Experimental analyses on shearing properties of hop stem

J Yang¹,³ and X K Li²

¹College of Electron-mechanics and Automobile Engineering, Tianshui Normal University, Tianshui, 741001, China
²Institute of Agricultural Machinery, Gansu Institute of Machinery Research Co., Ltd., Lanzhou, 730030, China
E-mail: lwg_yj@163.com

Abstract. In order to solve the problems of low cleaning rate and high breakage rate of the existing hop harvesting mechanical cutting devices, single factor and multi-factor orthogonal tests were carried out on hop stems of different varieties, such as Qingdao big flower, Marco Polo and Fragrant flower, by using the universal testing machine. The tests were focused on the influence of the factors, including moisture content, shearing mode and shearing velocity on shearing force. The results show that the influence of the above three factors are all significant, among which the first two are more significant. The shearing force will increase with the decrease of moisture content and it will decrease with the increase of shearing velocity. When the shearing velocity is kept between 100 mm/min and 200 mm/min, it will be the most advantageous to the cutting, and the slip cutting is the most labour-saving mode. The tests show that the cutting effect will be the best during the course of harvesting when the hop stems are fresh. The shearing velocity arrives at 100mm/min and the slip cutting mode is adopted. The results can provide a theoretical basis for improving the cutting devices of the existing hop harvesting machinery.

1. Introduction

Hops are climbing plants of the mulberry family [1]. Hops are oval and puffy in shape, which contain formic acid. When formic acid is added to beer, beer has aromatic bitterness and special fragrance, which is an important raw material for beer production. Hop cultivation in China is mainly distributed in Gansu and Xinjiang provinces. The warm temperate drought climate in Hexi Corridor of Gansu Province has promoted the fine cultivation of hops. At the same time, beer production enterprises have adopted the industrialization mechanism of "company + base + peasant household", which has made the production of hops increase continuously [2]. Therefore, Gansu Province has become the largest province of hop cultivation in China. The shape of hops is shown in Figure 1.

The main hop varieties in Gansu Province are Qingdao big flower, Marco Polo and Fragrant Flower. Due to the high content of formic acid, Qingdao big flower accounts for more than 80% of the total planting area in Hexi Corridor [3]. Field tests have showed that the mechanized harvesting performance of Qingdao big flower is poor, and it is not suitable for mechanized harvesting. Although hop harvesting machinery has been developed successfully for a long time, the difficulty of mechanized harvesting is different due to the different varieties of hop planting, which makes the existing machinery have the defects of low cleaning rate and high breakage rate. As a result, the imperfection of mechanized harvesting technology has become a bottleneck restricting the "13th Five-Year Plan for Agricultural Development of Gansu Province".
In order to improve the defects of hop harvesting machinery, it is necessary to determine the physic-mechanical properties hop stems such as shearing resistance strength. There are many studies on the mechanical properties of crop stems at home and abroad, and the main purpose is aimed at the mechanical properties of cash crops such as wheat, forage, corn, ramie, sugarcane and so on. Guo [4, 5] studied the relationship between the tensile strength of wheat stems and their chemical components, which provided a theoretical basis for improving lodging resistance of wheat. Su [6] studied the tensile and compressive properties of the xylem of ramie stem, which provided a reference for mechanized harvesting of ramie. Zhao [7-9] carried out the tests of tensile, bending and shearing of legume forage stems. The results of the tests provided basic information for selecting reasonable matching power and cutting system structure parameters. Liu [10, 11] studied the damage tests of sugarcane stems under torsion, compression and tension loads, which had an important influence on the cutting mechanism of sugarcane. Yu and Chen [12, 13] conducted the tensile test of maize straw to provide technical support for mechanized harvesting of maize. Zhou [14] obtained the elastic modulus, Poisson's ratio, bending and shear modulus of industrial hemp stem through tensile, bending and compression tests. Luo [15] obtained the optimal combination of cutting devices through the reciprocating cutting experiment of eulaliopsis binata stems. Song [16] studied the cutting performance of cotton stems through average speed, cutting inclination and cutting speed ratio. Li [17] measured the process of shearing stress of cotton stem changing with moisture content on a universal testing machine, and determined the optimum harvesting time of cotton stem. The purpose of the studies is also mostly focused on lodging resistance and mechanism. As one of the characteristic pillar industries in Gansu province, the research on the mechanical properties of hop stems is still blank. To improve the existing hop harvesting machinery, it is necessary to research the shearing mechanical properties of hops stems. In view of this, this paper takes hops stems of different varieties (Qingdao big flower, Marco Polo, Fragrant flower) as the research subjects, and chooses different shearing mode under different moisture content conditions. The optimum cutting parameters are determined by the orthogonal test, which provides a basis for improving the existing cutting device.

2. Test materials and methods

2.1. Test materials
The experimental materials were picked in the hop base of Yumen Agricultural Reclamation Construction Company in Gansu Province in mid-August 2018. In the experiment, the stems of Marco Polo, Qingdao big flower and Fragrant flower which were mature, intact and undamaged were selected. The diameter and wall thickness of the samples were measured by vernier caliper. Then, the stems were classified according to the diameter. The stems were made 150 mm length as specimens to complete the shearing test.

2.2. Test instrument
ETM105D, a universal testing machine manufactured by Shenzhen Wance company, was used for shearing test. During the test, the force, displacement, deformation, loading velocity and test curve can be displayed dynamically in real time by using the universal testing machine. The maximum test loading of this machine was 100KN, the relative error of force was less than 0.18%, the relative error of displacement and velocity were less than 0.19%, and the accuracy level was 0.5. During the test, the stems were fixed on the self-made fixture, and the self-made cylindrical fixture support was matched with the cylindrical hollow base of the universal testing machine. The cutting tool was in the form of a light knife with a thickness of 2 mm. The shearing modes were divided into transverse cutting, oblique cutting and slip cutting. In transverse cutting, the blade was kept vertical to the stems in the horizontal plane. In oblique cutting, the direction of the blade was changed. The cutter blade and the stems should have an angle in the horizontal plane. The test chose 45 degrees angle in oblique cutting. In sliding cutting, the angle between the fixture and the horizontal plane were changed to make it 30 degrees angle with the horizontal plane [18].

2.3. Test methods

2.3.1. Single factor test. The shearing force of hop stems were affected by many factors, such as shearing mode, shearing velocity, moisture content, holding conditions, blade form and so on. According to the working conditions of the existing hop harvesting machinery, the shearing mode, shearing velocity and moisture content were selected as the main factors affecting the shearing force of stems. The test conditions were shown in table 1.

| Test level | Factors A | Shearing velocity B | Moisture content C |
|------------|-----------|---------------------|--------------------|
| 1          | transverse cutting | 50 mm/min          | fresh samples     |
| 2          | oblique cutting    | 100 mm/min         | semi-dry samples  |
| 3          | slip cutting       | 150 mm/min         | dry samples       |
| 4          |                    | 200 mm/min         |                    |
| 5          |                    | 250 mm/min         |                    |

In the single-factor test of shearing force by velocity, 120 samples of different varieties (Qingdao big flower, Fragrant flower and Marco Polo) with similar diameters were selected as the test subjects. Under different shearing velocity in the range of 50 to 250mm/min, the shearing test was conducted by transverse mode. The test index was maximum shearing force. The test was repeated for eight times at each location, and the data were recorded and the average value was obtained.

In the single factor test of shearing mode and moisture content on shearing force, 135 samples with the same conditions were selected. Stems quality were measured by balance, and then the moisture content of the stems was determined by 105°C drying method. Among them, the moisture content of fresh samples remained between 70% and 80%, the moisture content of semi-dry samples was between 40% and 60% after one day in the ventilated and dried laboratory, and the moisture content of dry samples was between 20% and 30% after two days in the ventilated and dried laboratory. The test was repeated for five times at each location. Data were recorded and their average values were taken.

2.3.2. Multivariate factor test. In order to verify the influence degree and optimum level of each factor on shearing force, the orthogonal test of shearing velocity, shearing mode and moisture content were carried out. 135 samples were selected as the same as the single factor test, and the test conditions were the same as the single factor test conditions.

3. Results and analysis
3.1. Single factor test

3.1.1. Effect of shearing velocity on shearing force. In the velocity range of 50 to 250 mm/min, the shearing force tests of Qingdao big flower, Marco Polo and Fragrant flower were carried out. Test data were shown in table 2.

Table 2. Experimental data of shearing force of hop stems at different velocities.

| Varieties          | Maximum Shearing force at different shearing velocities (N) |
|--------------------|-------------------------------------------------------------|
|                    | 50 (mm/min) | 100 (mm/min) | 150 (mm/min) | 200 (mm/min) | 250 (mm/min) |
| Qingdao big flower | 258.01      | 237.22       | 224.24       | 200.61       | 246.14       |
| Marco Polo         | 215.05      | 203.30       | 254.53       | 197.22       | 229.40       |
| Fragrant flower    | 209.14      | 197.03       | 192.63       | 159.55       | 167.98       |

*aUsing fresh samples and transverse cutting.

Figure 2. Shearing force test at different velocities.

The results show that the shearing force of Qingdao big flower and Fragrant flower decreases with the increase of velocity in the range of 50 to 200 mm/min. The shearing force of Qingdao big flower changes 57.40N. The shearing force of fragrant flowers changes 49.59N. When the velocity is 200 mm/min, the shearing force reaches the minimum, Qingdao big flower is 200.61N and Fragrant flower is 159.55N. When the velocity increases gradually from 200 mm/min to 250 mm/min, the shearing force increases. The shearing force of Qingdao big flower increases by 45.53N and that of Fragrant flower by 8.43N. The reasons for this phenomenon are as follows: with the increase of shearing velocity, the proportion of extrusion stage before cutting decreases gradually, that is, the distance of cutter extruding the stem decreases, which leads to the decrease of the shearing force of stems. When the shearing velocity exceeds a certain value and continues to increase, the change of the distance of cutter extruding the stem is no longer significant [16]. The shearing force of Marco Polo varies smoothly with the increase of velocity and changes 57.31N. When the velocity is 150 mm/min, the maximum shearing force of Marco Polo is 254.53N, which decreases with the increase of velocity.

From the above single factor test data, it can be seen that too high or too low velocity will increase the shearing force, and the velocity in the middle section is the most favourable for shearing. Therefore, the optimum shearing velocity range of three varieties is from 100 mm/min to 200 mm/min.

3.1.2. Effect of shearing mode and moisture content on shearing force. According to the influence of shearing velocity on shearing force, the optimum shearing velocity range is 100 mm/min to 200
mm/min. Therefore, the shearing test of hop stems of different varieties with different shearing modes and different moisture content was carried out under the conditions of 200 mm/min and diameter 6~7 mm. The experimental data were shown in table 3. The results show that the shearing force of three varieties increases with the decrease of moisture content, that is, fresh samples need the least shearing force, followed by Semi-dry samples, and dry samples need the largest shearing force.

Table 3. Experimental data of shearing force in different shearing mode and moisture content.

| Varieties       | Maximum Shearing Force (N) | transverse cutting | oblique cutting | slip cutting |
|-----------------|----------------------------|--------------------|----------------|-------------|
| Qingdao big flower |                            |                    |                |             |
| fresh samples   | 175.48                     | 220.10             | 161.96         |             |
| semi-dry samples | 296.20                     | 321.68             | 208.32         |             |
| dry samples     | 326.49                     | 456.04             | 228.42         |             |
| fresh samples   | 207.08                     | 210.11             | 177.14         |             |
| Marco Polo      |                            |                    |                |             |
| semi-dry samples | 255.37                     | 270.33             | 217.60         |             |
| dry samples     | 398.54                     | 475.42             | 226.30         |             |
| fresh samples   | 169.18                     | 189.82             | 144.29         |             |
| Fragrant flower |                            |                    |                |             |
| semi-dry samples | 321.62                     | 208.80             | 159.59         |             |
| dry samples     | 360.86                     | 215.80             | 189.02         |             |

*Shearing velocity is 200mm/min.

As far as shearing mode is concerned, whether fresh, semi-dry or dry samples, oblique cutting of Qingdao big flower and Marco Polo needs the largest shearing force, followed by transverse cutting, and slip cutting requires the smallest shearing force. When fresh fragrant flowers are cut, the shearing force required by oblique cutting is the largest, followed by transverse cutting, and the shearing force needed by slip cutting is the smallest. The shearing force of semi-dried and dry samples of fragrant flowers is the greatest in transverse cutting, followed by oblique cutting, and the most labour-saving in slip cutting.

According to the single factor data, with the decrease of moisture content, the shearing force increases no matter what kind of shearing mode is. Therefore, in the same shearing mode, fresh samples are the most labour-saving. Three kinds of shearing modes are used to cut hop stems under three different varieties and different moisture content respectively. The shearing force needed for slipping fresh samples is the smallest, which is the best shearing mode. Compared with three different varieties of samples, under the same shearing mode, Marco Polo is the most laborious, followed by Qingdao big flower, and fragrant flower is the most labour-saving.

3.2. Multivariate test

Three factors including shearing mode, shearing velocity and moisture content were selected for orthogonal test. Compared with single factor test, the shearing force of hop stems of three varieties decreased gradually with the increase of velocity in the range of 50 mm/min to 250 mm/min. When the velocity exceeded 200 mm/min, the shearing force would increase. Therefore, the levels of selected velocity were 100 mm/min, 150 mm/min and 200 mm/min.

In the test, the moisture content of fresh sample was 70%~80%, the moisture content of semi-dry sample was 40%~60%, the moisture content of dry sample was 20%~30%, and the shearing mode was transverse cutting, oblique cutting and slip cutting. The L9 (34) orthogonal table [19-21] was selected. The test index was the maximum shearing force. The level of test factors was shown in table 4. The following tests were repeated five times, and the test data were shown in table 5.

Table 4. Multivariate orthogonal table.

| Number | Shearing mode A | Shearing velocity B (mm/min) | Moisture content C (%) |
|--------|-----------------|-----------------------------|------------------------|
| 1      | 1(transverse cutting) | 1(100)                      | 1(fresh samples)       |
The effect of shear force increases in turn; the optimum combination is slipping cutting, fresh samples, at a speed of 100 mm/min.

For Marco Polo, the effect of moisture content C and shearing mode A on the maximum shearing force is the most significant (P < 0.001), and the effect of shearing velocity B on the shearing force is more significant (P < 0.05). Moisture content has the greatest influence on Marco Polo, with the decrease of moisture content, the shearing force increases in turn; Secondly, slip cutting is the most labour-saving, then oblique cutting, transverse cutting is the most laborious. Shearing velocity also has a significant impact on the shearing force, with the increase of velocity, the shearing force increases. Therefore, when choosing the working velocity range of blade, the vibration and production efficiency of the unit should be considered comprehensively. For Marco Polo, the order of influence of each factor on shearing force is moisture content, shearing mode and shearing velocity. The optimal combination is slipping cutting, fresh samples at a speed of 100 mm/min.

For Fragrant flower, shearing mode A and moisture content C have a highly significant effect on shearing force (P < 0.001), and shearing velocity (P < 0.05) B is more significant. Among them, shearing mode has the greatest influence on shearing force, and slip cutting is the most labour-saving. It shows that the appropriate shearing mode is an important way to improve the shearing quality and reduce the breakage rate of Qingdao big flower. The effect of moisture content is extremely significant. With the decrease of moisture content, the flexibility of stems decreases, brittleness increases, and shearing force increases in turn. Therefore, fresh samples’ shearing force is the smallest. Through the above analysis, the order of the factors affecting the shearing force of Qingdao big flower is: shearing mode, moisture content and shearing velocity. The optimum combination is slipping cutting, fresh samples, at a speed of 100 mm/min.

| Test varieties | Test number | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      |
|----------------|-------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Qingdao        | 1           | 230.57 | 307.24 | 312.92 | 219.88 | 389.11 | 241.63 | 222.32 | 154.14 | 198.80 |
|                | 2           | 230.39 | 314.33 | 303.70 | 242.05 | 265.39 | 231.42 | 204.60 | 140.58 | 206.62 |
|                | 3           | 216.94 | 324.84 | 377.01 | 251.52 | 387.46 | 240.65 | 194.95 | 129.34 | 219.69 |
|                | 4           | 204.18 | 274.19 | 355.57 | 274.56 | 260.63 | 215.84 | 193.67 | 192.93 | 222.99 |
|                | 5           | 247.13 | 238.94 | 326.79 | 254.15 | 243.40 | 219.08 | 190.67 | 170.88 | 200.88 |
| Big flower     | 1           | 181.08 | 182.18 | 458.27 | 292.76 | 367.48 | 197.82 | 282.87 | 186.58 | 237.59 |
|                | 2           | 174.85 | 206.80 | 408.17 | 194.46 | 319.28 | 202.83 | 229.90 | 171.86 | 220.06 |
|                | 3           | 219.39 | 226.11 | 416.36 | 221.04 | 372.37 | 191.04 | 283.54 | 161.10 | 185.60 |
|                | 4           | 187.19 | 218.35 | 374.20 | 259.47 | 340.42 | 180.17 | 283.96 | 165.63 | 179.13 |
|                | 5           | 207.96 | 205.46 | 425.15 | 246.76 | 333.76 | 172.16 | 293.37 | 205.28 | 199.41 |
| Fragrant flower| 1           | 199.11 | 265.51 | 446.23 | 281.95 | 351.23 | 131.78 | 210.29 | 129.82 | 160.62 |
|                | 2           | 201.06 | 331.80 | 410.98 | 273.76 | 399.92 | 166.24 | 243.64 | 144.43 | 181.27 |
|                | 3           | 202.83 | 359.97 | 321.35 | 215.36 | 375.30 | 182.24 | 228.98 | 139.17 | 137.89 |
|                | 4           | 255.25 | 356.67 | 311.52 | 296.24 | 278.34 | 186.21 | 248.04 | 157.07 | 140.21 |
|                | 5           | 213.16 | 338.22 | 354.96 | 368.76 | 295.94 | 162.14 | 226.05 | 124.57 | 177.97 |

Table 5. Test data.

*Unit: Newton

The results of analysis of variance by table 6 show that for Qingdao big flower, shearing mode A and moisture content C have a highly significant effect on shearing force (P < 0.001), and shearing velocity (P < 0.05) B is more significant. Among them, shearing mode has the greatest influence on shearing force, and slip cutting is the most labour-saving. It shows that the appropriate shearing mode is an important way to improve the shearing quality and reduce the breakage rate of Qingdao big flower. The effect of moisture content is extremely significant. With the decrease of moisture content, the flexibility of stems decreases, brittleness increases, and shearing force increases in turn. Therefore, fresh samples’ shearing force is the smallest. Through the above analysis, the order of the factors affecting the shearing force of Qingdao big flower is: shearing mode, moisture content and shearing velocity. The optimum combination is slipping cutting, fresh samples, at a speed of 100 mm/min.
Sliding cutting is the most labour-saving, followed by oblique cutting, and transverse cutting needs the largest shearing force. Therefore, the order of the factors affecting the shearing force of fragrant flowers is moisture content, shearing mode and shearing velocity. The best combination scheme of shearing force is slipping cutting, fresh samples at a speed of 100 mm/min.

Table 6. Variance analysis.

| Varieties                  | Factors | Sum of squares of deviations | Freedoms | Mean square deviations deviation | F       | P       |
|----------------------------|---------|------------------------------|----------|----------------------------------|---------|---------|
| Qingdao big flower         | A       | 73888                        | 2        | 36944                            | 37.83   | 9.11e-10*** |
|                            | B       | 9453                         | 2        | 4726                             | 4.84    | 0.0134*   |
|                            | C       | 45524                        | 2        | 22762                            | 23.31   | 2.48e-7***  |
| Marco Polo                 | A       | 23469                        | 2        | 11734                            | 10.18   | 2.89e-4**  |
|                            | B       | 8861                         | 2        | 4431                             | 3.84    | 0.0302*   |
|                            | C       | 212632                       | 2        | 106316                           | 92.19   | 2.64e-15*** |
| Fragrant flower            | A       | 128336                       | 2        | 64168                            | 46.75   | 1.39e-10***|
|                            | B       | 11476                        | 2        | 5738                             | 3.91    | 0.0285*   |
|                            | C       | 150581                       | 2        | 75290                            | 51.33   | 1.59e-11***|

Based on the above experimental analysis, it is concluded that moisture content and shearing mode have rather significant effects on the shearing force of different varieties, and shearing velocity has also relatively significant effects on the shearing force. Based on the analysis of the above three kinds of stems, the optimal combination of shearing force is that fresh samples and slip cutting are adopted, and the velocity of 100mm/min is the most labour-saving. When slip cutting velocity is 100 mm/min, the
shearing force-displacement curves of the three varieties are shown in figure 3. The curve (a) is force and displacement curve of Qingdao big flower and the curve (b) is force and displacement curve of Marco Polo. The curve (c) is force and displacement curve of Fragrant flower. With the increase of displacement, the shearing force increases continuously. When it reaches the maximum value, stems are cut off and the shearing force drops rapidly to 0. It can be seen from the curve that when the shearing force reaches the maximum value, the displacement and the shearing force produced by Marco Polo are the largest among the three varieties, the displacement is 18 mm and the maximum shearing force is 242.12N. When Qingdao big flower is cut off, the displacement is 9mm and the maximum shearing force is 182.49N. When fragrant flower is cut, the shearing force increases with the increase of cutter stroke. When it reaches a certain peak, it keeps changing around the peak until it is cut off, and the maximum shear force is 123.23N. This phenomenon can be attributed to the differences of three different varieties’ lignin, cellulose content and micro-structure which lead to the difference of shearing force. Figure 4 shows the cross-section microstructures of three kinds of stems. Figure 4(a) is the microstructure map of Qingdao big flower (magnify 180 times). Figures 4(b) and 4(c) are the microstructure map of Marco Polo (magnify 190 times) and the microstructure map of Fragrant flower (magnify 190 times) respective.

4. Conclusions and discussions
The paper selects the structural parameters and material parameters related to shear to carry out simulation tests. The results show that:

- The effect of moisture content on shearing force is extremely significant. With the decrease of moisture content in stems, the flexibility decreases and brittleness increases, the shearing force increases gradually. Therefore, in hop harvesting, the shorter the time for hop feeding material to be separated from their parents and the sunlight, and the lower the temperature for doing this, the better it will be. That is to say, hops should usually be harvested in the morning and evening with soft materials, high moisture content, low shearing force and low breakage rate.
- Tests are carried out on three different varieties of hop stems. The effect of shearing mode on shearing force is extremely significant. Sliding cutting mode is the most labour-saving, followed by transverse cutting mode, and oblique cutting mode requires the largest shearing force. Therefore, sliding cutting is an important way to improve the cutting quality of hop harvesting machinery.
- Combining the single factor test and the multi-factor test, the best shearing mode is fresh sample, slip cutting with the speed of 100 mm/min.
- No matter what shearing mode, shearing velocity and moisture content are adopted, fragrant flowers’ shearing force is the smallest, followed by Qingdao big flower and Marco Polo. This is related to the micro-structure and tissue arrangement of different varieties of stems.
On the basis of single factor and multi-factor tests, the optimal cutting mode of hop stems was obtained by the orthogonal test. There are many factors affecting hop stem cutting. In addition to the three factors mentioned in the paper, there are also factors such as cutter type and cutting position and so on. Because of the complexity of external factors in the process of stem shearing, so a dynamic loading process instead of the quasi-static one in the test is more rational. Moreover, the research group is discussing further. The conclusion of the tests provides technical parameters for the difficult problem of mechanized harvesting of Qingdao big flower and the reasonable cutting mode of hop harvesting machinery to reduce energy consumption.

Acknowledgments
The work is supported by research grants from scientific research projects of colleges and universities in Gansu Province (2018B-46) and Research projects for Young and Middle-aged Teachers in Tianshui Normal University (YB-2017-07). The author is thankful to the anonymous referees for the constructive comments in enhancing the content.

References
[1] Wang C X 1998 Analysis of sustainable development potential of hops in Gansu ProvinceGansu Agric. Sci. Tech. 074-5
[2] Ran S B 2013 Current situation, existing problems and development countermeasure of hop industry in Gansu Province J. Zhejiang Agric. Sci. 11 1532-5
[3] Yang J 2016Study on hops production situation and mechanized harvesting technology Agric. Machinery 11 115-17+19
[4] Wang F E, Huang G B, Guo W J et al 2009 Mechanical properties and micro-structure of wheat stems Transact. CSAE 40 92-5
[5] Guo W J, Huang G B, Wang F E et al 2010 Mechanical properties and micro-structure of wheatroots Transac. CSAE 41 92-5
[6] Su G B, Liu J Y, Wang S C et al 2007 Study on mechanical properties of xylem of ramie stalk Transac. CSAE3862-5
[7] Zhao C H, Zhang F W and Cao Z Z 2009 Experiment on stalk mechanical properties of legume forage and grasses Transactions CSAE 25 122-5
[8] Zhao C H, Han Z S,Wang F E et al 2010 Experiment on biomechanical properties of bottom stems offorage in harvesting period Transac. CSAE 41 65-9
[9] Zhao C H, Zhang F W, Han Z S et al 2010 Stems biomechanical properties experiments of creeping tangled forageinharvesting period Transac. CSAE 41 85-89+100
[10] Liu Q T, Qv Y G, Qing S L et al 2007 Cutting force test of sugarcane stalk Transac. CSAE 07 90-4
[11] Liu Q T, QvY G, Qing S L et al 2007Study progress on mechanics properties of crop stalks Transac. CSAE 07 172-6
[12] Yu Y, Lin Y, Mao M et al 2012 Experimental study on tensile properties of corn straw Transa. CSAE 28 70-6
[13] Chen Z G,Wang D F, Li L Q et al 2012 Experiment on tensile and shearing characteristics of rind of corn stalk Transac. CSAE 28 59-65
[14] Zhou Y, Li X W, Shen C etal 2016 Experimental analysis on mechanical model of industrial hemp stalk Transac. CSAE 32 22-9
[15] Luo H F, Tang C Z, Zou D S et al 2012 Experiment on reciprocating cutting of eulaliopsisbinatatem Transac. CSAE 28 13-7
[16] Song Z H, Song H L, GengA J et al 2015 Experiment on cutting characteristics of cotton stalk withdouble supports Transac. CSAE 31 37-45
[17] Li X Q, Wang F E, Guo W J et al 2013 Influencing factor analysis of cabbage root cutting force based onorthogonal Transact. CSAE 29 42-8
[18] Li Y D, Du X J, Song Z H et al 2011 Test of shear mechanical properties of cotton stalks Transac.
[19] Chatopadhyay P S and Pandey K P 1999 Mechanical properties of sorghum stalk in relation to quasi-static deformation J. Agric. Engng. Res. 73 199-206

[20] Hirai Y, Inove E and Mori K 2004 Application of quasi-static stalk bending analysis to the dynamic response of rice and wheat stalks gathered by a combine harvester reel Biosys. Engin. 88 281-94

[21] Chen K 2005 Test Design and Analysis Beijing: Tsinghua University Press Beijing China