0.000	0.342
The cutter rotating speed C	7.742	4	1.936	21.058	0.000	0.609
The sugarcane transporting speed D	1.262	4	0.316	3.433	0.014	0.203
The cutter inclination angle E	1.582	4	0.395	4.303	0.004	0.242
Error	4.963	54	0.092			
Total value	3019.738	75				
Corrected total value	265.387	74				

a. R^2=0.981 (Corrected R^2=0.974)

As listed in Tables 14-16, when the axial cutter vibration displacement in the sugarcane cutting process is the dependent variable, the p value of the sugarcane transporting speed is smaller than 0.05 while those of the other four experimental factors are smaller than 0.01, so the sugarcane harvester travelling speed has a significant effect on the axial cutter vibration in the sugarcane cutting process while the cutter inclination angle, the sugarcane field excitation, the cutter rotating speed and the engine excitation have highly significant effects on the axial cutter vibration in the sugarcane cutting process. Moreover, partial eta square values of these five experimental factors are greater than 0.14, so effect sizes of the sugarcane field excitation, the engine excitation, the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle on the axial cutter vibration in the sugarcane cutting process are large.

Table 15 Main effect analysis result of the axial cutter vibration displacement in the sugarcane cutting process as the co-variate and three-directional cutting forces as dependent variables

Source	Dependent variable: three-directional cutting forces																	
	III-type quadratic sum			Freedom degree			Mean square value			F-value			p-value			Partial eta square		
	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z
Corrected model	1 848 069.754^{a}	6 188 978.115^{a}	4 138 789.808^{a}	21	21	21	88 003.322	294 713.244	197 085.229	20.344	12.004	55.158	.000	.000	.000	.890	.826	.956
Intercept	85 460.645	237 130.145	53 768.583	1	1	1	85 460.645	237 130.145	53 768.583	19.756	9.659	15.048	.000	.003	.000	.272	.154	.221
A	83 861.492	232 124.313	52 785.409	4	4	4	20 965.373	58 031.078	13 196.352	4.847	2.364	3.693	.002	.045	.010	.268	.151	.218
B	30 388.189	77 931.778	19 250.230	4	4	4	7597.047	19 482.945	4812.557	1.756	0.794	1.347	.152	.535	.265	.117	.057	.092
C	51 190.817	149 376.589	32 068.590	4	4	4	12 797.704	37 344.147	8017.148	2.958	1.521	2.244	.028	.209	.077	.183	.103	.145
D	16 854.042	49 835.837	10 544.992	4	4	4	4213.510	12 458.959	2636.248	0.974	0.507	0.738	.430	.730	.570	.068	.037	.053
E	21 046.915	55 002.884	13 312.254	4	4	4	5261.729	13 750.721	3328.063	1.216	0.560	0.931	.315	.693	.453	.084	.041	.066
G	219 503.045	20 673.922	2389.249	1	1	1	219 503.045	20 673.922	2389.249	50.743	2.842	4.669	.000	.043	.007	.489	.160	.312
Error	229 266.206	1 301 200.634	189 374.076	53	53	53	4325.777	24 550.955	3573.096									
Total value	19 249 394.378	73 010 425.262	48 135 884.017	75	75	75												
Corrected total value	2 077 335.960	7 490 178.749	4 328 163.884	74	74	74												
a. R^2	0.890	0.826	0.956															

Table 16 Main effect analysis result of the axial cutter vibration displacement in the sugarcane cutting process as the co-variate and the SCQEV as the dependent variable

Source	Dependent variable: SCQEV					
	III-type quadratic sum	Freedom degree	Mean square value	F-value	p-value	Partial eta square
The corrected model	2.150^{a}	21	0.102	0.663	0.849	0.208
The intercept	0.637	1	0.637	4.125	0.047	0.072
A	0.628	4	0.157	1.016	0.048	0.144
B	0.238	4	0.060	0.385	0.818	0.028
C	0.370	4	0.092	0.599	0.665	0.043
D	0.121	4	0.030	0.195	0.940	0.015
E	0.163	4	0.041	0.264	0.900	0.020
G	0.378	1	0.378	2.449	0.004	0.171
Error	8.186	53	0.154			
Total value	29.095	75				
Corrected total value	10.336	74				

a. R^2=0.208 (Corrected R^2=0.106)

When the x-directional cutting force is the dependent variable, p values of the actuating engine output frequency, the sugarcane transporting speed and the cutter inclination angle are greater than 0.05 while those of the SFED output frequency, the axial cutter vibration displacement are smaller than 0.01 and that of the cutter rotating speed is smaller than 0.05, so except the engine excitation, the sugarcane harvester travelling speed and the cutter inclination angle, the sugarcane field excitation and the axial cutter vibration have highly significant effects on the x-directional cutting force while the cutter rotating speed have a significant effect on the x-directional cutting force. Moreover, partial eta square values of the SFED output frequency, the axial cutter vibration displacement and the cutter rotating speed are greater than 0.14, so effect sizes of the sugarcane field excitation, the axial cutter vibration and the cutter rotating speed on the x-directional cutting force are large.

When the y-directional cutting force is the dependent variable, p values of the cutter rotating speed, the actuating engine output frequency, the sugarcane transporting speed and the cutter inclination angle are greater than 0.05 while those of the SFED output frequency and the axial cutter vibration displacement are smaller than 0.05, so except the cutter rotating speed, the engine excitation, the sugarcane harvester travelling speed and the cutter inclination, the sugarcane field excitation and the axial cutter vibration have significant effects on the y-directional cutting force. Moreover, partial eta square values of the SFED output frequency and the axial cutter vibration displacement are greater than 0.14, so effect sizes of the sugarcane field excitation and the axial cutter vibration on the y-directional cutting force are large.

When the z-directional cutting force is the dependent variable, p values of the cutter rotating speed, the actuating engine output frequency, the sugarcane transporting speed and the cutter inclination angle are greater than 0.05 while that of the SFED output frequency is smaller than 0.05 and that of the axial cutter vibration displacement are smaller than 0.01, so except the cutter rotating speed, the engine excitation, the sugarcane harvester travelling speed and the cutter inclination angle, the sugarcane field excitation has a significant effect on the z-directional cutting force and the axial cutter vibration has a highly significant effect on the z-directional cutting force. Moreover, partial eta square values of the SFED output frequency and the axial cutter vibration displacement are greater than 0.14, so effect sizes of the sugarcane field excitation and the axial cutter vibration on the z-directional cutting force are large.

When the SCQEV is the dependent variable, the p value of the SFED output frequency is smaller than 0.05 and that of the axial cutter vibration displacement is smaller than 0.01 while those of the other four experimental factors are greater than 0.05, so except the engine excitation, the cutter rotating speed, the sugarcane harvester moving speed and the cutter inclination angle, the sugarcane field excitation has a significant effect on the SCQ and the axial cutter vibration has a highly significant effect on the SCQ. Moreover, partial eta square values of the SFED output frequency and the axial cutter vibration displacement are greater than 0.14, so effect sizes of the sugarcane field excitation and the axial cutter vibration on the SCQ are large.

In addition, significance levels of effects of the sugarcane field excitation, the engine excitation, the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle on the axial cutter vibration in the sugarcane cutting process from high to low are $A>C>B>E>D$. Significance levels of effects of these five experimental factors and the axial cutter vibration on three-directional cutting forces and the SCQ from high to low are $G>A>C>B>E>D$.

Fitting equations of the axial cutter vibration displacement, three-directional cutting forces and the SCQEV changing with these five experimental factors obtained through multi-factor linear regression analysis of SPSS are shown in Equations (18)-(22), in which experimental factors with p values greater than 0.05, that is, without significant effects, were removed.

$$y_1 = 1.022 + 0.37A - 0.38B + 0.015C + 3.999D - 0.054E \tag{18}$$

$$y_2 = 59.121 + 29.426A + 1.156C + 308.059G \tag{19}$$

$$y_3 = 107.738 + 57.613A + 69.262G \tag{20}$$

$$y_4 = 149.544 + 46.357A + 58.608G \tag{21}$$

$$y_5 = 0.233 + 0.029A + 0.069G \tag{22}$$

where, y_1-y_5 are the axial cutter vibration displacement, the x-directional cutting force, the y-directional cutting force, the z-directional cutting force and the SCQEV; A-G are the SFED output frequency, the actuating engine output frequency, the cutter rotating speed, the sugarcane transporting speed, the cutter inclination angle and the axial cutter vibration displacement in the sugarcane cutting process.

Effects of the axial cutter vibration on three-directional cutting forces and the SCQ as well as effects of three-directional cutting forces on the SCQ were further studied. Fitting curves of three-directional cutting forces changing with the axial cutter vibration displacement, the fitting curve of the SCQEV changing with the axial cutter vibration displacement and fitting curves of the SCQEV changing with three-directional cutting forces drawn through Excel based on the orthogonal experiment result are shown in Figures 18-20.

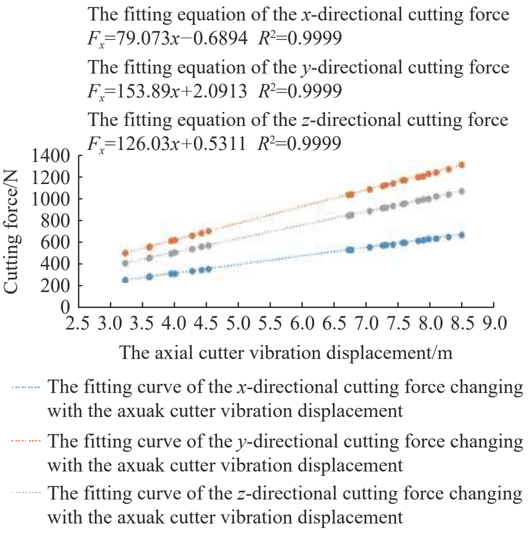


Figure 18 Fitting curves of three-directional cutting forces changing with the axial cutter vibration displacement

Determination coefficients of these fitting curves and fitting equations are all greater than 0.95, so they have high accuracies. There are obvious positive monotonic correlated relationships between the axial cutter vibration displacement and three-directional cutting forces, the axial cutter vibration displacement and the SCQEV, three-directional cutting forces and the SCQEV. That is, the greater the axial cutter vibration displacement is, the greater three-directional cutting forces are. The greater the axial cutter vibration displacement and three-directional cutting forces are, the greater the SCQEV is, the poorer the SCQ will be. Their monotonic correlation analysis results obtained through SPSS are listed in Tables 17 and 18.

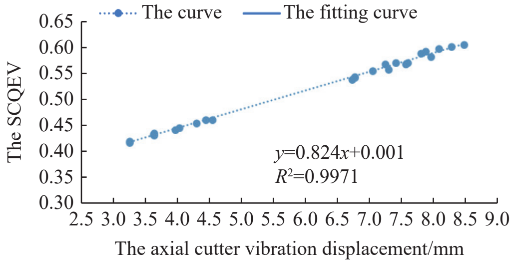


Figure 19 Fitting curve of the SCQEV changing with the axial cutter vibration displacement

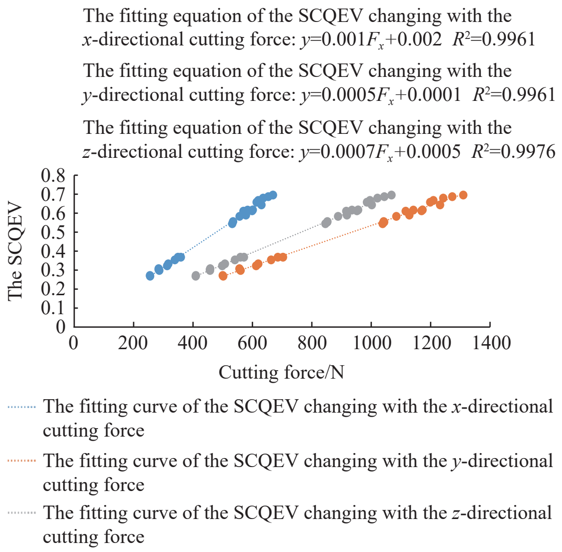


Figure 20 Fitting curves of the SCQEV changing with three-directional cutting forces

Table 17 Monotonic correlation analysis results of three-directional cutting forces and the axial cutter vibration displacement

Coefficient	Cutting force		
	x	y	z
Monotonous correlation coefficient	0.999	0.999	0.998
p value	0.000	0.000	0.000

As shown in Table 17 that p values are all 0, so there are significant monotonic correlated relationships between three-directional cutting forces and the axial cutter vibration displacement. Moreover, monotonic correlation coefficients are all greater than 0, so there are significant positive monotonic correlated relationships between three-directional cutting forces and the axial cutter vibration displacement, that is, the greater the axial cutter vibration displacement is, the greater three-directional cutting forces will be. Therefore, the more severe the axial cutter vibration in the sugarcane cutting process is, the greater three-directional cutting forces will be. This verifies the discovery about the effect of the axial cutter vibration on three-directional cutting forces obtained in single-factor experiments.

Table 18 Monotonic correlation analysis results of the SCQEV and the axial cutter vibration displacement, the SCQEV and three-directional cutting forces

Coefficient	Independent variable			
	Axial cutter vibration displacement	x-directional cutting force	y-directional cutting force	z-directional cutting force
Monotonous correlation coefficient	0.993	0.992	0.992	0.995
p value	0.000	0.000	0.000	0.000

What's more, as listed in Table 18 that p values are all 0, so there are significant monotonic correlation relationships between the SCQEV and the axial cutter vibration displacement, the SCQEV and three-directional cutting forces. Moreover, monotonic correlation coefficients are all greater than 0, so there are significant positive monotonic correlated relationships between the SCQEV and the axial cutter vibration displacement, the SCQEV and three-directional cutting forces, that is, the greater the axial cutter vibration displacement and three-directional cutting forces are, the greater the SCQEV will be, the poorer the SCQ will be. Therefore, the more severe the axial cutter vibration in the sugarcane cutting process is, the poorer the SCQ will be. This verifies the discovery about effects of the axial cutter vibration and three-directional cutting forces on the SCQ obtained in single-factor experiments.

On the other hand, there is an obviously positive monotonic correlated relationship between SCQEV and the axial cutter vibration amplitude according to Figure 19. That is, the greater the axial cutter vibration amplitude is, the greater the SCQEV is, the poorer the SCQ will be. It is also shown by their monotonic correlation analysis result that there is a highly significant positive monotonic correlated relationships between the SCQEV and the axial cutter vibration amplitude, matching the conclusion of the previous research[11,12] and the sugarcane cutting mechanism that the axial cutter vibration has a bad effect on the cutting quality of sugarcane harvesters. Therefore, the more severe the axial cutter vibration is, that is, the greater the axial cutter vibration amplitude and frequency are, the poorer the SCQ will be, so the more obvious the sugarcane field excitation is, that is, the hillier a sugarcane field is, the poorer the SCQ will be in that the more obvious the sugarcane field excitation is, the more severe the axial cutter vibration will be, making the axial cutter vibration amplitude and frequency greater, further matching what are found through Figures 4a and 4b. The greater the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle are, the better the SCQ will be in that the greater the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle are, the weaker the axial cutter vibration is, making the axial cutter vibration amplitude and frequency smaller, further matching what are found through Figures 4c-4e.

6 Analysis and discussions

According to the sugarcane cutting mechanism, the pressure F_z and the bending moment M_z generated by the cutter acting on the sugarcane increase along with the axial cutter vibration amplitude and frequency increasing. This will make axial cracks of the sugarcane appear and the ratoon broken.

There are height differences among different cut-in points. This is bad for the cutting quality of sugarcane harvesters, making a sugarcane cut off by more than one time of cutting and F_z increase. Then M_z generated by F_z will make axial cracks of the sugarcane appear. When a sugarcane is cut for the second time, the cutters will press the sugarcane and the axial cutter vibration will make the sugarcane ratoon broken. The breaking degree of the sugarcane is dependent on the axial cutter vibration amplitude and frequency, so the axial cutter vibration amplitude and frequency directly affect the SCQ, matching the sugarcane cutting mechanism.

There are positive monotonic correlated relationships between three-directional cutting forces and the axial cutter vibration amplitude and frequency. The greater the axial cutter vibration amplitude is, the greater the pressure, the friction force and the z-directional cutting force generated by the cutters acting on the sugarcane will be, which makes the x-directional and the y-directional cutting forces also increase.

Along with the cutter rotating speed increasing, three-directional cutting forces increased firstly and then decreased. This is mainly relative to cutter rotations around cutter axes and sugarcane toughness. Effects of the axial cutter vibration amplitude on three-directional cutting forces are significant. When the cutter rotating speed decreases, causing lack of cutting energies, the cutters will push down and compress the sugarcane instead of cutting off the sugarcane at once. This will cause a cutting force accumulation.

Three-directional cutting forces increase along with the cutter inclination angle increasing in that the contact area between the cutters and the sugarcane is increased when the cutter inclination angle increases. When the sugarcane harvester moves forward, the cutters will generate a pushing force acting on the sugarcane. The cutters are inclined, so this pushing force can be decomposed into three-directional component forces, that is, three-directional cutting forces. The greater the cutter inclination angle is, the greater these three-directional component forces will be.

Three-directional cutting forces increase along with the sugarcane harvester travelling speed increasing. This is similar to effects of the cutter inclination angle on three-directional cutting forces, so Figures 12 and 13 are similar. When the cutter inclination angle is constant, the greater the sugarcane harvester travelling speed is, the greater the pushing force generated by the cutters acting on the sugarcane will be. Thus, three-directional cutting forces will be greater. Based on analysis above, some SCQ-improving methods can be obtained as follow:

When the axial cutter vibration amplitude and frequency increase, the sugarcane will suffer from the pressure F_z and the bending moment M_z. When the sugarcane is cut for the second time, the sugarcane will be easy to be compressed and torn. The sugarcane ratoon will be broken if the axial cutter vibration amplitude is extremely great, so the axial cutter vibration amplitude should be reduced through vibration reducing methods of sugarcane harvesters. Inherent frequencies of sugarcane harvesters should be increased to avoid their resonance. Besides, it is good for improving the cutting quality of sugarcane harvesters to increase the cutter rotating speed. Lack of cutting energies appear with a low cutter rotating speed, making the cutters generate shocks acting on the sugarcane, compress and shock it instead of cutting it off rapidly. Then sugarcane toughness prevents cutting energies and the cutters reaching the interior of the sugarcane rapidly, causing damages and cracks of the sugarcane. Therefore, the cutter rotating speed ought to be great enough to cut off the sugarcane rapidly in order to effectively improve the cutting quality of sugarcane harvesters. Moreover, a great cutter inclination angle increases the contact area between the cutters and the sugarcane, making the sugarcane ratoon not easy to be broken by the cutters. The axial tensile strength of the cutters is much greater than the radial one, so a great cutter inclination angle is able to help cut off the sugarcane. Additionally, under a low sugarcane harvester travelling speed, the sugarcane may be cut off after several times of cutting, which leads to a poor SCQ while under a high sugarcane harvester travelling speed, the cutters may generate a great pushing force acting on the sugarcane, which makes it easy to break the sugarcane ratoon. Therefore, it is necessary to find suitable values of such cutting parameters as the cutter rotating speed, the cutter inclination angle and the sugarcane harvester travelling speed for sugarcane harvesters with a good SCQ.

7 Conclusions

1) The sugarcane field excitation, the sugarcane harvester travelling speed and the cutter inclination angle have significantly positive monotonic correlated effects on the axial cutter vibration and three-directional cutting forces while the cutter rotating speed has a significantly negative monotonic correlated effect on the axial cutter vibration and three-directional cutting forces.

2) The sugarcane field excitation, the axial cutter vibration amplitude and frequency have significantly negative monotonic correlated effects on SCQ while the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle have significantly positive monotonic correlated effects on the SCQ.

3) Optimal level combination of the cutter rotating speed, the sugarcane harvester travelling speed, and the cutter inclination angle is 700 r/min, 0.6 m/s, and 8° for sugarcane harvesters with a good SCQ.

4) The sugarcane harvester travelling speed has a significant effect on the axial cutter vibration in the sugarcane cutting process while the cutter inclination angle, the sugarcane field excitation, the cutter rotating speed and the engine excitation have highly significant effects on the axial cutter vibration in the sugarcane cutting process.

Except the engine excitation, the sugarcane harvester travelling speed and the cutter inclination angle, the sugarcane field excitation and the axial cutter vibration have highly significant effects on the x-directional cutting force while the cutter rotating speed have a significant effect on the x-directional cutting force.

Except the cutter rotating speed, the engine excitation, the sugarcane harvester travelling speed and the cutter inclination, the sugarcane field excitation and the axial cutter vibration have significant effects on the y-directional cutting force, the z-directional cutting force and the SCQ.

Significance levels of effects of the sugarcane field excitation, the engine excitation, the cutter rotating speed, the sugarcane harvester travelling speed and the cutter inclination angle on the axial cutter vibration in the sugarcane cutting process from high to low are $A>C>B>E>D$. Significance levels of effects of these five experimental factors and the axial cutter vibration on three-directional cutting forces and the SCQ from high to low are $G>A>C>B>E>D$.

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