LIGHTWEIGHT DESIGN OF THE SEEDING WHEEL STRUCTURE OF RICE DIRECT SEEDER BASED ON TOPOLOGY OPTIMIZATION

基于拓扑优化的水稻直播机排种轮结构轻量化设计

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ABSTRACT
Abaqus software is used to analyze the seeding wheel's stress distribution and displacement deformation during the working process, and the seeding wheel's stress distribution and displacement cloud maps are obtained. Topology optimization analysis was conducted on the seeding wheel to obtain the optimized finite element model. Based on the finite element model, the original 3D model was modified to obtain the topologically optimized 3D model of the seeding wheel. The results show that the optimized seeding wheel reduces its mass by 48.4%, achieving a lightweight design of the seeding wheel structure.

摘要
运用 Abaqus 软件分析排种轮在工作过程中的应力分布和位移变形，得到排种轮的应力分布云图和位移云图。对排种轮进行拓扑优化设计，得到了优化后的有限元模型，根据有限元模型对原始三维模型进行修正，得到拓扑优化后的排种轮三维模型。结果表明，优化后的排种轮其质量减少 48.4%，实现了排种轮结构轻量化设计。

INTRODUCTION

The seeder is the core component of the rice direct seeder, and the performance of the seeder directly affects the quality and efficiency of rice sowing. The seeding wheel is the key component of the seeder. Therefore, the design, analysis, and optimization of the seeding wheel are important links in the design process of rice direct seeders. The lightweight design of the seeding wheel can reduce the use of materials and improve the performance of the seeding wheel. Structural optimization design, as one of the effective means of lightweight design, is mainly divided into structural topology optimization, structural size optimization, and structural shape optimization *(Bendsoe et al., 2003; Karadere et al., 2020)*. Topology optimization aims to obtain the optimal distribution of materials within a given design domain. When designers lack direct experience guidance and cannot determine the initial configuration of the structure, topology optimization design reveals innovative structural configurations under established loads through certain constraints such as stress and displacement, maximizing material potential and significantly improving the quality and efficiency of engineering design *(Sui et al., 2017)*. In recent years, topology optimization has made significant progress in both theoretical research and practical applications. With the continuous development of numerical analysis technology, structural topology optimization methods have been widely applied in fields such as architecture, shipbuilding (*Jang et al., 2014),* aerospace *(Berrocal et al., 2019; Zhu et al., 2015)*, and automotive *(Karadere et al., 2020; Wu et al., 2016).*

Since Bendsøe and Kikuchi proposed topology optimization in their groundbreaking paper in 1988, topology optimization has undergone tremendous development. Currently, research algorithms for topology optimization mainly include homogenization methods *(Ganghoffer et al., 2023; March et al., 2023)*, variable density methods *(Wang et al., 2024)*, level set methods *(Gao et al., 2021; Wang et al., 2015; Zhang et al., 2017)*, and evolutionary structural optimization methods *(He et al., 2016; Huang et al., 2011; Huang et al., 2010)*. Among them, the variable density method is more mature and most widely used. The interpolation models of the variable density method include SIMP (Solid Isotropic Microstructures with Penalization) and RAMP (Rational Approximation of Material Properties), and the SIMP method is mainly adopted. In recent years, Hassani et al. *(Hassani et al., 2012)* proposed for the first time the isogeometric topology optimization method based on the SIMP method and combined it with the isogeometric analysis method.

This method improves the solving efficiency and suppresses the checkerboard phenomenon. Subsequently, Liu et al. *(Liu et al., 2018)* studied the topology optimization problem involving stress constraints in continuum structures based on the SIMP method and isometric analysis theory. Lieu and Lee *(Lieu et al., 2017)* proposed a multi-resolution isometric topology optimization method using the SIMP method and isometric geometric framework, which can achieve high-resolution topology optimization design with less computational complexity. Subsequently, Xuan et al. *(Liang et al., 2019)* proposed a universal multi-scale material interpolation model based on the SIMP method, and used this model to complete the multi-scale, multi-material parallel topology optimization design of vibration acoustic structures. After more than 30 years of development, the SIMP method has matured and is almost the most well-known and representative topology optimization method. In addition to the classic flexible optimization problem of elastic structures, it also has effectiveness in nonlinear structural optimization, stress optimization, and other aspects. In addition, this method has also demonstrated good performance in many physical problems and has been successfully applied to thermoelastic structures, fluid problems, acoustic problems, and optical problems.

In this paper, the variable density method is used for the topology optimization of the rice direct seeder's seeding wheel. Finite element simulation technology is used to simulate and analyze the stiffness and strength of the structure of the rice direct seeder's seeding wheel and obtain its displacement and stress distribution. In response to practical application needs, the optimization module of Abaqus software was used for structural topology optimization design, and the optimized topology model was obtained, providing a basis for the optimization design of the seeding wheel structure of the rice direct seeder.

MATERIALS AND METHODS

1. Finite element simulation analysis of the seeding wheel

1.1. Implementation of Topology Optimization in Abaqus

As one of the large general-purpose nonlinear finite element analysis software, Abaqus covers a variety of unit models, and material models and supports a variety of analysis processes with its excellent computational power and simulation performance. For basic linear elastic problems, or problems involving multiple substances, complex mechanical processes, and nonlinear combinations, Abaqus can give satisfactory results whether implicit or explicit solutions are chosen. In this paper, Abaqus is adopted to achieve the topology optimization design of the seeding wheel. The optimization design in Abaqus relies on the powerful analysis and calculation power of computers and carries out structural optimization based on optimization theory. According to the objective function and constraints set by users, the optimal solution of structural design is obtained through accurate calculation. Abaqus/CAE topology Optimization Module is abbreviated as ATOM. Abaqus provides two algorithms for topology optimization: general-purpose algorithm and conditional algorithm. The general topology optimization algorithm takes the pseudo-density and stiffness of the structure as the objective function and constraint and can deal with most topology optimization problems. In the design structure, the conditional algorithm will optimize the stress and strain energy of the unit nodes, which is the basis of the design, and the calculation efficiency is higher, the design effect is better, mainly solving more specific problems.

1.2 Modeling

Abaqus has a common interface with SolidWorks software. Models established through SolidWorks can be imported into Abaqus for subsequent mesh partitioning and finite element simulation. The results obtained through Abaqus topology optimization can be imported into SolidWorks for measurement, and the common units and coordinates between software can be kept consistent.

The initial 3D model of the seeding wheel was created using SolidWorks software, as shown in Fig. 1. The material of the seeding wheel is stainless steel, with an initial volume of 338752 mm^3 and an initial mass of 2663 g. To facilitate grid partitioning and computational analysis, the seeding wheel model is simplified. Because the spur gear pair can be equivalent to two elastic circular contacts during the meshing process, the gear teeth are simplified to a cylindrical surface, resulting in a simplified seeding wheel model as shown in Fig.2.

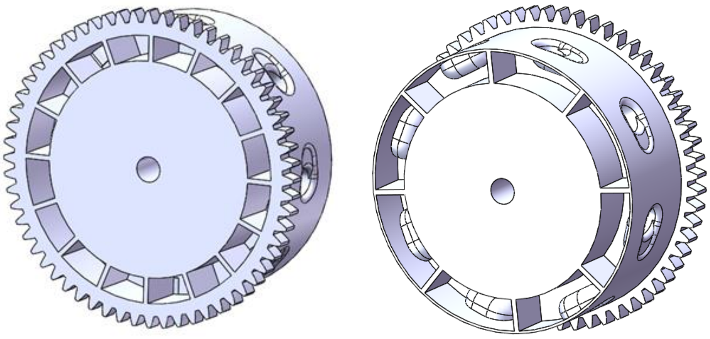


Fig. 1 - 3D model of the seeding wheel

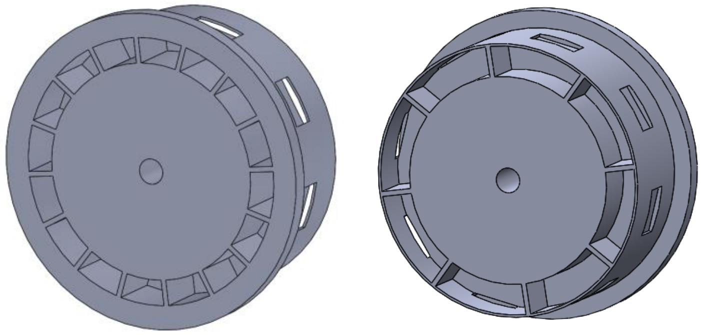


Fig. 2 - Simplified model of the seeding wheel

The protruding surface on one side of the model in Fig. 2 is the simplified gear teeth. The material of the seeding wheel is stainless steel, which has good plasticity and toughness and is suitable for processing and manufacturing. Its mechanical properties are shown in Table 1.

Table 1

Mechanical property

Density (kg/m^3)	Poisson's ratio	Elastic modulus / (GPa)	Yield strength (MPa)	Tensile strength (MPa)
7860	0.27	207	272	685

1.3 Finite element model settings

Import the simplified seeding wheel model into the finite element analysis software Abaqus, and use tetrahedral elements to mesh it. The total number of mesh elements is 94209, and the meshed model is shown in Fig. 3. Set material properties: elastic modulus $E = 2.07 \times 10^{11}$ Pa, Poisson's ratio $\mu = 0.27$, and density ρ=7860 kg/m^3.

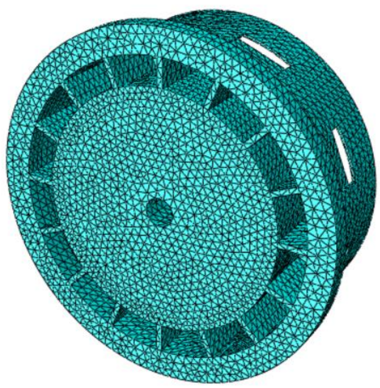


Fig. 3 - Grid division of the seeding wheel

Set boundary conditions in Abaqus software, and the seeding wheel rotates around the central axis while working, with the central axis fixed. Fix the inner surface of the center hole of the seeding wheel completely, and the constraint method is shown in Fig. 4. Adding load points on the model surface and applying loads, the actual loads on the seeding wheel during operation are simplified to the loads shown in Fig. 5.

The size of these loads is all 200 N, and the direction is shown in Fig. 5. At the same time, to obtain a structure that can withstand the corresponding loads, loads as shown in Fig. 6 are added to the front side of the seeding wheel, and loads as shown in Fig. 7 are added to the rear side of the seeding wheel, all of which are 100 N in size.

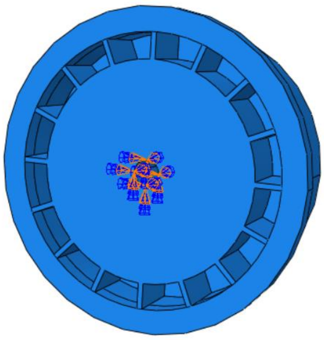


Fig. 4 - Boundary condition settings

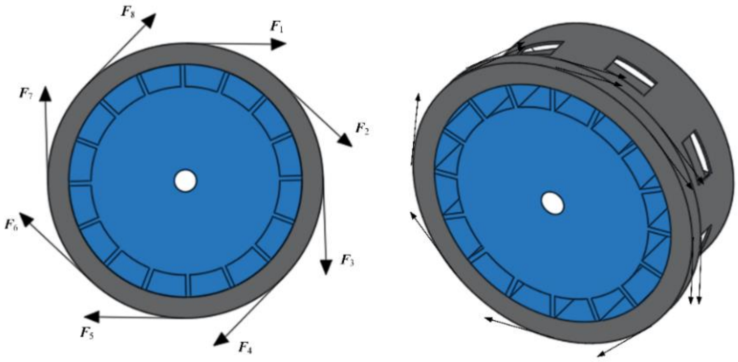


Fig. 5 - Direction of surface load on gear teeth

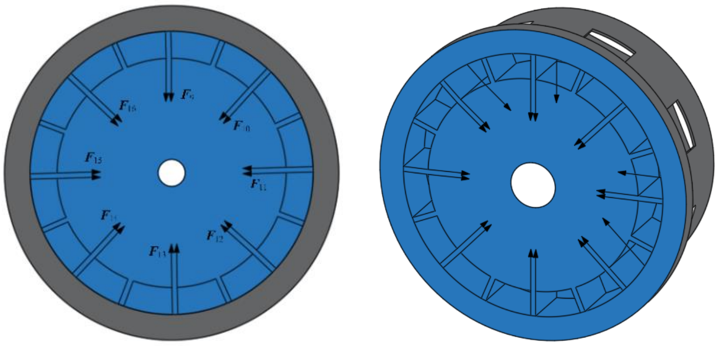


Fig. 6 - Loads applied on the front side of the seeding wheel

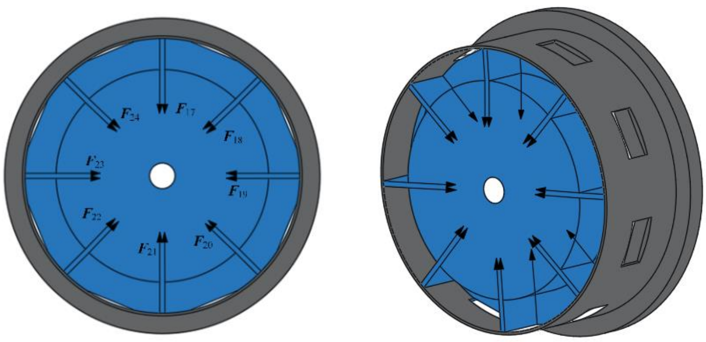


Fig. 7 - Loads applied to the rear side of the seeding wheel

2. Topological optimization mathematical model

2.1 Basic Theory of Variable Density Method

The variable density method characterizes the mapping relationship between unit density and material elastic modulus in the form of a continuous function, thereby transforming discrete optimization problems into continuous optimization problems. The basic idea is to use artificially assumed density variable units and set the density values of the units as continuous variables between [0,1]. In structural topology optimization, when density variable units are introduced, many intermediate density units will appear in the results. However, in the actual manufacturing process, there are only two filling states for a unit: with material and without material, and the presence of intermediate density greatly reduces the manufacturability of the structure. So, effective measures should be taken to suppress the generation of intermediate density units. To reduce intermediate density, a material interpolation model with an intermediate density penalty function is proposed, which promotes the optimization of materials towards extreme values of all 0 or all 1, which is beneficial for material production and processing.

2.2 SIMP method topology optimization model

In structural topology optimization, the interpolation models of the variable density method include the Solid Isotropic Microstructures with Penalization (SIMP) and the Rational Approximation of Material Properties (RAMP). At present, the SIMP model is mature and mainly used, and the material interpolation model based on SIMP is:

$$E(x_i) = E_{\min} + (x_i)^p (E_0 - E_{\min}), x_i \in [0,1] \tag{1}$$

where: $E(x_i)$ is the elastic modulus, E_0 is the elastic modulus of the solid element, and $E_{\min}$ is the minimum positive stiffness to prevent singularity in the stiffness matrix. *p* is the penalty factor, x_i represents the relative density of each unit. When x_i is set to 1, it indicates that there is material filling here, and when x_i is set to 0, it indicates that there is no material filling here.

Due to $E_{\min} \ll E_0$, Eq. (1) can be transformed into:

$$E(x_i) = E_{\min} + (x_i)^p (E_0 - E_{\min}) = x_i{}^p E_0, x_i \in [0,1] \tag{2}$$

By using the density interpolation function of continuous variables to represent the correspondence between the relative density and elastic modulus of structural units, a smooth material interpolation model can be obtained. The size of the penalty factor *p* varies, and its inhibitory effect on intermediate density units also varies. Usually, the inhibitory effect increases with the increase of the *p* value, but when the *p* value is too large, it often leads to the occurrence of the checkerboard phenomenon. Bendsøe and Sigmund *(Bendsoe et al., 2003)* pointed out theoretically that the material corresponding to the SIMP interpolation model can be simulated through microstructure by satisfying condition $p \geq 3$, and it can be ensured that the obtained material exists physically. In general, when the penalty factor p satisfies the following equation, the SIMP model can be considered as a material model.

$$\begin{aligned} & p \geq \max\left\{\frac{2}{1-\upsilon^0}, \frac{4}{1+\upsilon^0}\right\} \qquad 2D \\ & p \geq \max\left\{15\frac{1-\upsilon^0}{7-5\upsilon^0}, \frac{3(1-\upsilon^0)}{2(1-2\upsilon^0)}\right\} \quad 3D \end{aligned} \tag{3}$$

where: υ^0 is the Poisson's ratio of the material.

Under the constraint of a given structural volume, with the objective function of minimizing the compliance of a continuum structure, the topology optimization mathematical model based on the SIMP method is:

$$\begin{aligned} & find\ X = (x_1, x_2, x_3, \ldots, x_i)^{\mathrm{T}} \in R \\ & \quad i = 1, 2, \ldots m \\ & \min c = \boldsymbol{F}\boldsymbol{U} = \boldsymbol{U}^{\boldsymbol{T}}\boldsymbol{K}\boldsymbol{U} = \sum_{i=1}^{m} (x_i)^p u_i{}^{\mathrm{T}} k_0 u_i \\ & s.t. \boldsymbol{K}\boldsymbol{U} = \boldsymbol{F} \\ & \quad V = f V_0 = \sum_{i=1}^{m} x_i v_i \\ & \quad 0 < x_{\min} \leq x_i \leq x_{\max} \leq 1 \end{aligned} \tag{4}$$

This model is used to solve the minimum compliance of the optimized structure under volume or mass constraints so that the optimization results can reach the maximum stiffness under the constraint conditions. Where, *X* is the unit design variable and *c* is the structural compliance. ***F*** and ***U*** are the load vector and displacement vector, respectively, and ***K*** represents the unit stiffness matrix. k_0 is the initial unit stiffness matrix, *f* is the retained volume fraction, V_0 is the initial volume, v_i is the unit volume, $x_{\min}$ and $x_{\max}$ are the minimum and maximum values of the design variables, and *m* is the number of units.

To obtain higher computational efficiency, the optimization method based on derivative information is generally adopted in the process of solving optimization problems. To implement such a method, the corresponding sensitivity analysis must be carried out.

The structural objective function is as follows.

$$c = FU = U^{\mathrm{T}}KU = \sum_{i=1}^{m}(x_i)^p u_i{}^{\mathrm{T}} k_0 u_i \tag{5}$$

Taking the partial derivative of the objective function over the design variable x_i yields

$$\frac{\partial c}{\partial x_i} = \sum_{i=1}^{m} p(x_i)^{p-1} u_i{}^{\mathrm{T}} k_0 u_i \tag{6}$$

RESULTS

3. Topology optimization of the seeding wheel

3.1 Static analysis

The static analysis of the seeding wheel was carried out. The stress and displacement cloud maps of the seeding wheel were obtained, as shown in Fig. 8 and Fig. 9. It can be seen from Fig. 8 that, compared with other positions inside the seeding wheel, the stress at the point where loads acts are slightly larger, but are still far less than the yield strength of the material. As can be seen from Fig. 9, the maximum displacement of the seeding wheel is 1.336×10^{-8} mm, and its deformation is very small. According to the data obtained from the analysis, there is room for structural optimization and lightweight design of the seeding wheel.

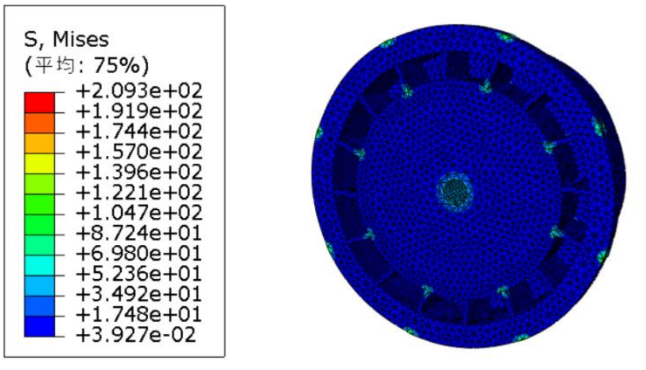


Fig. 8 - Stress program of the seeding wheel

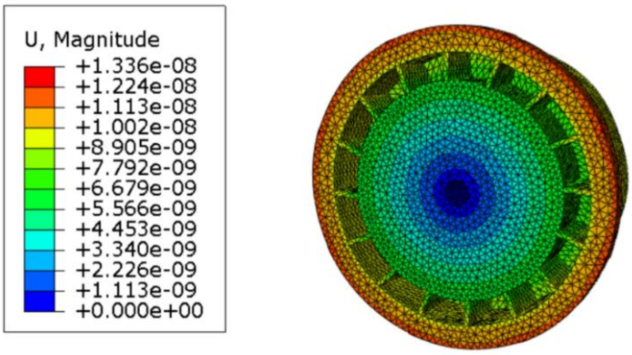


Fig. 9 - Displacement program of the seeding wheel

3.2. Topology Optimization Analysis

The seeding wheel operates under a single load case. The topology optimization of the seeding wheel aims to minimize the structural strain energy and the allowable volume of the material is set to 50% of the design domain. Due to the transmission function of the seeding wheel gear, this part cannot be used as a design domain for optimization design. The size and position of the seeding hole cannot be changed arbitrarily. therefore, this part should also be set as a non-design domain.

As shown in Fig. 10, during the topology optimization process, the blue area represents the designable domain and the gray area represents the non-design domain.

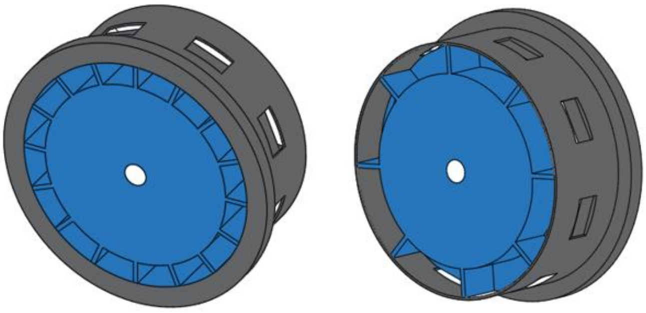


Fig. 10 - Design domain of the seeding wheel

After topology optimization calculation, the seeding wheel reached the optimal result after 30 iterations of analysis, as shown in Fig. 11. Then, the optimized seeding wheel model was exported and the original 3D model was modified using SolidWorks to obtain the optimized 3D model as shown in Fig. 12.

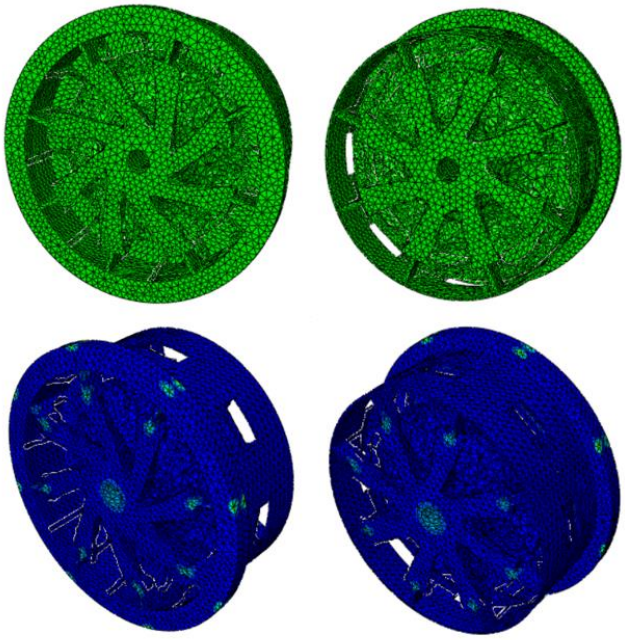


Fig. 11 - Topology optimization results of the seeding wheel

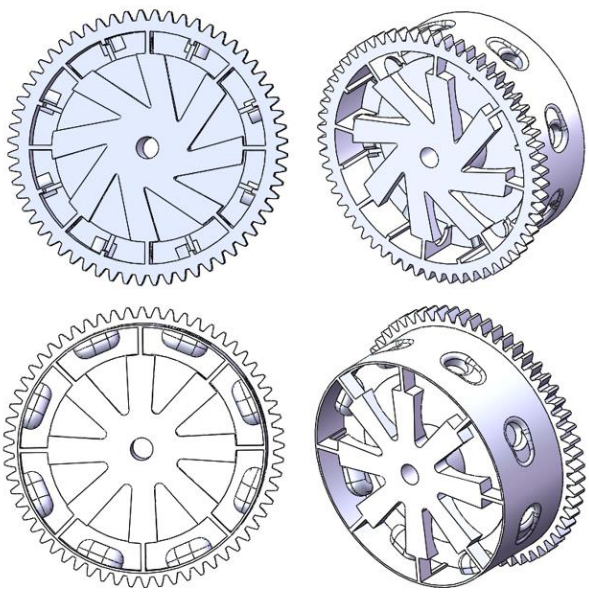
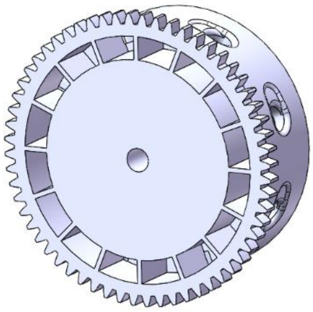
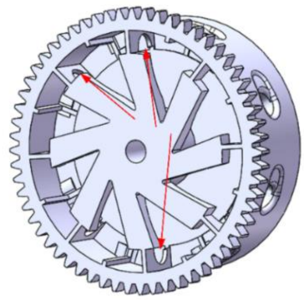


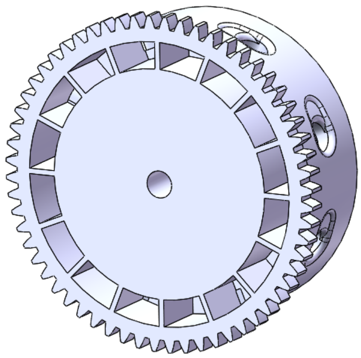
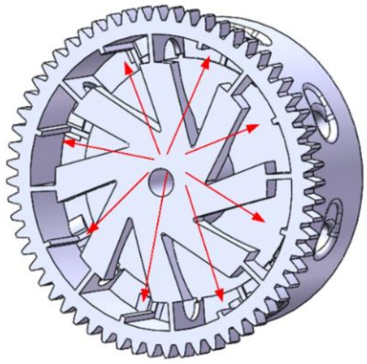
Fig. 12 - Revised 3D model

Comparing the optimized seeding wheel model with the original 3D model, it can be seen that:

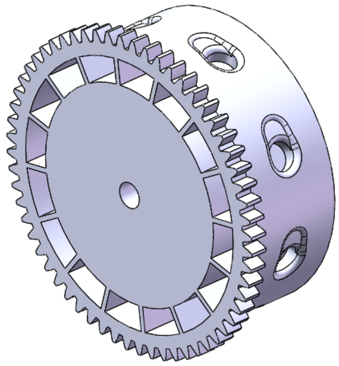
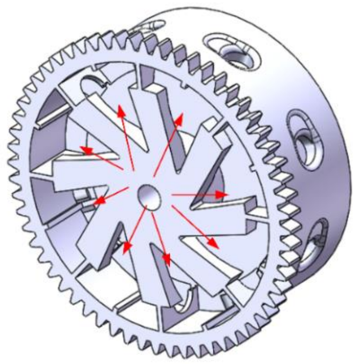
(1) There are curved holes uniformly distributed on the front side plates of the seeding wheel.

Before	After
	

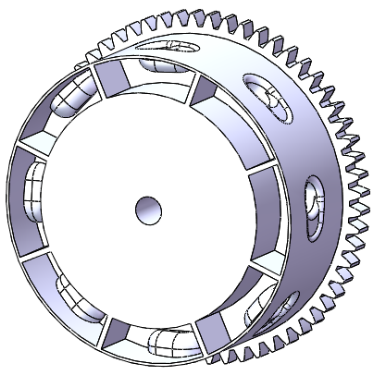
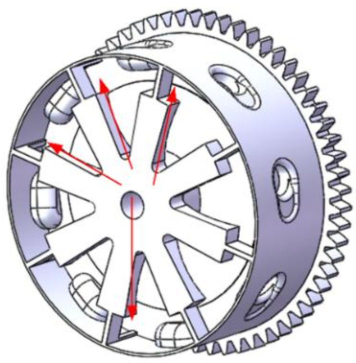
(2) Remove the partial plate on the front side of the seeding wheel

Before	After
	

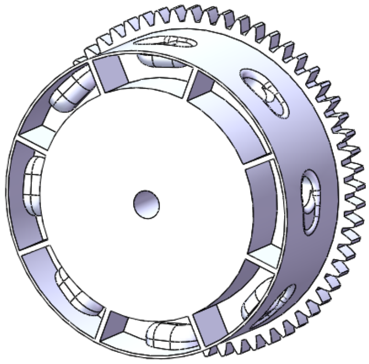
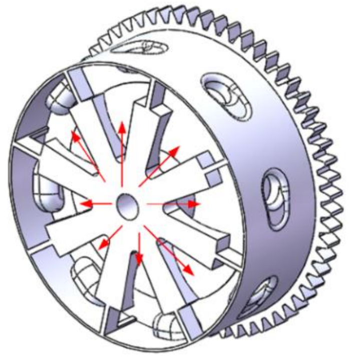
(3) Part of the material is removed from the front side of the seeding wheel, and the remaining material is evenly distributed along the arc direction.

Before	After
	

(4) Remove the material from the inner side of the side panel behind the seeding wheel.

Before	After
	

(5) Remove some materials from the rear side of the seeding wheel and distribute the remaining materials symmetrically.

Before	After
	

The optimized seeding wheel model has a volume of 174729 mm^3 and a mass of 1373 g. Compared to the original model, the volume and mass have decreased by 48.4%, greatly reducing the distribution of structural materials and achieving a lightweight design of the seeding wheel structure.

CONCLUSIONS

In this paper, the finite element analysis was carried out on the seeding wheel of the rice direct seeder, and the static simulation analysis was carried out by Abaqus software. The stress and displacement program of the seeding wheel were obtained. The mathematical model of topology optimization based on the SIMP method is given, the topology optimization module of Abaqus software is used to optimize the seeding wheel, and the optimized structure of the seeding wheel is obtained. The optimized model was imported into SolidWorks software for 3D model correction, and the 3D model of the seeding wheel after topology optimization was obtained. Compared with the original 3D model, the volume and mass of the optimized seeding wheel were reduced by 48.4%, which greatly reduced the material use and realized the lightweight design of the seeding wheel without affecting the performance of the seeding wheel.

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