Rind-Pith Separation Equipment for Corn Stalk: Simulation and Analysis

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Abstract — The corn stalk rind-pith separating machine born from this project performs the function of separating the rind particles from the pith particles to achieve the high value utilization of corn stalk by the methods of rolling, cutting and impacting. Rollers of 4 types: tooth-type, blade-type, screw-type and rivet-type, were designed depending on the material characteristics of corn stalks. To avoid the machine's instability of running and mechanical disruptions caused by vibration in the process of rolling and cutting, we analyzed the relationship between vibration and the damage of rolling-cutting mechanism, and the rolling form influence on the response frequency of the whole machine, by extracting & contrasting the modal features and simulating the mechanical vibration during running process using FEM analysis and the calculation method of Block Lanczos. To determine complete simulation analysis, the resonance frequency of 4 different rollers shows the arrangement to be from low to high: tooth-type < blade-type < screw-type < rivet-type. According to the results a high risk interval with high participation factor of mechanical vibration, high damage rate, and strong noise appears between 180Hz-260Hz, thus the selected motor should avoid this frequency range. Based on resonance simulation, it shows that below 150Hz the vibration is smooth, and reaches peak values at 180Hz, 240Hz, and 310Hz during the process of rolling and cutting. And then, as the results of simulations show that the rolling-cutting mechanisms would have better adaptability and be more stable and reliable by optimizing the mechanisms and adjusting the length of cut corn stalk with differential mechanism.

Keywords - Rind-pith separation; Corn stalk; Rolling cutting; Simulation; Vibration

I. INTRODUCTION

Corn is one of the main crops in China. With the successive harvest of corn, the production of corn stalks has increased year by year. The discard and burn of corn stalks polluted environment seriously, so, the acceleration of corn stalks' high-value reuse has a great significance to stabilize the ecological balance of agriculture, ease resource constraints and reduce environmental stress [1-3].

Domestic and foreign scholars have carried out a number of rind-pith separation machinery research, the stiffness, strength of rind-pith separator and the wear caused by friction between materials and machinery have been researched [4-15]. In the above researches, scholars mainly studied the working mechanism of the machines and optimized the working state and mechanical properties; they did not consider the impact of mechanical vibration on the machine work.

In agricultural machinery, mechanical vibration is one of the main forms of mechanical damage, and it is the main reason of agricultural machinery damage and short service life [22]. According to the mechanical properties of stalk, this paper designed a stalk rolling cutting device. With the analysis of its core working parts, the body’s stability and reliability after forced vibration has been verified, and determined the suitable structural parameters for the rind-pith separation. Therefore, the rolling cutting efficiency can be maximized and energy consumption and failure rate can be reduced. This paper can provide reference for the design and promotion of batch-processing rind-pith separator s.

II. TEST EQUIPMENT AND WORKING PRINCIPLE

A. Equipment structure

The mechanism of straw roller cutting is shown in Figure 1, which is mainly constructed by pressure roller, pulley, cutter, fixed plate and the overall frame, etc.

Figure 1. Configuration of rind-pith separation equipment.

1: Straw cutter.2: Cutting tool rest .3: Belt pulley .4: Compression roller .5: Pressure roller .6: Shaft fixed plate .7: Frame.

B. Working principle

The rind-pith separation device use rolling, cutting and impact to achieve the separation of corn stalks flesh. Corn stalk was fed into the roller along the feed port, and was rolled by roller with opposite rotational direction, then it was
is \{u\} i: degrees of freedom. The corresponding characteristic vector characteristic value, where i ranges from 1 to the number of A. structure and the damping is ignored:

The root of the equation is \(W_{i2}\), namely is the Free vibration is assumed for the natural frequency of the 

\[ [K] - \omega^2 [M][u] = \{0\} \]  (3)

Where the force and displacement are in the form of harmonics:

\[ \{F\} = \{F_{exc}e^{i\omega t}\}e^{int} = (\{f\_1\} + i\{f\_2\})e^{int} \]

\[ \{u\} = \{u_{exc}e^{i\omega t}\}e^{int} = (\{u\_1\} + i\{u\_2\})e^{int} \]  (4)

Motion equation of resonance analysis:

\[ (-\omega^2\{M\} + i\omega[C]) (\{u\_1\} + i\{u\_2\}) = (\{f\_1\} + i\{f\_2\}) \]  (5)+

Where: \([M]\) and \([K]\) are kept constant. Simple harmonic equation of motion is \(u = u_0\cos (wt)\), where \(w\) is the natural frequency of vibration.

Resonance analysis assumes that the applied load varies over time according to the harmonic (sinusoidal) law, and it allows multiple loads of different phase angles to be applied at the same time, with the phase angle defaulting to zero. All applied loads are assumed to vary in harmonic form, including temperature and gravity fields. The study of mechanical vibration is based on the study of the natural frequency of the structure itself, and the comparison of the modal eigenvalue extraction methods is shown in Table II [15, 16]. From Table II, we can see that for the rolling cutting mechanism, the partitioning nodes are within 1 × 10^5, the grid form is mainly composed of solid elements, so it is the best to choose the Block Lanczos method.

III. VIBRATION CHARACTERISTIC ANALYSIS

A. Vibration Principle of Straw Rolling Cutting Device

Studies have shown that the majority of agricultural machinery has the problems of fast failure, fragile quality and other issues; one of the reasons is that the vibration problem is not considered at the beginning of the design. According to the mechanical natural frequency theory, in order to make sure that the straw rolling cutting device can withstand all kinds of sinusoidal alternating load with different frequency, it is necessary to detect the resonant response of its main working parts, so as to avoid the occurrence of damage caused by resonance and make sure the device can work smoothly.

The dynamic equation for roller cutting device is [16]:

\[ [\dot{u}] + [C][u] + [K][u] = \{F\} \]  (1)

Free vibration is assumed for the natural frequency of the structure and the damping is ignored:

\[ [\dot{u}] + [K][u] = \{0\} \]  (2)

The root of the equation is \(W_{i2}\), namely is the characteristic value, where i ranges from 1 to the number of degrees of freedom. The corresponding characteristic vector is \{u\} i:

| TABLE I. AIN TECHNICAL PARAMETERS OF RIND-PITH SEPARATION EQUIPMENT |
|-------------------------|-----------------|
| Technical Parameters    | Design value    |
| Productivity/(kgh⁻¹)    | 300             |
| Cutting particle length/(mm) | 5 ~ 10         |
| Supporting power/(kW)   | 55              |
| Length*width* height/(mm*mm*mm) | 1250*830*410 |
| Spindle speed/(r/min⁻¹) | 2950            |
| Number of cutters/pieces| 3               |

<p>| TABLE II. ODAL EIGENVALUE EXTRACTION METHOD EQUIPMENT |
|-------------------------------------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Extraction method</th>
<th>Solver</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block Lanczos</td>
<td>Sparse matrix solver</td>
<td>The method is effective when extracting a large number of modes from 5 × 10⁴ to 1 × 10⁵ degrees of freedom. It is allowed to extract the vibration modes higher than a given frequency in solid element and shell element model. It can deal with the rigid body shape well and require high memory.</td>
</tr>
<tr>
<td>Subspace method</td>
<td>Wavefront solver</td>
<td>This method has high requirements on element quality, and it may be difficult to converge when there are rigid body modes. Do not use this method with constraint equations. It needs less memory.</td>
</tr>
<tr>
<td>Dynamic method</td>
<td>Dynamic solver</td>
<td>It may not converge when ill conditioned matrix appears, so it is suggested that this method should be used as an alternative to the large-scale model. Its computing is faster than the subspace method and requires a lot of memory.</td>
</tr>
</tbody>
</table>
Matrix reduction, ie, selecting a set of main DOFs to reduce the size of \([K]\) and \([M]\), the reduced stiffness matrix \([K]\) is exact but the reduced mass matrix \([M]\) is approximate. This method is not recommended when the structure is weak in bending resistance such as slender beams and thin shells. This method requires less memory space and requires less computation.

**B. Mechanical vibration simulation**

In this paper, the finite element simulation software ANSYS is used to simulate the vibration characteristics. As shown in Fig 2, four different rollers (gear rolls, edge rolls, spiral rolls and rivet rolls) are designed for the core components of the roll cut. The tooth roller is shown in Figure 2 (a), there are 24 alveoles in the roller, which produce the cutting force, the impact force, the squeezing force and the small friction force in the stalk rolling; The blade roller is shown in Fig.2 (b), 20 blades were distributed on the blade roller, which can produce the pith cutting operations; the spiral roller is shown in Figure 2 (c), there are 12 spiral lines on the roller to produce the spinning pressure, the rolling force and the large friction force; the rivet press roller is shown in Figure 2 (d), there are 12 columns rivets on the roller, and every column have 18 rivets, which produces the cutting force, impact force, squeezing force and a small friction.

\[
\sigma_{df} = -m \lg N_i + n
\]  

(7)

The dynamic input source of roller cutting device is realized by the pulley rotation. The vibration of the motor will cause the whole mechanical resonance to the machine. The natural vibration frequency of rolling shear apparatus is simulated to determine the natural frequency of the structure and deformation effect. Add bind contact relationship to these 4 types of roller structure parts. The bottom end of the machine frame is fixed, and the first 30 order modes of the rolling cutting device are set, because the first 30 order frequency can cover the scope of mechanical vibration excitation frequency.
basically the same in the first 15 order modes (less than 370 Hz). In the high frequency range, the rivet roller is rigid and the resonant frequency is the highest; the tooth roller’s rigidity is weak and the resonance frequency is the lowest; the blade roller is slightly higher than tooth roller, but lower than screw roller. The resonant frequencies of four pressure rollers are as follows: tooth type < blade type < screw type < rivet type.

From the mode results of 4 types of rolling cutting device, we can see that resonant effect area is concentrated in the cutter and the pressure roller, which makes the working parts prone to damage and produces a lot vibration noise. Based on this situation, we analyzed the forced vibration response of the structure.

<table>
<thead>
<tr>
<th>Type / Resonance Frequency</th>
<th>First order</th>
<th>Second order</th>
<th>Third order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riveting type</td>
<td>155Hz</td>
<td>220Hz</td>
<td>370Hz</td>
</tr>
<tr>
<td>Spiral type</td>
<td>165Hz</td>
<td>225Hz</td>
<td>400Hz</td>
</tr>
<tr>
<td>Blade type</td>
<td>170Hz</td>
<td>240Hz</td>
<td>375Hz</td>
</tr>
<tr>
<td>Tooth type</td>
<td>175Hz</td>
<td>235Hz</td>
<td>345Hz</td>
</tr>
</tbody>
</table>

In ANSYS, there are three methods for resonant analysis: Full, Reduced, and Mode Superposition [23].

The modal superposition method is faster than the other two and the cost is low, and the result is more accurate [25]. The results can include prestress results that allow for consideration of modal damping (the damping coefficient is a function of frequency).

In the Modal superposition method, the vibration mode (eigenvector) obtained by modal analysis is multiplied by a factor to obtain a response result [26]. Therefore, modal superposition method has obvious advantages in the calculation of agricultural machinery vibration.

There are some limitations in the resonance analysis based on modal analysis, that is, all loads must change with time according to the law of sinusoidal load, the load must have the same frequency and the calculation does not allow non-linear participation, and it does not allow transient effects. The input load of roller cutting structure changes exactly with time according to sinusoidal load law, so there is no effect on the simulation results.

In the ANSYS, modal superposition resonance analysis is carried out based on modal analysis. The pulley’s load changes under sinusoidal load, the constraint is kept constant.
and the time step is adjusted. And we can see that the pulsator and body are damaged by harmonic vibration.

Through the mechanical resonance simulation of the four kinds of roller mechanism, the maximum stress values of the a, b, c, d-type rollers’ belt pulley and the body connection under the simple harmonic spectrum are shown in Figure 5. Figure 5 shows that: 4 models remain relatively stable before 150Hz, and in 180Hz, 240Hz, 310Hz, it reached several fixed resonance point, which indicates that mechanical resonance occurred when frequency near these points. The frequency of the motor should resonant frequencies, which makes the structure relatively stable.

Three times resonance frequency peak point of 4 type of roller obtained by the analysis of Figure 5 are shown in Table III.

From Fig.5 and Table 3, we can see that the forced frequencies of four types of roller structures are the same before 150Hz. In the high-order frequency, the forced vibration frequency is different due to the different form of the roller; the rivet-type roller has good rigidity and the highest forced vibration frequency; the tooth roller’s rigidity is low and it has the lowest forced vibration frequency; the blade roller has a slightly higher frequency than the tooth roller but is lower than the screw roller frequency.

4 kinds of rollers’ forced stability under forced vibration can be ranked as follows: tooth <blade <spiral <riveting.

IV. CONCLUSION

(1) According to the characteristics of straw material, the paper designed the rind-pith separation equipment; this device uses the form of rolling, cutting and impact to achieve the corn stalks rind-pith separation. We designed 4 types of roller according to different forms of rolling: riveting type. Spiral type, blade type and tooth type.

(2) Research in based on the modal eigenvalue extraction method. Results show that the rolling cutting machine node’s mode frequency is high. The resonant frequencies of four types of roller structures are the same before 150Hz, and in 180Hz, 240Hz, 310Hz, it reached several fixed resonance point, which indicates that mechanical resonance occurred when frequency near these points. The frequency of the motor should resonant frequencies, which makes the structure relatively stable.

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REFERENCES


