DESIGN AND FINITE ELEMENT ANALYSIS OF VARIABLE-DIAMETER THRESHING DRUM WITH MOVABLE RADIAL PLATES

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幅盘移动式变直径脱粒滚筒的设计与有限元分析

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ABSTRACT

In view of the fact that the threshing gap of combine harvester can only be controlled by adjusting gravure screen and it is time-consuming and laboring, a kind of variable-diameter threshing drum with movable radial plates is developed by changing the diameter of threshing drum to adjust the threshing gap concentrically. All parts of the threshing drum were designed and checked by mechanical design principle, and the statics and modal analysis of the whole structure were carried out by ANSYS Workbench. The results show that the maximum deformation of the variable-diameter threshing drum with movable radial plates is 0.29 mm under boundary conditions. The maximum allowable deformation of the threshing drum in use is 3 mm, which meets the requirements of use. The equivalent stress of the threshing drum with variable diameter is up to 100 MPa, which is less than the yield strength of the material, and will not cause structural damage. According to the modal analysis, the natural frequency of the threshing drum does not cause resonance phenomenon. The field test of wheat was carried out after the processing of the variable-diameter threshing drum with movable radial plates was installed, and the working performance was compared with that of the ordinary drum. The results showed that the threshing performance was the best when the forward speed was 1 m/s, the grain entrainment loss rate was 0.53%, and the grain un-threshed rate was 0.065%. The grain breakage rate is 0.54%, and the performance is more than 50% higher than that of ordinary rollers. It lays a foundation for the adaptive adjustment of threshing gap in combine harvester.

摘要

针对目前联合收获机脱粒间隙只能调节凹版筛来控制且费时费力，研制了一种通过改变脱粒滚筒直径同心调节脱粒间隙的辐盘移动式变直径脱粒滚筒，同时对脱粒滚筒直径变化对脱粒性能的影响进行了分析。利用机械设计原理对脱粒滚筒进行了所有部件的设计校核，并利用 ANSYS Workbench 对整体结构进行了静力学和模态分析，结果表明， 在边界条件下幅盘移动式变直径脱粒滚筒的最大变形量为 0.29 mm，小于脱粒滚筒在使用中允许最大变形量为 3 mm，符合使用要求，变直径脱粒滚筒等效应力最大为 100 MPa，小于材料的屈服强度，不会产生结构的损坏。根据模态分析， 脱粒滚筒的固有频率不会造成共振现象， 将加工好的辐盘移动式变直径脱粒滚筒安装后进行了小麦的田间试验， 并与普通滚筒进行作业性能对比，结果证明 ， 在前进速度为 1 m/s 时， 脱粒性能最好． 夹带损失率为 0.53%， 未脱净率为 0.065%， 破损率为 0.54%， 性能较普通滚筒相比提升 50%以上。为联合收获机脱粒间隙自适应调节奠定了基础。

INTRODUCTION

In recent years, in order to improve the utilization rate of combine harvesters, combine harvesters that can be suitable for multiple crops by changing the relevant parts and parameters have appeared (*Kang J et al, 2023*) The adjustment of threshing device is an important part, and the threshing device is directly related to the threshing performance (*Deng X. et al, 2022*). Different varieties, different types and different characteristics of crops need different working parameters during harvest, threshing gap is a very important parameter, which affects the grain entrainment loss rate, grain un-threshed rate and crushing rate and other evaluation indicators (*Teng Y et al, 2020*). Therefore, a convenient device to adjust the threshing gap is needed.

For this reason, a platter mobile variable diameter threshing drum was designed, which can change the threshing gap by changing the diameter of the drum, so as to adapt to different kinds of crops in various complex working environments.

Due to the non-uniformity of materials and processing accuracy, the threshing drum is prone to unbalanced problems during operation. At the same time, the threshing drum with high-speed rotation generates excitation frequency in the periodic movement process. If the excitation frequency is similar to the natural frequency, resonance phenomenon will easily occur, which will lead to damage of the threshing drum components in the long run. The threshing performance of combine harvester is affected, so the corresponding analysis should be carried out in the design process of threshing drum to ensure its reliability.

The simulation analysis of mechanical parts in the design process has been widely used. Zhang Jian et al designed the buckwheat threshing device and carried out static and dynamic analysis with ANSYS (*Zhang J. et al, 2019*). Li Yongchun et al. designed a rice spiral drum and carried out modal analysis using ANSYS to avoid resonance (*Li Y et al, 2022*). He Ke et al designed a flexible corn threshing drum, and used ADAMS and Abaqus to carry out dynamic balance analysis, modal analysis and net stress analysis of the threshing drum (*He K. et al, 2018*).

In this paper, a variable-diameter threshing drum with movable radial plates is designed, and SolidWorks is used to model it. Statics and dynamics analysis are carried out by ANSYS Workbench to analyze and check the strength and stiffness of the threshing drum, and the natural frequency and vibration mode are obtained to prevent resonance. It provides a basis for the structural check of the variable diameter threshing drum and a reference for the design of drum components.

MATERIALS AND METHODS

Design of variable-diameter threshing drum with movable radial plates

Influence of cylinder diameter adjustment on threshing performance

The principle of threshing drum mainly includes impact, rubbing, brushing, vibration and rolling (*Kong D. et al, 2020; Liu P. et al, 2020; Ni G. et al, 2019*), through which the grain is removed from the stalk. This time, the variable diameter mobile threshing drum with movable radial plates adopts the nail tooth type, so the main threshing principle depends on the impact force, and the impact force of the threshing drum is mainly determined by the linear speed from the top of the drum.

The formula for the linear velocity of circular motion can be known as:

$$v = \frac{2\pi \cdot r}{T} \tag{1}$$

where:

v is the linear velocity, m/s; r is the radius of the threshing drum, m; T is the time required for the threshing cylinder to turn one circle, s.

It can be seen from the formula that when the speed remains unchanged, the larger the radius, the greater the linear speed, and the greater the impact force on the grain, and vice versa.

Drum structure design

Determination of spindle diameter

As for the spindle of the threshing drum, it is mainly used to transmit torque, and the longer the drum, the more torque it needs to transmit. The threshing drum designed in this paper is based on the Super Ruilong series of Wode Agricultural Machinery, and the length of the drum reaches 2.5 m. Therefore, the minimum diameter of the shaft is roughly estimated based on the torsion strength of the shaft. Therefore, it is necessary to design the spindle into a hollow shaft, and the design of a hollow shaft can save materials and reduce weight while meeting the strength. According to the torsional strength formula of the hollow shaft, the diameter of the main shaft can be obtained as:

$$D \geq A_0 \sqrt[3]{\frac{P}{n(1-\beta^4)}} \tag{2}$$

where:

$\beta = \frac{D_1}{D}$ that is, the ratio of the inner diameter D_1 of the hollow shaft to the outer diameter D, usually β=0.5~0.6

The engine power of the combined harvester is 103 kW, and the power consumption of the threshing drum during operation can account for about 20% to 30% of the engine, so the maximum power transmitted by the threshing drum is about 30.9 kW, and the rotational speed n of the drum is 800 r/min. A_0 is obtained by looking up the table. Bring all the data into equation (2) to obtain the outer diameter of the hollow shaft $D \geq 35.1$ mm. According to the mechanical design requirements, if there is a keyway on the same section, the shaft diameter should be increased by 5% to 7%.

However, the above calculation can only be used as a rough calculation, the spindle is not only subject to torque, but also the existence of bending moments during operation, so the bending moment and torque should be considered at the same time. The shaft diameter is calculated according to the bending moment and torque synthesis.

$$d \geq \sqrt[3]{\frac{M_e}{0.1[\sigma_{-1}]}} \tag{3}$$

where: $[\sigma_{-1}]$ is the allowable bending stress (MPa) of the shaft under symmetric cyclic variable stress, and M_e is the equivalent bending moment.

$$M_e = \sqrt{M^2 + (\alpha T)^2} \tag{4}$$

In the formula, $T = \frac{9550P}{n}$, M is the bending moment, and alpha is the conversion coefficient based on the properties of torque, P is the power of the drum, and n is the rotational speed of the drum.

In order to achieve good interchangeability of the combine and facilitate the replacement and disassembly of parts, the main shaft and the main shaft at the feeding end are splined and fastened by bolts to prevent axial movement. All the parts on the spindle can be easily removed, and the hydraulic cylinder is designed to be hollow and directly attached to the spindle. Finally, the total length of the spindle is determined to be 2713 mm. The outer diameter of the spindle is 65 mm and the inner diameter is 45 mm.

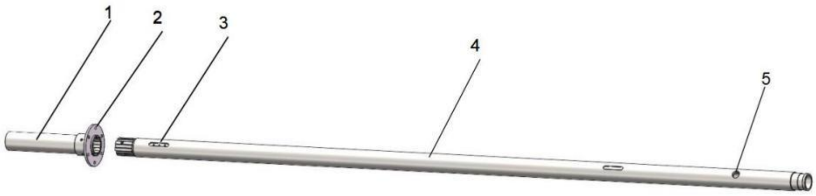


Fig. 1 - Principal axis

1. Spline shaft; 2. Spline shaft flange; 3. Parallel key; 4. Spindle body; 5. Tubing hole

Shaft sleeve design

The movable variable diameter threshing drum realizes the movement of the support plate by installing the support plate on the shaft sleeve. The support plate is welded on the shaft sleeve, the shaft sleeve is covered on the spindle, and the hydraulic cylinder is pushed to realize the forward and backward movement of the support plate, and then the diameter adjustment operation is completed with the mechanism.

The original bushing design is that the size of the inner diameter of the bushing is the same as the size of the outer diameter of the spindle, so that the bushing can be matched with the spindle, so the inner diameter of the bushing is 65 mm, and the outer diameter of the bushing is 71 mm in order to ensure a certain strength. At the same time, the parallel keyway is obtained on both sides, and the installation position of the flange is set aside on both sides to connect with the hydraulic cylinder and the guide rail pusher. According to the size relationship, the shaft sleeve is designed to be 1675 mm.

Later, considering the reasons of friction and processing conditions, the optimization design was further carried out. Because the length of the shaft sleeve design is too long, if the whole shaft sleeve is in contact with the spindle, the friction will be very large, resulting in the hydraulic cylinder thrust requirements being larger, which will lead to the weight of the hydraulic cylinder being increased. Affecting the use of the hydraulic cylinder may also be too large friction resistance, resulting in the hydraulic cylinder in the process of pushing and pulling will damage parts, resulting in the threshing cylinder not being able to be used normally. Another reason is that the shaft sleeve is too long, and the contact with the spindle requires the surface roughness of the inner surface of the shaft sleeve as small as possible, but if the shaft sleeve is too long, the existing tool cannot bore out the internal hole that meets the requirements, so it was found a way to reduce the contact between the shaft sleeve and the spindle, but also to meet the coordination with the spindle. So, the spindle is designed in sections, divided into the front axle sleeve base, the middle axle sleeve, and the rear axle sleeve base.

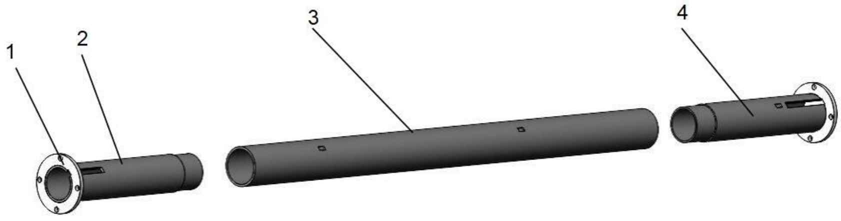


Fig. 2 - Shaft sleeve
1. Flange; 2. Front sleeve base; 3. Middle sleeve; 4. Rear sleeve base

The front and back bushings are still matched with the original scheme with the spindle, so the inner diameter of the front and back bushings is 65 mm, the outer diameter on the step is 72 mm, and the outer diameter under the step is 68 mm. With the sleeve base, the inner diameter of the middle sleeve is 68 mm, and the outer diameter is 76 mm. The convex parts of the front and rear bushing bases are inserted into the middle bushing and then welded to make it a whole. The flange of the front axle sleeve base is connected with the push plate of the guide rail by bolts, and the rear axle sleeve base is connected with the piston rod of the hydraulic cylinder by bolts. The small square hole on the shaft sleeve is the positioning hole for supporting the plate, which determines the welding installation position of the plate.

The overall structure after designing other structures is shown in Figure 3 below.

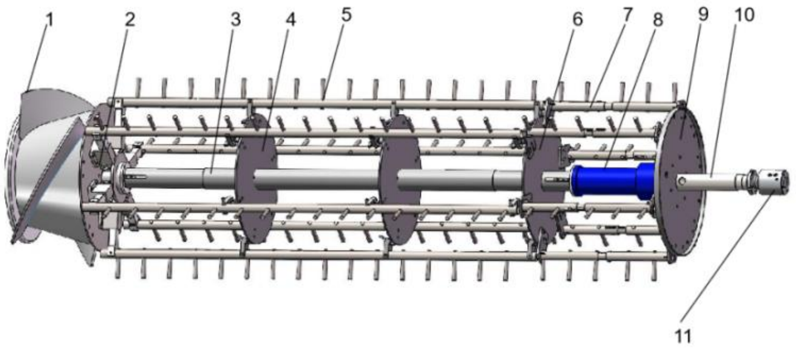


Fig. 3 - Structure diagram of Variable-diameter threshing drum with movable radial plates
1. Feeding wheel; 2. Side plate adjusting mechanism; 3. Shaft sleeve; 4. First middle plate adjusting mechanism; 5. Fixed gear rod; 6. Second intermediate plate adjusting mechanism; 7. Retractable gear rod; 8. Single piston rod hollow hydraulic cylinder; 9. Rear side plate; 10. Spindle; 11. Hydraulic rotary joint

Finite element simulation analysis

To check the rationality and safety of the variable diameter threshing drum designed with movable radial plates and to avoid accidents during use that may affect the harvest and even cause safety problems a simulation analysis has been provide. Therefore, the 3D model established in Solid Works was imported into ANSYS Workbench for statics and modal analysis. Through static analysis and research, the strength and stiffness of the movable variable diameter threshing drum are checked. The modal analysis is used to analyze whether there will be resonance phenomenon in the movable variable diameter threshing drum, which will destroy the structure.

Static analysis

After setting up a movable variable diameter threshing drum in solid works, the 3D model was output in Parasolid format with file suffix x-t after interference check on the model. The model was imported into ANSYS Workbench for static analysis. The operation process of static analysis is mainly divided into three stages: pre-processing, solving and post-processing. The pre-processing is the focus of its operation, which mainly includes the process of creating or importing geometric models, defining parameters, dividing grids, checking grid quality and setting boundary conditions.

Define the material and set the contact

When using ANSYS analysis, the first and important step is to define the properties of the material, only by defining the correct parameters, can you get the simulation results consistent with the actual situation (*Li H et al, 2012*). Material properties have been obtained by consulting relevant literature. In actual production, 45 steel and Q235A steel will be used, (*Yue F et al, 2018*), so the parameters of these two kinds of steel are set, and the details of parameters are shown in Table 1.

Table 1

Material attribute table

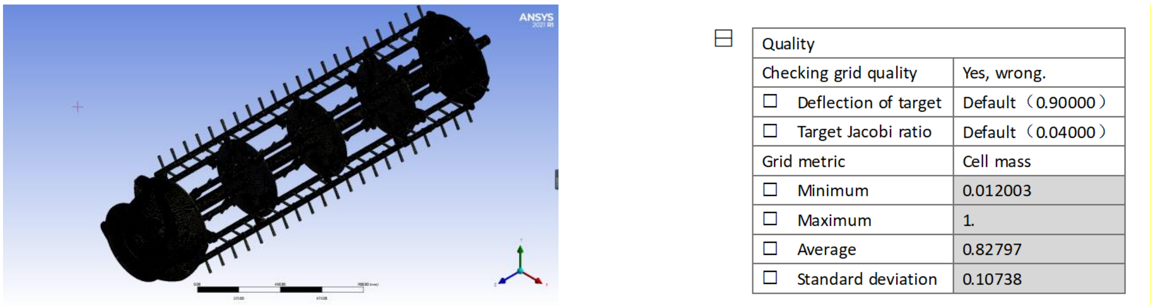
Materials	Density (kg/m^3)	Poisson's ratio	Modulus of elasticity	Yield strength (MPa)	Tensile strength (MPa)
45#	7.89 x 10^3	0.269	2.09 x 10^{11}	340	600
Q235A	7.86 x 10^3	0.288	2.12 x 10^{11}	235	390

After the material definition is completed, the Parasolid format model is imported into ANSYS Works2021, and corresponding materials are assigned to each part.

The imported model was divided into 248 geometries. Automatic contact was used and modified according to the actual situation. Binding contact and friction contact were set in total, and the friction coefficient was set at 0.15. A total of 315 connections are set.

Meshing

Grid division is the most important step in the pre-processing of finite element analysis, and the quality of grid division directly affects the accuracy of the simulation results. Because the structure of the movable variable diameter threshing drum is complex and its components are fine, automatic grid division is adopted, and only the size of the grid is set, and the size of the unit is set to 4.00 mm. The rest are default Settings, as shown in Figure 4 (a).



Quality	
Checking grid quality	Yes, wrong.
☐ Deflection of target	Default（0.90000）
☐ Target Jacobi ratio	Default（0.04000）
Grid metric	Cell mass
☐ Minimum	0.012003
☐ Maximum	1.
☐ Average	0.82797
☐ Standard deviation	0.10738

a Meshing situation *b Mesh quality*

Fig. 4 - Grid of variable-diameter threshing drum with movable radial plates

The result of grid division is as follows: the number of nodes is 5904704 and the number of cells is 3004536. Open the grid metric as cell quality, and you can see that the minimum mass is 0.012003, the maximum mass is 1, the average mass is 0.82797, and the average mass is greater than 0.7, so the grid quality is good as shown in Figure 4 (b).

Setting of boundary conditions

The boundary conditions set in the finite element analysis are mainly load and constraint. This simulation is based on the idling condition of the threshing drum, and the air resistance and friction between bearings are ignored. Therefore, the boundary conditions of the drum are mainly derived from the limiting displacement of the bearing, the centrifugal force of the threshing tooth rod, the torque transmitted by the engine to the exiting drum and its own gravity (*Chen L. et al, 2023*).

The calculation formula of torque is:

$$T = \frac{9550P}{n} \tag{5}$$

where:

P is power, kW; n is the speed, r/min; T is the torque N/m.

The centrifugal force is calculated as follows:

$$F = ma = 4\pi^2 mn^2 r \tag{6}$$

where:

F is the centrifugal force and N; m is the mass of the tooth rod, kg; r indicates the distance between the center of mass of the tooth rod and the center of rotation of the drum.

According to the formula, the torque added to the drum is 246067 N.mm, the centrifugal force on the ordinary tooth rod is 10261.2 N, and the centrifugal force acting on the telescopic tooth rod is 3958.37 N. The boundary condition settings are shown in Figure 5. Centrifugal force is B, C, D, F, G, H, I, J.

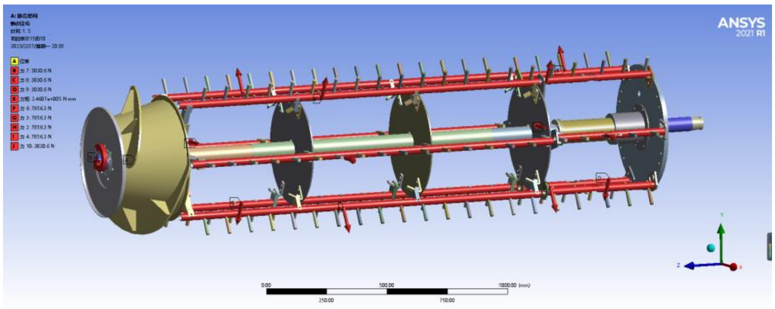


Fig. 5 - Boundary condition setting

Kinetic analysis

For the Variable-diameter threshing drum with movable radial plates, modal analysis is divided into two kinds, one is without prestress, that is, the drum is in a free state, not subject to any constraints and forces, and the actual situation is too big, the result is not of reference value, so choose the condition with prestress for simulation, that is, the application of boundary conditions. Under normal circumstances, the low-order frequency has a greater impact on the structure and is easy to destroy the structure. In order to make the simulation more realistic and better test the reliability of the design, under the above constraints, the lateral resistance of each tooth rod is increased to simulate the resistance of crops to the threshing tooth rod during the threshing process. Considering that the object has 6 degrees of freedom in the free state, the first 6 orders of the variable diameter threshing drum are mainly studied.

Field trial

After the preliminary design and finite element analysis, the Variable-diameter threshing drum with movable radial plates was processed and installed in the field test of the Wode Super Ryzen combine. At the same time, the working quality was compared with that of ordinary rollers. A field test of wheat was carried out in Danyang, Jiangsu Province, in June 2023. Before the test, oilcloth was bundled to the straw outlet of the combine to collect the outfall, and a 20-meter-long test area was marked with a marker. After the test, the grain entrainment loss rate and the Grain un-threshed rate were calculated by selecting the entrainment loss kernel and the unstripped kernel. The grain unloading in the grain box was weighed and the grain crushing rate was measured by random sampling. Each group of tests was repeated three times, and the performance indexes were averaged (*Yang L. et al, 2018; Li Y. et al, 2016*).

Fig. 6 - Wheat field trial

According to the national standard GB/T 5262-2008 "General Provisions for the Determination of Agricultural machinery test conditions" and GB/T 8097-2008 "Test Methods for Harvesting machinery Combine Harvester” relevant provisions for harvesting machinery test, the crop weight W(kg/m^2) per unit area was calculated in the field in a 1 m^2 square area according to the five-point sampling method before the test. Thus, the relationship between the traveling speed and the feeding amount is calculated:

$$q = B \cdot V_m \cdot W \tag{7}$$

where: q is the total feeding amount per unit time, kg/s; B is the working width of the combine harvester, m;

V_m is the working speed of the combine, m/s.

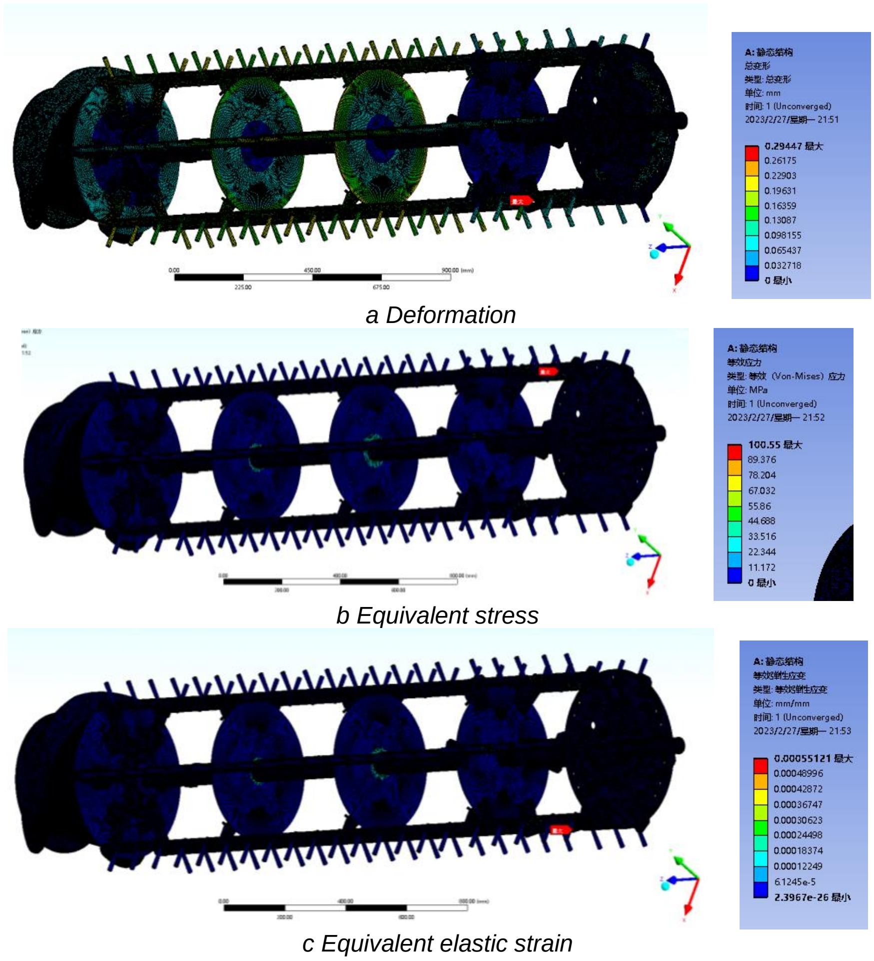
Therefore, in order to obtain different feeding amounts in the test, it can be achieved by changing the working speed of the combine. According to NY/T 995-2006 "Operation Quality of Grain (Wheat) Combined Harvesting Machinery", the evaluation indexes of threshing performance are grain entrainment loss rate, grain un-threshed rate and crushing rate. The test results of different harvesting speeds were obtained by weighing each group of samples through the test of the variable-diameter threshing drum with movable radial plates and the ordinary nail tooth drum.

RESULTS

Result of finite element analysis

Results of static analysis

The distribution of deformation, stress and strain is checked. As shown in Figure 7, the maximum deformation of the variable-diameter threshing drum with movable radial plates is 0.29 mm under the above boundary. According to the existing data, the maximum allowable deformation of the threshing drum in use is 3 mm, so this design is far less than 3 mm and meets the application requirements. The maximum equivalent stress of the variable diameter threshing drum is 100 MPa, which is less than the yield strength of the material, and will not cause structural damage.



a Deformation

b Equivalent stress

c Equivalent elastic strain

Fig. 7 - Static simulation results

Modal analysis results

The obtained natural frequencies and modes of the first six orders are shown in Table 2.

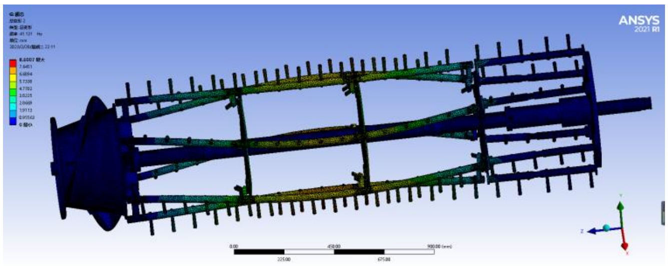
Table 2

The first six modal frequencies and modes of a variable-diameter threshing cylinder

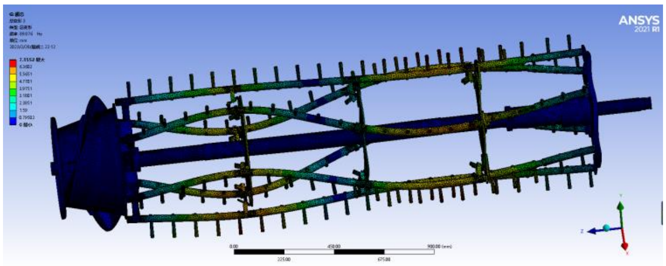
Rank	Natural frequency	Maximum deformation	Mode description
1	41.131	8.6007 mm	The overall distortion of the drum, the bending of the threshing tooth rod in the -Y direction
2	89.876	7.1552 mm	The whole twist of the roller
3	101.46	4.4572 mm	The bend of the drum in the -Z direction, especially the plate
4	117	7.7289 mm	The bending twist of the drum in the +Y direction
5	123.21	9.6035 mm	The overall bend of the cylinder in the +Y direction

6	130.69	10.524 mm	The bending deformation of the whole cylinder along the +X direction

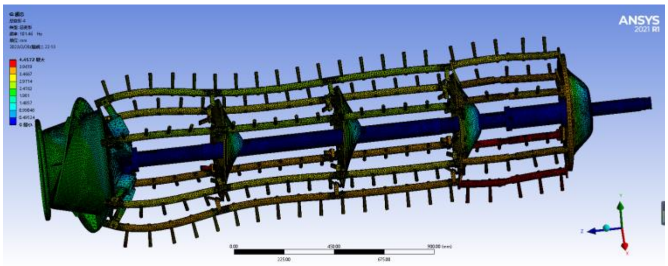
The modal analysis was carried out on the first six stages of the variable-diameter threshing drum with movable radial plates, and the deformation of each mode was briefly described. Figure 8 is the modal figure of the first six modes.



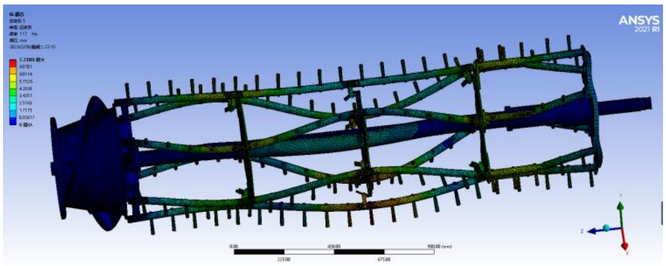
a) First mode pattern diagram



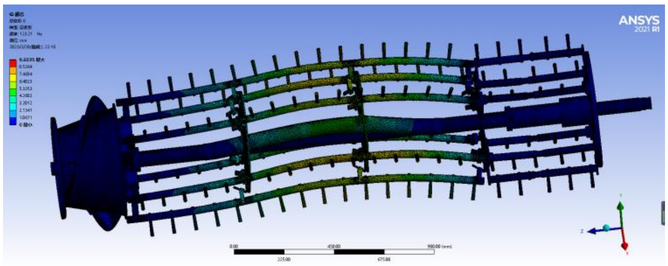
b) Second order mode pattern diagram



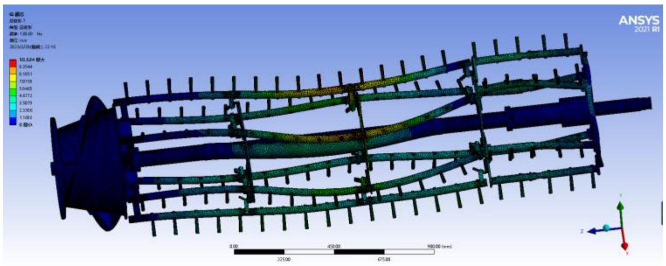
c) Third order mode pattern diagram



d) The fourth mode pattern diagram



e) The fifth mode pattern diagram



f) Sixth order mode pattern diagram

Fig. 8 - Figure of the first six modes

As can be seen from Table 2 and Figure 8, the first six deformations are mainly bending and twisting. Generally speaking, the first mode has the largest energy and is most likely to cause structural damage. The general conclusion is that the external excitation frequency should be less than 75% of the first-order natural frequency, otherwise it will be dangerous. The natural frequency of the first mode is 41.131, and 75% of it is 30.84825. Then it can be calculated according to the calculation formula of the external excitation frequency:

$$\mathrm{f} = \frac{n}{60} \tag{8}$$

where: n is the rotational speed of the drum; f is the excitation frequency

The rotating speed of the roller in this design is 700~900 r/min, and the range of f obtained is 11.67~15, which is less than 75% of the natural frequency of the first order mode, so it meets the safety requirements, and the design avoids the structural damage caused by resonance.

Field test results

Field test results are shown in Table 3.

Table 3

Field test results

Rate of harvest (m/s)	Type of drum	Grain entrainment loss rate (%)	Grain un-threshed rate (%)	Percentage of breakage (%)
0.6	Variable-diameter threshing drum with movable radial plates	0.98	0.124	0.98
	Plain drum	2.16	0.45	2.13
0.8	Variable-diameter threshing drum with movable radial plates	0.76	0.108	0.67

Rate of harvest (m/s)	Type of drum	Grain entrainment loss rate (%)	Grain un-threshed rate (%)	Percentage of breakage (%)
	Plain drum	1.86	0.32	1.86
1.0	Variable-diameter threshing drum with movable radial plates	0.53	0.065	0.54
	Plain drum	1.56	0.24	1.54
1.2	Variable-diameter threshing drum with movable radial plates	0.87	0.098	0.76
	Plain drum	1.79	0.43	1.62
1.4	Variable-diameter threshing drum with movable radial plates	1.13	0.153	0.87
	Plain drum	2.31	0.67	1.93

After data processing of the test results in Table 3, line charts of the effects of two drum harvesting speeds on grain entrainment loss rate, grain un-threshed rate and crushing rate were drawn, as shown in Fig. 9-11.

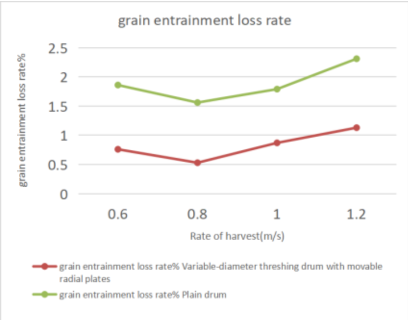


Fig. 9 - Effect of harvest speed on grain entrainment loss rate

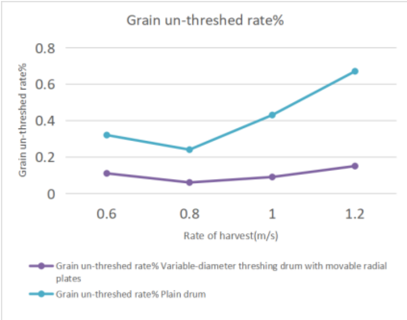


Fig. 10 - Effect of harvest speed on grain un-threshed rate

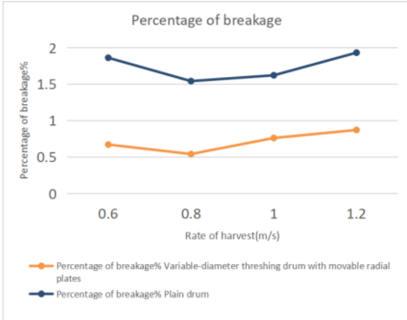


Fig. 11 - Effect of harvest speed on Grain breakage rate

As can be seen from Fig. 9, the loss rate of the variable diameter threshing drum decreases first and then increases, and the grain entrainment loss rate is in the range of 0.53% ~ 1.13% when the harvesting speed keeps increasing. Under the condition of increasing harvest speed, the grain entrainment loss rate decreases first and then increases, and the loss rate is in the range of 1.56% ~ 2.31%. From the broken line, the grain entrainment loss rate of the variable diameter threshing drum is smaller than that of the ordinary nail tooth drum.

As can be seen from Figures 10 and 11, the grain un-threshed rate and the grain breakage rate also decrease first and then increase with the increase of the advancing speed of the harvester, and the data of the variable-diameter threshing drum is better than that of the ordinary drum, which is in line with the national design standards.

To sum up, the threshing performance of the variable-diameter threshing drum with movable radial plates is generally better than that of the ordinary threshing drum. In the test process, the structure is reliable, there is no accident, and the reliability is high.

CONCLUSIONS

(1) The relationship between threshing performance and the diameter of the threshing drum was studied, and based on the principle of changing the diameter of the threshing drum, a variable-diameter threshing drum with movable radial plates was designed, which could realize the real-time adjustment of the threshing gap during the operation of the threshing drum to achieve the best threshing performance.

(2) Based on the variable-diameter threshing drum with movable radial plates, static and modal analysis were carried out by ANSYS Workbench to verify the strength and stiffness of the structure and ensure that the deformation under maximum stress meets the requirements. The maximum deformation is 0.29 mm, which meets the requirements of use. The first six natural frequencies were obtained through modal analysis to prevent resonance and ensure the reliability and safety of the design.

(3) The designed variable diameter threshing drum was processed and installed for wheat field test, and the operation effect was compared with that of ordinary threshing drum. The forward speed of the combine was taken as the influencing factor, when the forward speed is 1 m/s, the threshing performance is the best, the grain entrainment loss rate is 0.53%, the grain un-threshed rate is 0.065%, and the damage rate is 0.54%. The performance is more than 50% higher than that of the ordinary drum.

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REFERENCES

[1] Chen L., Li Y, Su Z., Liu Y., Yin Q. (2023). Design and test of a threshing cylinder with single motion and variable diameter of tooth bar (一种齿杆单动变直径脱粒滚筒的设计与试验) *Agricultural mechanization research* (05), 43-48. Doi: 10.13427 / j.carol carroll nki njyi. 2023.05.008.

[2] Deng X., Zhang T., Tang X., Pang Y., Ye F., Lin T., Luo S. (2022). Design and experiment of 4LZ-2.4S hand-held mung bean combine harvester (4LZ-2.4S 型手扶式绿豆联合收获机的设计与试验） Agricultural mechanization research (10), 43-51. Doi: 10.13427 / j.carol carroll nki njyi. 2022.10.010.

[3] He K., Wang Q., Geng D., Jin C., Zhu J., Zhang M. (2018). Simulation analysis of corn flexible threshing drum. Journal of Chinese agricultural mechanization （玉米柔性脱粒滚筒仿真分析）(07), 53-58. Doi: 10.13733 / j.j CAM. Issn 2095-5553.2018.07.011.

[4] Kong D.D., Lu H.C., Hu X. (2020). Development status and trend of semi-feeding rice combine harvester in China（我国半喂入式水稻联合收割机发展现状与趋势） *Times Agricultural Machinery*. (05), 19-21.

[5] Kang J., Wang X., Xie F., Luo Y, Li Q., Huang X. (2023). Performance test and analysis of differential threshing roller adapted to different maturity of soybean (适应不同成熟度大豆的差速脱粒滚筒性能试验与分析) *Chinese Journal of Agricultural Engineering.* (01), 38-49.

[6] Li.H. (2012). *Dynamic pillar type double spindle gantry CNC drilling machine design and finite element analysis* (动柱式双主轴龙门数控钻床设计及其有限元分析）(master's degree thesis, Nanjing Agricultural University).

[7] Li Y., Wang H., Wang Y., Yang M., Wang H., Liu X. (2022). Design and experiment of spiral drum for rice combine harvester（水稻联合收割机螺旋滚筒设计与试验） *Agricultural mechanization research* (09), 121-128. DOI: 10.13427 / j.carol carroll nki njyi. 2022.09.012.

[8] Li Y.M., Chen Y., Xu L.Z. & Li L. (2016). Optimization of structural parameters of threshing and separating device of inclined cut longitudinal combine （大豆机收清选筛田间性能试验与分析） *Chinese Journal of Agricultural Machinery* (09), 56-61.

[9] Liu P., Jin C., Ning X., Ni Y., Wang T., Yin X. (2020). Field performance test and analysis of soybean harvester cleaning screen（大豆机收清选筛田间性能试验与分析） *Chinese Journal of Agricultural Engineering.* (09), 36-43. https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CMFD201401&filena me=1013284993.nh

[10] Ministry of Agriculture of the People's Republic of China (2008). GB/T 5262-2008（农业机械试验条件测定方法的一般规定） *General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China*; Standardization Administration of China.

[11] Ni G., Qin Y., Han K., Hou X., Zhang X. (2019). Ideas and technical ways to improve the profit of rice harvester operation. *Agricultural Equipment and Vehicle Engineering.* (S1), 71-73.

[12] Teng Y., Jin C., Chen Y., Liu P., Yin X., Wang T., Yu K. (2020). Design and optimization of segmented threshing device for rice and wheat combine（稻麦联合收获机分段式脱粒装置设计与优化） *Chinese Journal of Agricultural Engineering*. (12), 1-12.

[13] Yue F., Luo X., Ma F., Tang S., Jiang Y., Li H. (2018). Structure design and research of cylindrical backwashing filter for micro-irrigation（微灌用筒式反冲洗过滤器结构设计与研究） *Jiangsu Agricultural Sciences* (24), 248-251. doi:10.15889/j.issn.1002-1302.2018.24.068.

[14] Yang L., Wang W., Zhang H., Li L., Wang M., Hou M. (2018). Improved design and bench test of tangential flow - transverse axial flow corn threshing system（切流-横轴流玉米脱粒系统改进设计及台架试验） *Chinese Journal of Agricultural Engineering.* (01), 35-43.

[15] Zhang J., Gan P., Guan W.W. (2019). Design and finite element analysis of buckwheat threshing device（荞麦脱粒装置的设计及有限元分析） *Journal of Chinese agricultural mechanization* (07), 7 to 12. Doi: 10.13733 / j.j CAM. Issn 2095-5553.2019.07.02.