Lightweight Design of an Axial Flow Roller Based on Sensitivity Analysis

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Abstract. In order to improve the working performance of axial flow roller of harvester, light weight design of an axial flow roller was conducted based on sensitivity analysis. Under the CAD/CAE integrated design platforms, the statics finite analysis and sensitivity analysis of the axial flow roller were executed by ANSYS Workbench. According to statics analysis and modal analysis results, sensitivity analysis was implemented to acquire the optimal design parameters. By selecting the appropriate design variables and state variables that were obtained from the sensitivity analysis, lightweight design of the axial flow roller was carried out. Comparative analysis on axial flow roller before and after optimization design showed that the mass of axial flow roller was reduced by 15% under the premise that the part satisfied the performance requirements. The result also proved that the proposed structural optimization design method for the axial flow roller based on sensitivity analysis was reasonable and feasible.

Introduction

An axial flow roller has been a type of threshing roller with rapid growth in recent years. It has high percentage of threshing, low percentage of broken grain, strong separation capacity, and can be used in the combine harvester without separation device, which simplify the structure and improve the operational reliability [1, 2]. However, due to the impact on grain, the long period of rubbing, and much grass stubble, the power consumption of the axial flow roller is relatively large [3-5]. Light weight design of an axial flow roller can not only reduce power consumption but also make it possible to reduce the startup time and production costs [6]. At present, lightweight design has been used widely in the field of industrial design [7-10].

This paper presents the lightweight design of an axial flow roller based on sensitivity analysis. The sensitivity analysis for the axial flow roller is conducted based on the static analysis and model analysis. Selecting appropriate design variables and state variables, the light weight design is implemented. Finally the mass of the axial flow roller is reduced while the strength and the mode of vibration still satisfy the requirements.

Statics Analysis and Modal Analysis

a) Establishment of the Finite Element Model

A three-dimensional model of a certain axial roller is established by Pro/E software in which some non-critical structures such as the bolt can be simplified. The final model is shown in Fig. 1. The axial flow roller is an assembly consisting of a variety of materials, and the material property of each part is listed in Table 1.
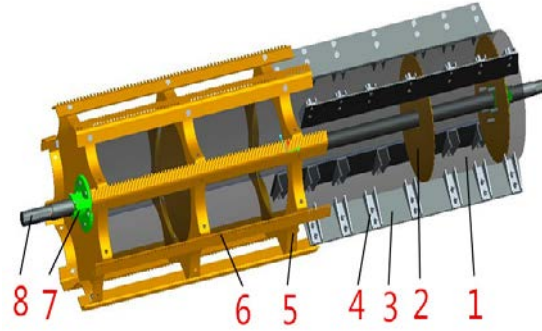
Fig.1. 3D model of axial flow roller

Table 1 Material attribute of axial flow roller

Part name	Materials	Elasticity modulus（Pa）	Poisson's ratio	Density（kg/m^3）
Body of roller	Q235	2.12E11	0.288	7.86E03
Radials-in	Q235	2.12E11	0.288	7.86E03
Radials-out	Q235	2.12E11	0.288	7.86E03
Toothholder	Q235	2.12E11	0.288	7.86E03
Separating plate	Q235	2.12E11	0.288	7.86E03
Rasp bar	35Mn2	2.06E11	0.300	7.65E03
Hub	35	2.12E11	0.291	7.87E03
Roller	45	2.09E11	0.269	7.89E03
Bolt	45	2.09E11	0.269	7.89E03
Nut	45	2.09E11	0.269	7.89E03

The main parts of the axial flow roller are connected by welding and bolts structure. The two contact surfaces of welding and contact surfaces between the bolt and the parts are designed as binding contacts, while contact surfaces of bolted connection are set to no separate contact. Automatic meshing method is used to partition finite element mesh of the axial flow roller.

b) Definition of the Load and Constraints

The axial flow roller is mainly subjected to centrifugal forces, pressure of its own weight and the grain pattern on the rod during operation. The gravity and centrifugal force can be ignored as compared with its effect on the axial flow roller due to the large mass (160 kg), the relatively high rated rotational speed (900 r/min), as well as a large inertia force. In addition, the specific pressure between grain and bar can be expressed in the approximate empirical Eq. 1:

$$p = Ae^{c\sigma} \tag{1}$$

Where, A and c are coefficients, which depend on materials; σ is the relative density of grain and can be calculated by Eq. 2.

$$\sigma = \frac{(a-a')}{a} = 1 - \frac{a'}{a} \tag{2}$$

Where, a is the thickness of the grain without pressure applied; a' is the thickness of the grain between the surface of the rasp rod and concave lattice bar.

The specific pressure between grain and bar vary from different grains, different feed thickness to different humidity, but statistics show that the specific pressure between grain and bar is very small. Therefore the axial flow roller is mainly affected by the centrifugal force during operation.

The centrifugal load is applied through the rotational speed in ANSYS Workbench, so that the rotational speed is applied on the axial flow roller, value of ω is defined by Eq. 2.

$$\omega = \frac{2\pi n}{60} \tag{3}$$

Inputting the data, the ω is calculated. In this case, the value of ω is 95 rad/s.

The axial flow roller rotates around itself central axis during operation, and a cylindrical constraint is imposed at the contact surfaces between the axle and the bearing. Both ends of the

roller shaft are regarded as simply supported beam, by defining the constraints of the radial, axial and tangential displacement of the input terminal and constraints of the radial and tangential displacement of the other end, and allowing axial sliding a small margin.

c) Statics Analysis

Stress nephogram and displacement nephogram of the axial flow roller are shown in Fig.2 and Fig.3, respectively.
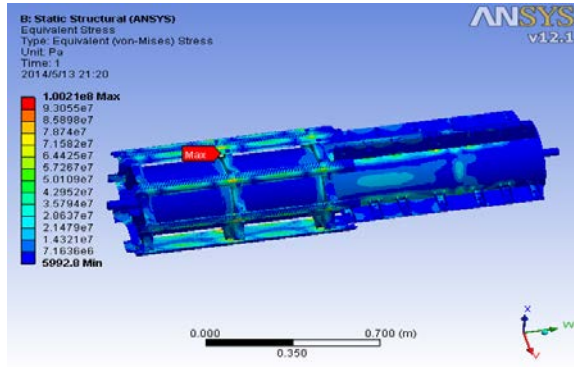

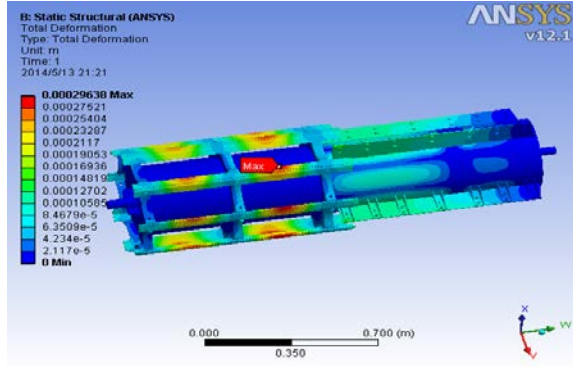
Fig.2. Stress nephogram　　　　　　　Fig.3. Displacement nephogram

When the axial flow roller works, maximum axial stress occurs at the middle position of the rasp bar with the value of 100.2 MPa, and the maximum displacement occurs at an intermediate position of the rasp bar of the radiation pattern with the value of 0.296 mm. The material of the rasp bar is 35Mn2 with the yield strength of 685 MPa, which is much greater than the maximum stress of the rasp bar. Therefore, the strength is sufficient. Meanwhile, according to NJ10575 standard, the allowable displacement is 1.6 mm. Obviously, the maximum displacement in this case satisfies the criteria. The yield stress of steel sheet material Q235 parts is 235 MPa and less than the rasp bar material 35Mn2, thus the stress conditions need to be considered. The maximum stress (92.55 MPa) is extracted from the statics analysis, and the safety factor of the sheet in current condition reaches 2.54, which satisfies the strength requirements. At the same time, there is affluent stress for the axial flow roller, and further lightweight design can be conducted.

d) Modal Analysis

The prestressed modal analysis for the axial flow roller is carried out based on the statics analysis. Six lowest order modal' parameters have been obtained and are listed in Table 2.

Table 2 Six lowest order frequency

Order	1	2	3	4	5	6
Frequency	56.98	60.58	60.71	70.77	133.73	134.1

The first critical speed is $56.98 \times 60 = 3418.8$ r/min, while the design speed of the axial flow roller during operation is 900 r/min. It is found that the latter is far less than the former, accordingly, the resonance does not occur.

Sensitivity Analysis

a) Sensitivity Analysis Theory

Sensitivity analysis includes following steps: (1) calculate the derivative of structural response with respect to every design variable; (2) determine the most sensitive part in the process of optimal design; (3) Obtain the best design parameter and the interested sensitivity coefficient.

Sensitivity analysis of structure is to analysis the sensibility of structural performance parameters T_j with respect to structure design parameters x_i, namely

$$\text{Sen}\left\{\frac{T_j}{x_i}\right\} = \frac{\partial T_j}{\partial x_i} \tag{4}$$

The numerical value of the sensitivity can reflect the influence of each design variable on structural performance [3].

b) Definition of Parameters

The thickness of sheet-metal part T, the distance of inner spoke disc sticking into barrel in the isolated segment W_1 and the distance of inner spoke disc sticking into barrel in the threshing section W_2 are selected as input parameters. The axial roller mass, the maximum stress and displacement of sheet-metal part and the first-order frequency are selected as output parameters. The initial values and ranges of input parameters are listed in Table 3.

Table 3 Initial value of input parameters

Input parameters	Initial value	Upper limit	Lower limit
T	4	4	2
W_1	350	450	250
W_2	300	400	200

c) Analysis of Sensitivity Results

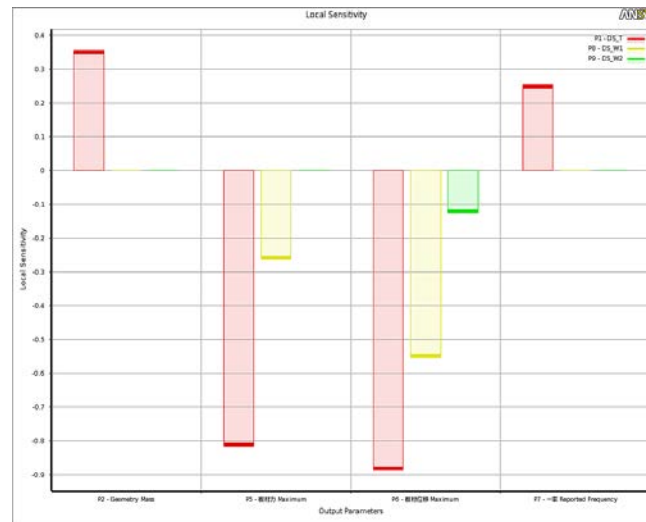The sensitivity results of the axial flow roller are shown in Fig. 4.

Fig.4. Results of sensitivity analysis

It is found that all output parameters are affected by every input parameter and the sensitivity of T is the maximum, W_1 comes second, W_2 is minimum. Therefore, T and W_1 are selected as design variables, and the influence of them on each output parameter is described in Fig.5.
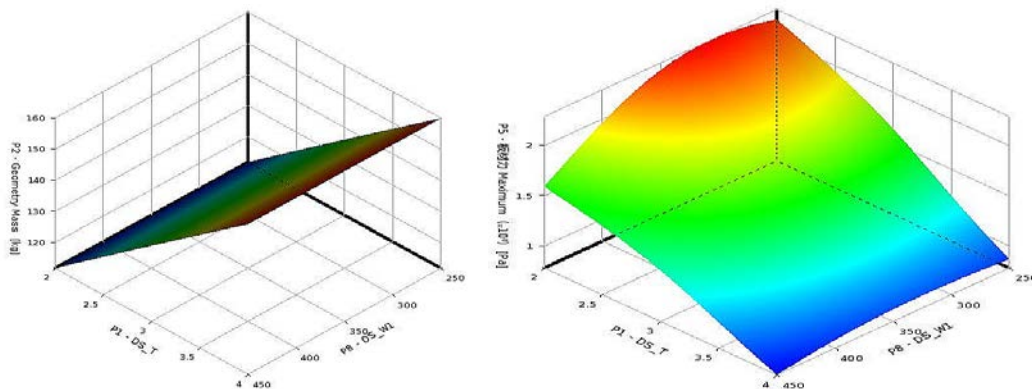
a) Mass of axial flow roller

b) Max stress of plant parts
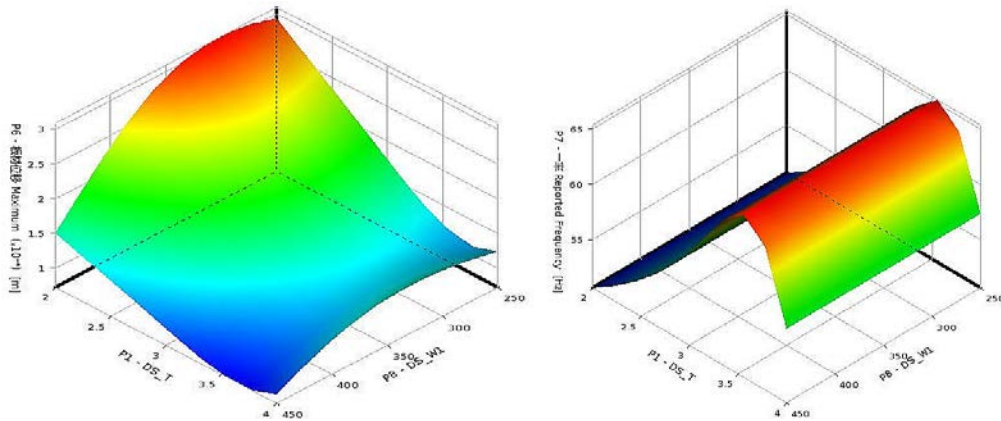
c) Max displacement of plant parts   d) The first order frequency

Fig.5. Influence of design parameters on output parameters

From the above figures, one important fact becomes clear: only the maximum stress of sheet metal parts may exceed the allowable stress with change of T and W_1. As a result, the maximum stress of sheet-metal parts is chosen as a state variable.

Lightweight Design

Through the above analysis, the design parameters and the state variable are determined. Taking the mass of axial flow roller as the objective function, the lightweight design is implemented. A safety factor is set at 1.88, and the allowable stress is 125 MPa. The final result of the optimization is shown in Fig.6.

▼	A	B	C	D	E
1		P1 - DS_T	P2 - DS_W1	P3 - Geometry Mass (kg)	P4 - 板材应力 Maximum (Pa)
2	⊟ Optimization Study				
3	Objective	No Objective ▼	No Objective ▼	Minimize ▼	Values <= Target ▼
4	Target Value				1.25E+08
5	Importance	Default ▼	Default ▼	Default ▼	Higher ▼
6	⊟ Candidate Points				
7	Candidate A	⇨ 2.9095	⇨ 449.91	★★ 133.73	⇨ 1.2615E+08
8	Candidate B	⇨ 2.9943	⇨ 429.36	★★ 135.77	⇨ 1.2546E+08
9	Candidate C	⇨ 3.0799	⇨ 408.46	★ 137.85	⇨ 1.2471E+08

Fig.6. Results of optimization design

Since the parts are made of hot rolled steel plate, the thickness range is from 2mm to 4 mm. According to the national standard GB-T709-88, the predetermined thickness have 2.0 mm, 2.5 mm, 2.8 mm, 3.0 mm, 3.2 mm, 3.5 mm, 3.8 mm and 4.0 mm. The candidate B in the Fig.6 is chosen as the plate thickness T is close to 3.0 mm. Meanwhile, in order to facilitate the positioning of welding robot, the W_1 is rounded to 430 mm.

Static analysis and model analysis for the optimized axial flow roller are performed, and the results comparing with the previous are listed in Table 4.

Table 4 Compare results of before and after optimization design

Option	Before optimizing	After optimizing	Results contrast
Mass(kg)	160	136	-15%
Max stress of Rasp bar (10^8 Pa)	1.002	1.012	1%
Max displacement of rasp bar (mm)	0.296	0.282	-4.70%
Max stress of plant parts (10^8 Pa)	0.926	1.275	37.70%

Max displacement of plant parts (mm)	0.145	0.112	-22.80%
The first order frequency (Hz)	56.977	59.032	3.60%

It can be seen from Tab.4 that the optimized roller's mass decreased by 15%, the maximal displacement of the rasp bar and sheet metal part are reduced, and the first order frequency of the axial flow roller increases. However, the maximum stress of the rasp bar almost remains the same. In conclusion, the optimization design is successful, which improves the whole performance of the axial flow roller.

Conclusion

Static analysis and model analysis for the axial flow roller are implemented using Ansys Workbench, and based on the above analysis results the sensitivity analysis is carried out to determine the appropriate design variables and state variables. The lightweight design for the structure of the axial flow roller is put forward. The optimal result shows that the mass of axial flow roller is reduced by 15% after optimization and the whole performance has been significantly improved, which indicates the sensitivity analysis is an effective way to lightweight design for mechanical structure.

Acknowledgement

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