Strength analysis and optimal design of transmission system of sugarcane leaf stripping machine

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Abstract: In order to find out the causes of crackles grown on rubber wheels and improve the reliability of the sugarcane leaf stripping machine, strength analysis and optimal design were studied on the transmission system. With the introduction of the structure, working process and strength problem, multi-body dynamics was carried out based on virtual prototype model of the sugarcane leaf stripper. Dynamics simulation showed that the relatively large forces on rubber wheels were the major reason for crackles. Experiments were used to verify the accuracy of the model and the result. In order to reduce the forces on cracked rubber wheels, optimal design was carried out based on orthogonal test with taking front distance, front spring's stiffness and preload, rear distance, rear spring's stiffness and preload as variables, taking maximum absolute value and mean value of the forces as observations. Range analysis showed that preload of rear spring and stiffness of front spring had significant effect on the maximum absolute value of the force on front under wheel, while stiffness of rear spring and preload of front spring affected that on rear upper wheel significantly. The optimal results showed that when the six selected variables were chosen as 15 mm, 10 N/mm, 40 N, 18 mm, 15 N/mm and 45 N respectively, the maximum absolute value of forces on four rubber wheels had reduced 29.63%, 32.16%, 46.68% and 2.5% compared with initial parameters. At the same time, the mean value had reduced 43.73%, 29.33%, 45.63% and 58.04%. The optimal design has obvious effect and provides strong evidence for improving the machine.

Keywords: sugarcane leaf stripping machine, crackle, multi-body dynamics, orthogonal test, optimal design

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1 Introduction

Guangxi is Chinese largest sugarcane planting area and sugar producing area (Ma et al., 2012; Zhan, 2013). Both planting size and sugar yield account for more than 60% of China. The industrial scale ranks the first in China, which benefits 20 million farmers (Zhan, 2013). However, most of the sugarcane planting regions in Guangxi are narrow hilly topography (Huang et al., 2009). At present, in these areas, mechanization lags behind and large combine harvester is difficult to be widely used. Sectional type of harvest, cutting sugarcane and peeling leaf separately, is the main way to take (Zhan, 2013; Shen et al., 2014). In face of so huge a scale, the problems of harvesting sugarcane and stripping leaf fast and efficiently need to be solved urgently.

The sugarcane harvester consists of cut-section and whole-stalk sugarcane harvester. Whole-stalk type contains joint type and sectional type. Cut-section harvester is commonly used in sugar industry developed countries, such as America, Australia and Brazil, while whole-stalk harvester is widely used in our country, especially sectional type (Zhan, 2013). With the promotion of agricultural mechanization, more and more sugarcane harvesting and leaf stripping machinery have been invented and used (Huang et al., 2008; Yao et al., 2007; Li et al., 2008), and the relevant theoretical and practical research were carried out as well.

In the aspect of whole-stalk joint sugarcane harvester, researches mainly focused on analysis and improvement of sugarcane cutter and lifting mechanism (Li et al.,

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2016), feeding system (Shen et al., 2014) and breaking tails mechanism (Ma et al., 2012; Luo et al., 2013).

In the aspect of stripping leaf, Shang et al. (2000) studied the stripping principle with computer image technology. Wang et al. (2007) established the dynamics model of stripping leaf and studied the relationship between stripping quality and influencing factors. Liu et al. (2007) explored the mechanics properties of crop stalks, as well as the damage process in cutting sugarcane stalk with smooth-edge blade. Mou et al. (2014) researched the elastic dentations in the process of sugarcane leaf sheath stripping with analysis and experiment. Meng et al. (2003) analyzed the design and property of the cleaning element with virtual experiments.

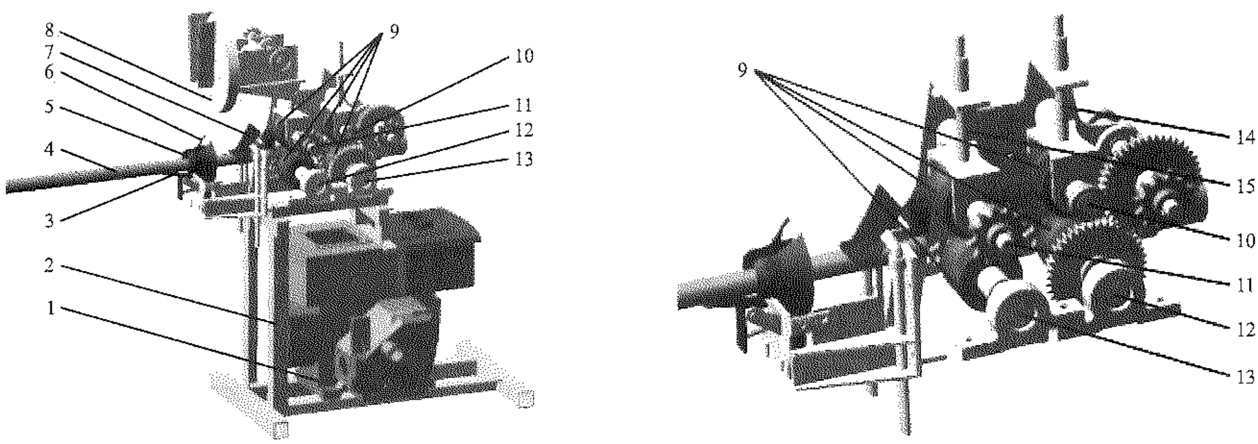
By referring to the previous research experience, a new type of sugarcane leaf stripper was developed, which is different from the machine depends on the hitting of flexible element. The machine works through the rational arrangement of cutting tools and feeding mechanism. Experimental results showed that the stripping effect was improved. However, because of the long working hours and poor working environment, the issues of poor reliability occurred.

In order to find out the causes of crackles grown on rubber wheels and improve the reliability of the sugarcane leaf stripping machine, strength analysis and optimal design were carried out on the transmission system. Strength analysis aimed at finding out the reason for the crackles on rubber wheels. Optimal design was expected to seek out the better parameters' combination to reduce force on the rubber wheels and improve the reliability of the machine.

2 Materials and methods

2.1 Sugarcane leaf stripping machine

Based on the majority of sugarcane leaf stripping machine on the market, the fulfilling of the stripping depends on the hitting of the leaf stripping element (Meng et al., 2003). But the machine in the paper works through the rational arrangement of cutting tools and feeding mechanism. The structure of the machine is shown in Figure 1.



1. Engine 2. Machine frame 3. Front knife 4. Sugarcane 5. Left knife 6. Right knife 7. Back knife 8. Circular saw 9. Rubber wheel 10. Rear upper shaft 11. Front upper shaft 12. Front under shaft 13. Rear under shaft 14. Rear spring 15. Front spring

Figure 1 Structure of the sugarcane leaf stripping machine

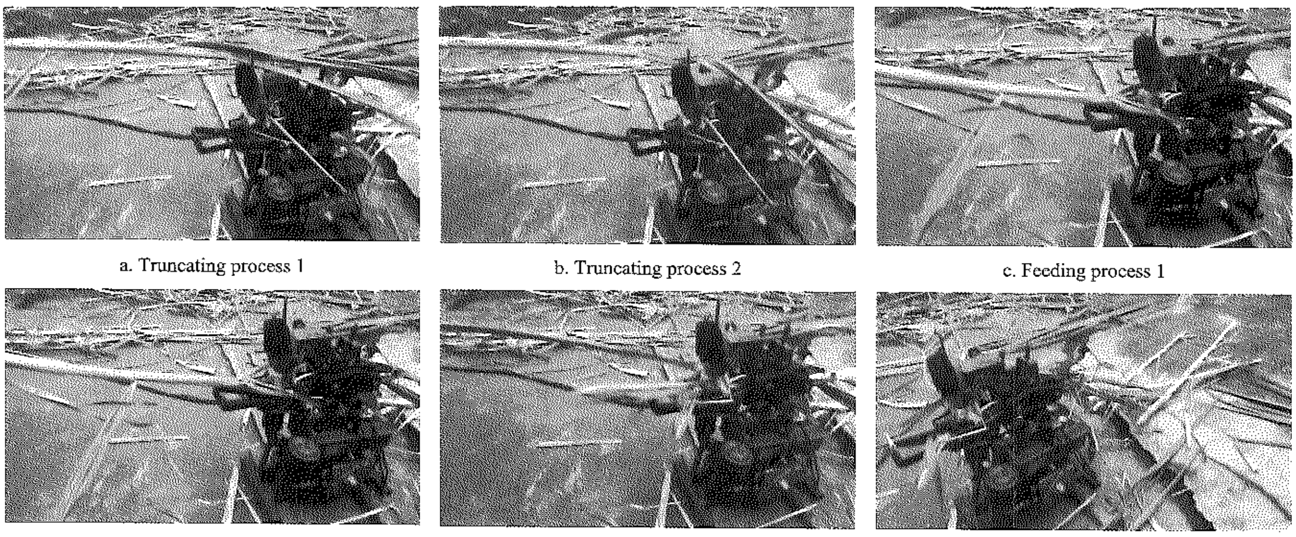
2.1.1 Working process

The using process of the leaf stripping machine consists of truncation, feeding, and transmission, as shown in Figure 2. When the machine works, the tail of the sugarcane was cut off by the circular saw at first. And then give the sugarcane an initial force to make it enter the drive mechanism through knife tools in every direction. At last, the sugarcane moved forward under the driving of the rubber wheel. And at the same time, the leaf of the sugarcane was cut off by the combined knife tools.

After the above 3 processes, the leaf on the sugarcane was stripped by the combined tools.

2.1.2 Strength problem

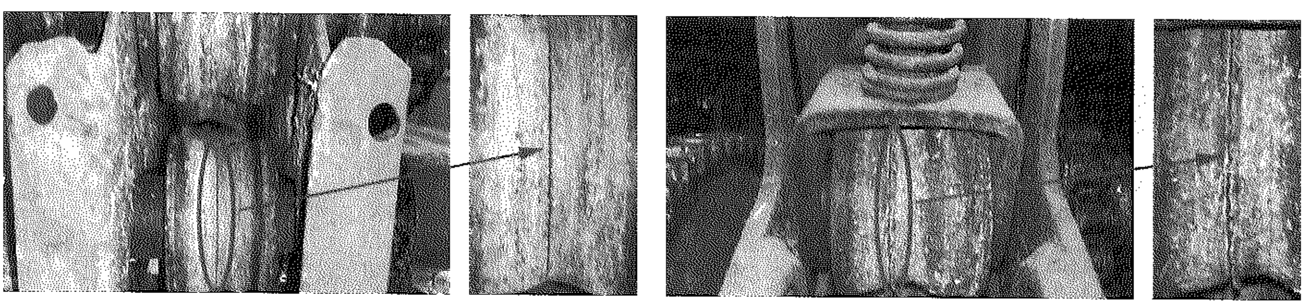
According to the experimental test, stripping effect of the machine was better, as well as lower impurity rate and acceptable structural strength of the frame (Yang et al., 2016; Xu et al., 2016). However, after using for a period of time, different degrees of wear and crackle appeared on the surface of the front under wheel and rear upper wheel. Figure 3 shows different degrees of wear and extrusion crackles. Besides, it found that the crackle on rear upper wheel was more serious.



a. Truncating process 1 b. Truncating process 2 c. Feeding process 1

d. Feeding process 2 e. Transmission process 1 f. Transmission process 2

Figure 2 Structural analysis of the machine



a. Crackle on front under wheel b. Crackle on rear upper wheel

Figure 3 Crackles on rubber wheels

2.2 Strength analysis

In this part, strength analysis was carried out with dynamics simulation, aiming at finding out the internal mechanical cause of the crackles.

2.2.1 Dynamics analysis

Virtual prototype model of the sugarcane leaf stripper was built according to the design drawings. According to the above working process in Figure 2, giving the sugarcane two initial forces to make it entered the drive mechanism. The two initial forces, as shown in Figure 4, point to the direction of front and up respectively. The upward force was used to balance the gravity of sugarcane, which was set as 5 N lasting for 0.2 s. At the same time, the effect of the forward force made the sugarcane move forward. The original value was set as 60 N lasting for 0.2 s, which was gotten from practical experience.

Under the effect of the two forces, the sugarcane entered the drive mechanism along the forward direction, as similar as the practical experiments.

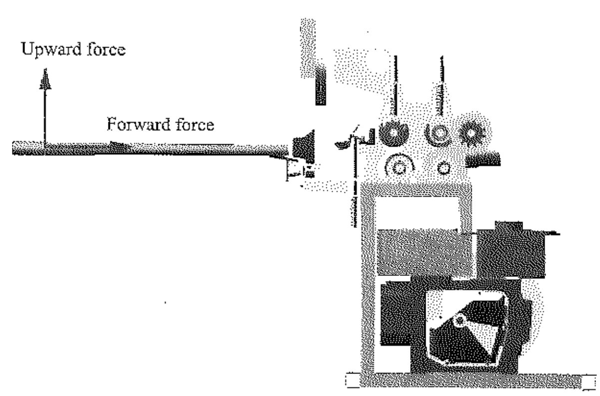


Figure 4 Virtual prototype model

Setting the motion speed as 2000 r/min, the sugarcane moved forward under the driving of the rubber wheel. A series of the parameters used in the simulation experiment were set through practical experience, as is shown in

Table 1, including the characteristic of the sugarcane. The front spring, rear spring, front bracket, rear bracket and the distances are shown in Figure 5.

Table 1 Settings of parameters

Parameters	Value
Minimum diameter of sugarcane, mm	20 mm
Maximum diameter of sugarcane, mm	30 mm
Effective length of sugarcane, mm	1500 mm
Density of the sugarcane, kg/m^3	1.1×10^3 kg/m^3
Poisson ratio of the sugarcane	0.33
Elastic modulus of the sugarcane, MPa	1.1×10^4 MPa
Distance between front upper and under wheel, mm	15 mm
Stiffness of the front spring, N/mm	20 N/mm
Preload of front spring, N	40 N
Distance between rear upper and under wheel, mm	15 mm
Stiffness of the rear spring, N/mm	20 N/mm
Preload of rear spring, N	40 N

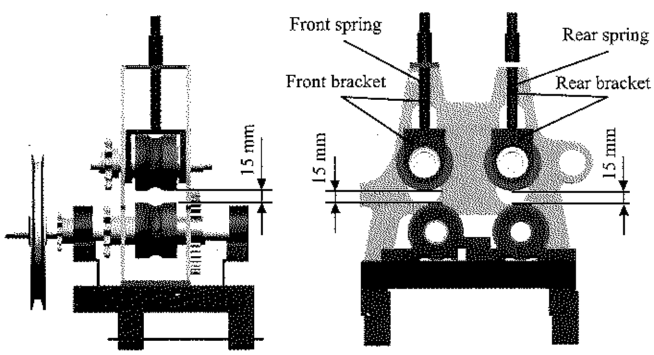


Figure 5 Interpretation of the structural parameters

2.2.2 Mechanical analysis of rubber wheels

Through dynamics simulation, contact state and forces on the four rubber wheels were obtained, as shown in Figure 6. After calculation, it found that, to front couple of rubber wheels, the mean value of under wheel's force (371.04 N) is bigger than the upper (143.91 N). There is some different in the rear couple of wheels. The force of under wheel is not constant. But the maximum absolute value of the upper wheel reaches 3411.05 N. The high force is the internal mechanical cause of the crackles.

2.3 Experimental verification

2.3.1 High-speed photography

An experiment was carried out to verify the accuracy of the above analysis with high-speed photography (Cui et al., 2013). From the experiment, in the process of entering the driving mechanism, contact was taken place firstly between sugarcane and front under rubber wheel (Figure 7 b), and then the upper wheel (Figure 7 c-d). On the contrary, sugarcane reached the rear upper wheel firstly (Figure 7 e). It was in agreement with dynamics simulation.

2.3.2 Displacement test

In order to verify the accuracy of the analysis, an experiment was carried on with DH5981 dynamic analyzer and displacement transducers. The settings of the experiment are shown in Table 2. The connection of experimental equipment and tested data curve was displayed in Figure 8.

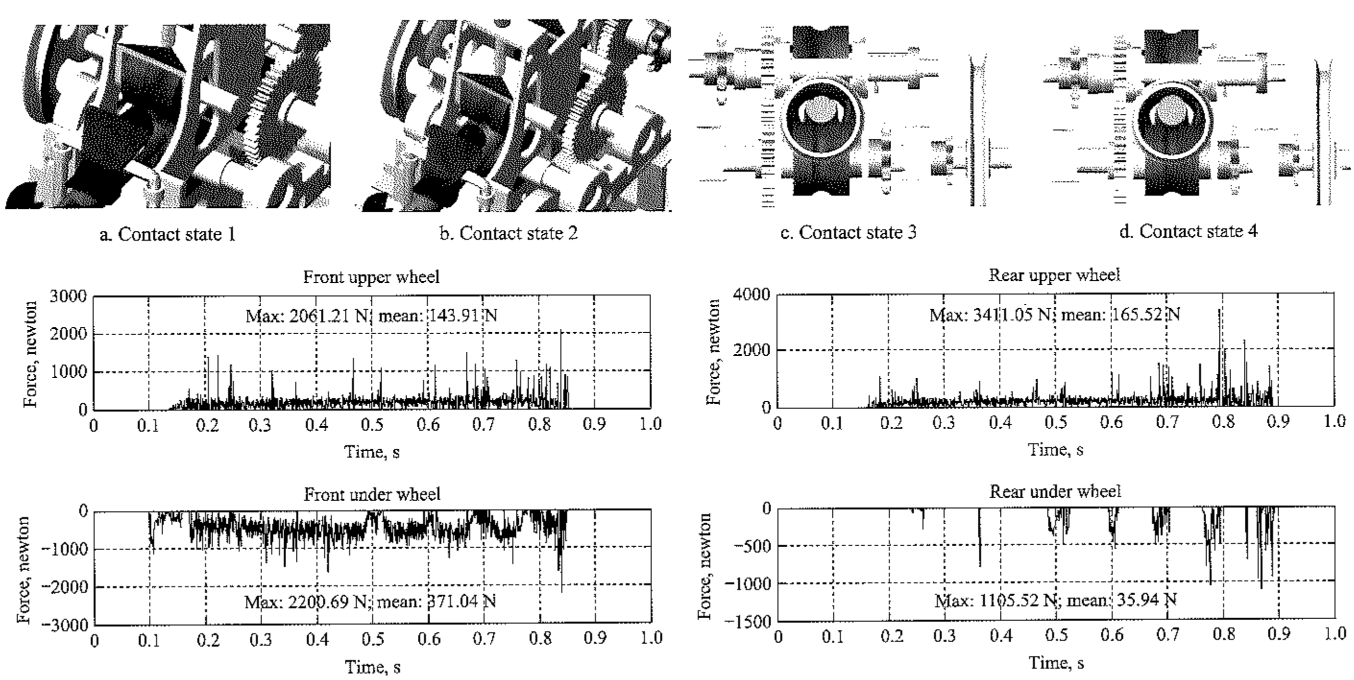
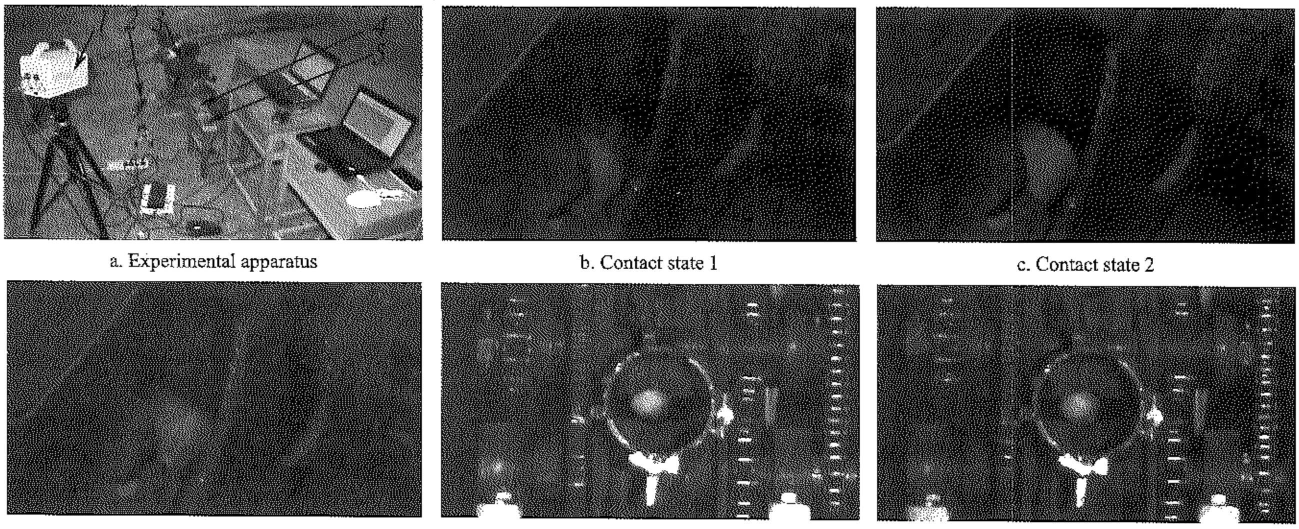


Figure 6 Contact state and forces on rubber wheels



a. Experimental apparatus b. Contact state 1 c. Contact state 2

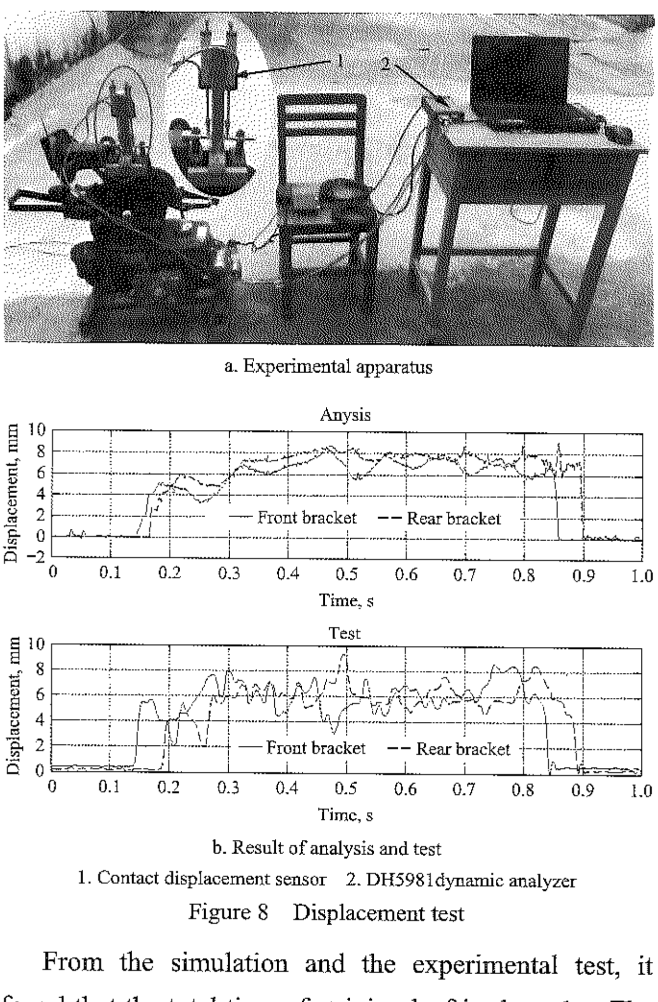
d. Contact state 3 e. Contact state 4 f. Contact state 5

1. High-speed camera FASTCAM SA-X2 2. Spotlight 3. Sugarcane leaf stripping machine 4 .DH5981 dynamic analyzer 5. DH5901 vibration analyzer

Figure 7 Result of high-speed photography

Table 2 Settings of parameters

Parameters	Value
Test instrument	DH5981
Channel number	Using 2
Connection mode of displacement transducers	Half-bridge connection
Sensor power supply voltage, V	2 V
Sensor sensitivity, mm	0.01 mm



a. Experimental apparatus

b. Result of analysis and test

1. Contact displacement sensor 2. DH5981dynamic analyzer

Figure 8 Displacement test

From the simulation and the experimental test, it found that the total time of striping leaf is about 1 s. The sugarcane entered the drive mechanism before 0.2 s, and then front upper and rear upper rubber wheel rose successively. The sugarcane is transmitted stably between 0.2 s and 0.8 s. Because of the changing diameter, the displacement of the front bracket and rear bracket rise up and down. Even though there are some concrete change differences between analysis and test, the general trend, range of motion and beginning and ending time displayed better consistency, which verified the accuracy of the simulation and the model.

2.4 Optimal design based on the orthogonal test

In view of the previous research, the contact force exerted on the rubber wheels was the major reason for the crackles. Consequently, optimal design was expected to reduce the force on the rubber wheels. The smaller force is, the longer life will be. In this part, selecting six parameters as variables, an orthogonal test (Wang, 1986) was carried out to find out the better parameters combination to reduce the force on the cracked rubber wheels.

As shown in multi-body dynamics analysis, the structure parameters mainly contain distance between front upper and under wheel (x_1 mm), stiffness of the front spring (x_2 N/mm), preload of front spring (x_3 N), distance between rear upper and under wheel (x_4 mm), stiffness of the rear spring (x_5 N/mm), preload of rear spring (x_6 N). The original value and the change value of the six variables were shown in Table 3.

According to the simulations, maximum absolute value and mean value the forces, the most important digital features, were chosen as the observed objects. In the result data, y_1, y_3, y_5, y_7 were used to stand the maximum absolute value of the force on front upper wheel, front under wheel, rear upper wheel, rear under wheel respectively. At the same time, y_2, y_4, y_6, y_8 stand the mean value of them. The data of the oethogonal test was shown in Table 4.

Table 3 Value of the six variables

Variable	Original value	Change value
x_1	15	12, 13.5, 15, 16.5, 18
x_2	20	10, 15, 20, 25, 30
x_3	40	30, 35, 40, 45, 50
x_4	15	12, 13.5, 15, 16.5, 18
x_5	20	10, 15, 20, 25, 30
x_6	40	30, 35, 40, 45, 50

Table 4 Data of the orthogonal test

Num	x_1	x_2	x_3	x_4	x_5	x_6	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8
0	15	20	40	15	20	40	2061.12	143.91	2200.69	371.04	3411.05	165.52	1105.52	35.94
1	12	10	30	12	10	30	1733.33	101.12	1903.24	306.36	1601.59	110.95	1478.77	25.09
2	12	15	35	13.5	15	35	1505.99	141.05	2986.40	360.50	1909.34	137.35	872.79	28.12
3	12	20	40	15	20	40	2044.24	184.87	1681.07	405.95	3313.48	156.83	1115.81	31.74
4	12	25	45	16.5	25	45	1905.43	217.13	2372.12	440.59	2201.75	153.08	1292.73	36.02
5	12	30	50	18	30	50	2904.11	268.10	2408.17	483.49	2473.58	147.87	2103.76	28.37
6	13.5	10	35	15	25	50	1395.72	103.14	1455.53	311.67	2072.70	191.86	1352.98	55.20
7	13.5	15	40	16.5	30	30	2353.17	135.98	2390.32	349.58	2850.42	165.99	1041.69	38.75
8	13.5	20	45	18	10	35	3309.55	155.33	1445.65	322.22	1528.94	66.38	1047.58	6.87
9	13.5	25	50	12	15	40	1443.65	200.55	1786.98	431.69	1945.54	157.35	1576.07	37.77
10	13.5	30	30	13.5	20	45	1953.95	211.07	2562.42	441.23	1936.76	181.46	1539.66	45.10
11	15	10	40	18	15	45	1450.40	80.98	1492.92	262.23	1819.19	89.99	1077.89	15.08
12	15	15	45	12	20	50	1786.13	129.62	2011.75	373.84	3166.00	226.89	1657.65	68.25
13	15	20	50	13.5	25	30	1762.79	150.83	1785.84	380.63	2447.49	208.40	1595.81	57.03
14	15	25	30	15	30	35	1373.29	154.11	2980.03	387.20	1591.67	200.36	1708.79	64.64
15	15	30	35	16.5	10	40	1837.23	179.25	1785.84	345.10	2265.17	88.01	1247.10	13.65
16	16.5	10	45	13.5	30	40	2129.91	88.94	1800.41	324.25	2103.34	252.43	1671.78	102.79
17	16.5	15	50	15	10	45	1550.17	95.48	1918.85	291.47	1835.50	98.82	1074.65	17.90
18	16.5	20	30	16.5	15	50	1262.83	97.41	1823.62	304.03	1136.23	109.62	1080.42	23.36
19	16.5	25	35	18	20	30	1189.52	121.56	2188.56	324.21	1368.94	98.53	1619.29	17.73
20	16.5	30	40	12	25	35	1742.76	155.88	1788.51	397.09	2493.23	237.07	2103.23	92.46
21	18	10	50	16.5	20	35	1499.70	63.39	2929.35	282.21	2768.34	115.54	1941.24	31.37
22	18	15	30	18	25	40	2164.10	69.72	1855.76	274.90	2492.16	117.60	1289.94	25.52
23	18	20	35	12	30	45	1378.70	97.65	1744.64	340.14	2115.14	282.74	1195.20	131.78
24	18	25	40	13.5	10	50	1447.99	96.29	1716.48	298.48	1792.31	114.25	1162.95	21.85
25	18	30	45	15	15	30	2774.40	122.69	2615.58	325.00	1878.59	119.82	1019.75	21.12

3 Results and discussion

The original design values were shown in the zeroth group. The varying curves of the maximum absolute value and mean value the forces are shown in Figure 9.

In Figure 9, the maximum absolute value had larger fluctuations, while mean value changed little. Consequently, the lower maximum absolute value was the primary consideration.

3.1 Range analysis

According to the mathematical statistics principle, the range analysis results were shown in Table 5 and Figure 10. Cracked rubber wheels were analyzed emphatically.

Range analysis showed that preload of rear spring and stiffness of front spring had significant effect on the maximum absolute value of the force on front under wheel, while stiffness of rear spring and preload of front spring affected that on rear upper wheel significantly.

3.2 Optimal results

According to orthogonal test and comprehensive equilibrium method (Yang et al., 2011), taking into account of the maximum absolute value and mean value, the most optimal set of the structure parameter was the 11th group: 15 mm, 10 N/mm, 40 N, 18 mm, 15 N/mm, 45 N. Compared with initial parameters, the maximum absolute value of the contact force reduced 29.63%, 32.16%, 46.68% and 2.50% respectively, reaching the best. At the same time, the mean values had reached the best combination, reduced 43.73%, 29.33%, 45.63% and 58.04%.

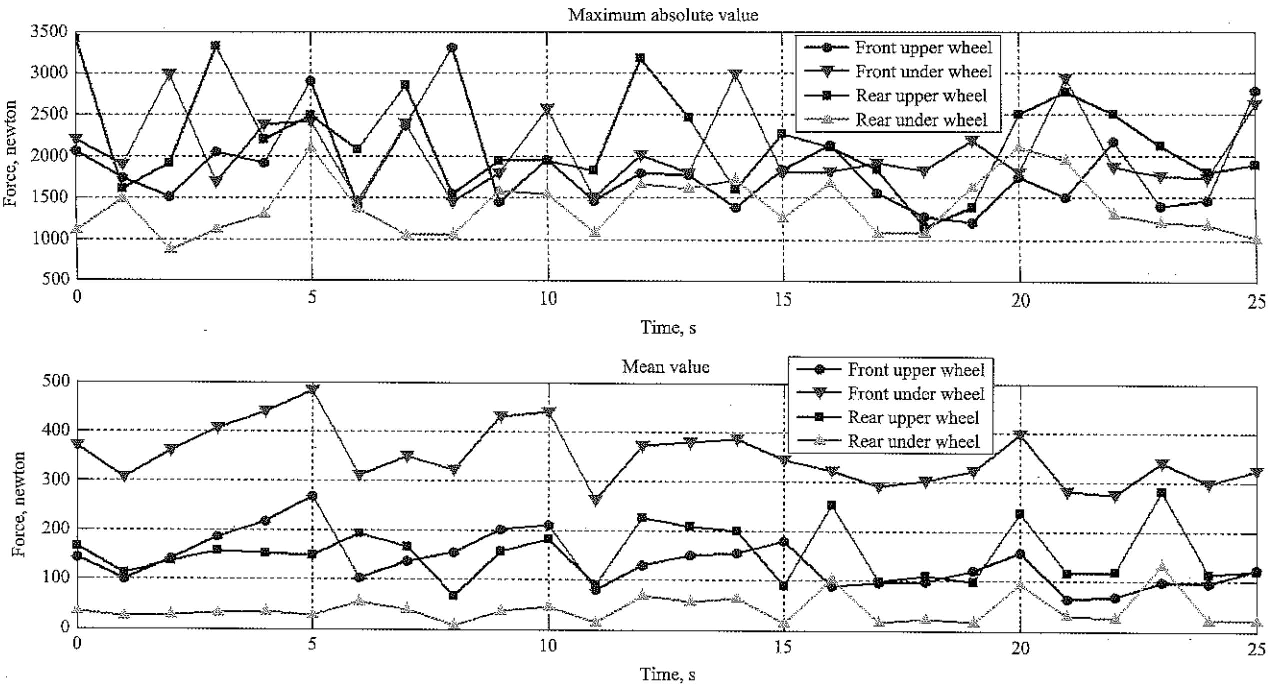
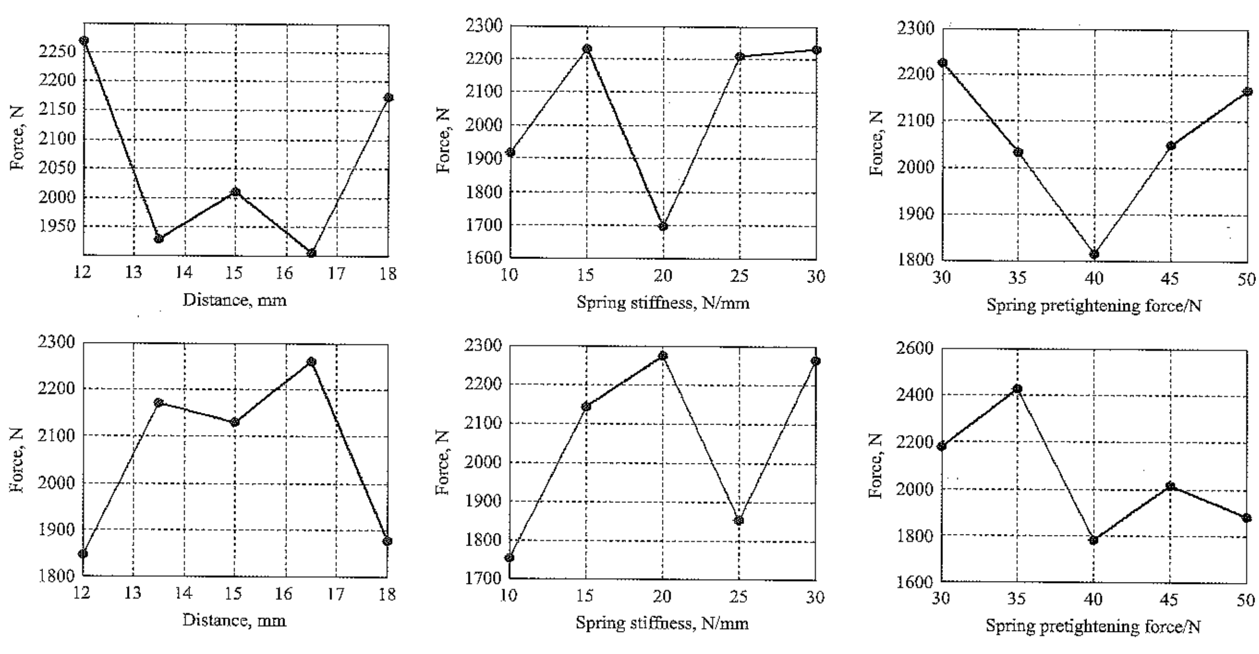


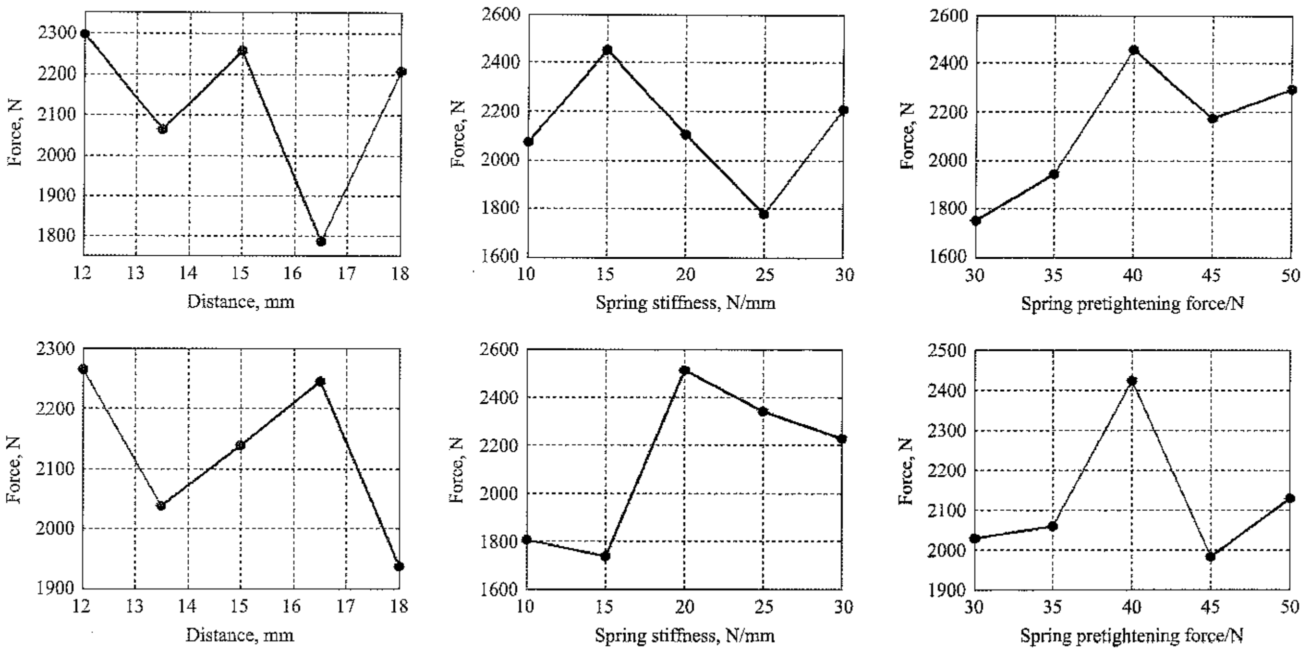
Figure 9 Varying curves of observed objects

Table 5 Chart of range analysis

	Factor	k_1^M	k_2^M	k_3^M	k_4^M	k_5^M	Range	Rank
Front under wheel	A	2270.20	1928.18	2011.28	1903.99	2172.36	366.21	6
	B	1916.29	2232.62	1696.16	2208.83	2232.10	536.46	2
	C	2225.01	2032.19	1813.86	2049.10	2165.84	411.15	5
	D	1847.02	2170.31	2130.21	2260.25	1878.21	413.23	4
	E	1754.01	2141.10	2274.63	1851.55	2264.71	520.62	3
	F	2176.71	2425.99	1782.01	2018.19	1883.11	643.98	1
Rear upper wheel	A	2299.95	2066.87	2257.90	1787.45	2209.31	512.50	4
	B	2073.03	2450.68	2108.26	1780.04	2209.47	670.64	3
	C	1751.68	1946.26	2453.73	2175.72	2294.09	702.05	2
	D	2264.30	2037.85	2138.39	2244.38	1936.56	327.74	6
	E	1804.70	1737.78	2510.70	2341.47	2226.83	772.92	1
	F	2029.41	2058.30	2423.94	1981.67	2128.16	442.27	5



a. Range analysis of front under wheel



b. Range analysis of rear upper wheel

Figure 10 Range analysis

The structure of the prototype was adjusted according to the optimal design. Tested by experiment, the stripping effect and impurity rate satisfies the design requirement. Working for a period of time, there were no crackles. Consequently, fatigue life of rubber wheels will be longer than before. However, the life after optimization needs further research and experiment.

4 Conclusions

According to the full text, the following conclusions were obtained.

(1) The crackles on the rubber wheels were caused by the high contact force between sugarcane and wheels. What's more, the maximum absolute value of the forces on the cracked rubber wheel were relatively large, reaching 3411.05 N.

(2) Range analysis showed that preload of rear spring and stiffness of front spring affected the force of front under wheel significantly, while stiffness of rear spring and preload of front spring had significant influence on rear upper wheel.

(3) The optimal design showed that when the six variables were chosen as 15 mm, 10 N/mm, 40 N, 18 mm, 15 N/mm, 45 N respectively, the maximum absolute value of the force on four wheels had reduced 29.63%, 32.16%, 46.68% and 2.50% compared with the original value. The optimal design has obvious effect and provides strong evidence for improving the machine.

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