Optimization design of digging mechanism for onion harvester based on finite element simulation technology

Yong Yang\textsuperscript{1*}, Tianxin Kou, Shuai Peng, Chao Wang and Guofang Hu

\textsuperscript{1}School of Mechanical and Automotive Engineering, Qingdao University of Technology, Qingdao, Shandong Province, 266520, China
\textsuperscript{*}E-mail: yyong901@163.com

Abstract. Digging mechanism plays an important role for onion harvester, which can affect the digging quality and efficiency of onion harvester. In this paper, the digging mechanism for onion harvester was studied and optimized based on finite element simulation technology. First, the parameters and shape of digging mechanism were researched and determined according to the work conditions. Further, the finite element simulating process of digging for above new-type of mechanism was performed. At last, the new-type of digging mechanism was analyzed and optimized based on finite element simulation technology. The studies show that the stress value of digging mechanism decreases, also the weight of digging mechanism reduces by $5.18\%$, which can cut short the cost of onion harvester and promote the advance speed effectively.

1. Structural design of digging mechanism

There are two-sided wedge digging mechanisms for root and stem crops harvest in figure 1. From the perspective of motion mode, the digging shovel includes fixed shovel and mobile shovel. The digging shovel can be also divided into triangle shovel, groove shovel and curved shovel based on shape of it. Moreover, to meet different width of harvest, there are single shovel, two shovel and multiple shovel. The resistance of the vibrating shovel is smaller than that of the fixed shovel. However, vibrating consumes extra energy and the power consumption of them is not different from each other actually. Besides, additional mechanism will be designed for vibration and the corresponding structure will be complex. The welsh onion is planted in a ridge and according to the results of the survey above, the deviation welsh onion relative to ridge axis is not large so a single shovel can meet the requirement. Because the distribution of welsh onion is deep, the shape of the digging shovel was triangle for reducing the resistance in digging.

Figure 1. Two-sided wedge digging mechanisms.

The structural design of the shovel is to determine the shape and size of the shovel. The main dimensional parameters of triangular planar shovel including the width, length, incline angle and blade angle are shown in figure 2.
In Figure 2, L is the length of shovel (mm); H is the height between rear of the shovel and ground, (mm); α is the incline angle of shovel (°); B is the width of shovel (mm); γ is the blade angle of shovel (°).

In order to meet the self-cleaning function of the blade, the blade angle should be satisfied:

$$90° - γ ≥ α$$  \( (1) \)

Where, α is the incline angle of shovel (°). It is selected as 30°.

The resistance of digging declines with decrease of incline angle but the effect of soil uplifting will be reduced. If the incline angle is chosen as small the length of shovel will be huge for raising the welsh onion and soil mixture to a certain height. So two-level structure of shovel was designed. The former shovel has a small inclination for cutting the soil and the latter shovel has a larger inclination for lifting the soil. Moreover, the latter one is designed with bars which reduces the resistance of digging by transporting loose soil to the field quickly. The two-level structure of the shovel is shown in Figure.3, the incline angle (α1) of former shovel is 20 ° and the incline angle (α2) of latter shovel is 30 °.

The length of the shovel is determined by the height of uplifting of soil and the length is calculated as

$$L = \frac{h}{\tan \alpha}$$  \( (2) \)

Where, h is the height between rear of the shovel and ground (mm). According to the requirements of the digging depth and the cooperation of the digging and clamping mechanism, the lengths of former and latter shovels are 300mm and 187mm respectively.

The width of the shovel should be appropriate. If it is too wide, the digging resistance will increase and if it is too narrow, welsh onion may be missed. The size of the width can be calculated by the following formula

$$B = b + 2c + 3\sigma$$  \( (3) \)

$$\sigma = \sqrt{\sigma_M^2 + \sigma_b^2}$$  \( (4) \)

Where, b is the width of stem relative to the ridge, mm; c is the driving deviation of harvester, mm; σ is the comprehensive standard deviation, mm; σ_M is the standard deviation of ridge, mm; σ_b is the standard deviation of stem relative to ridge, mm. According to table of the survey results on the physical properties parameters of welsh onion, the average distribution width of welsh onion relative to ridge is 36mm and c is generally 50mm~80mm. The driving deviation is determined as 50mm, σ_M as 22mm and σ_b as 14mm, so B is calculated as 250mm.

2. Finite element analysis of the digging mechanism

Digging mechanism is of vital importance to the whole harvest operation. Firstly, it is the first process and its working effect will directly affect the subsequent process. In addition, digging mechanism is also the one that bears the maximum load. Therefore, whether it can meet the requirements of mechanical
properties and work stably and reliably is particularly important. In this paper, finite element analysis is used to verify the rationality of design of structure and material.

ANSYS is the most common element analysis software, which can be used in the fields of structure, fluid, electric, magnetic, sound and multiple coupled fields. Besides structure analysis includes static analysis, modal analysis, spectral analysis, harmonic analysis, transient dynamic analysis, buckling analysis and display dynamic analysis. The digging resistance will fluctuate due to the change of the digging depth and the appearance of rocks in the soil during the digging process. Actually, the ridge bottom of field of welsh onion is flat relatively, and there are few big rocks in the field. Moreover, the harvester keeps constant speed during steering, so the digging resistance can be regarded as a constant load.

The digging shovel bears considerable load and contacts with soil for a long time in operation, so higher strength, hardness and excellent wear resistance are required. The former shovel is applied to crush the soil and it bears the maximum load. So its material is 65Mn which is commonly used in agricultural machinery. The remaining parts have no special requirements for mechanical properties and they are connected by welding and bolting. Therefore, the material of them is selected as Q235 for welding and machining smoothly. The safety factor of structural steel is 1.5~2.5 and the safety factor is determined as 2. The performance parameters of 65Mn and Q235 are shown in table 1.

| Material | Young modulus (N/m²) | Poisson’s ratio | Density (kg/m³) | Yield strength (MPa) | Allowable stress (MPa) |
|----------|----------------------|----------------|-----------------|----------------------|-----------------------|
| 65Mn     | 2.11×10¹¹            | 0.288          | 7.82×10³        | 785                  | 393                   |
| Q235     | 2.12×10¹¹            | 0.288          | 7.86×10³        | 235                  | 118                   |

The process of finite element analysis of ANSYS workbench includes establishing model, meshing, loading, solving, and post-processing. The analysis process of digging mechanism is as follows. NX10 is used to create the digging mechanism model and the model is imported into the software. According to the table above, the material library is built, then material properties is assigned to the corresponding components. The adaptive mesh division can meet the requirements, because the shape of the part of the digging mechanism is flat mostly, and there is no complex surface for the connection and transition between the parts. The mesh size is set as 4 x 10⁻³m, the number of nodes is 130920 and the number of units is 51010 after meshing. The two pillars of the digging mechanism are connected with frame of conveying mechanism by bolts, so the upper surface of the pillars is fixed constraint. The external load of the mechanism is the digging resistance, and it is divided into 2/3 and 1/3 for former shovel and latter shovel according to the relationship between them. The resistance on latter shovel is imposed to each bar in average. After application of constraints and loads, the stress and strain digging mechanism are shown in figure 3 and 4.

![Figure 3. Stress of digging mechanism before optimization.](image-url)
The maximum stress value is 253MPa, which exists at the joint of the former shovel and latter shovel. In addition, the stress of bolt hole between pillar and frame is relatively large, of which the value is 196MPa~225MPa. The value above exceeds the allowable stress of Q235 and the parts should be optimized. However, the stress of the former shovel is between 22MPa~28MPa by a majority, which is far less than the allowable stress. The mechanical performance is somewhat excessive and it also should to be optimized in term of the economic principle of the design. The optimization of the mechanism mainly aims to structure and materials, and the principle of optimization makes the mechanism optimum in reliability and economy on the premise of satisfying the function. The optimizations for the digging shovel are follows: 1) replacing the bars with steel 45 and adding two transverse bars to reduce the stress at the edge; 2) reducing the thickness of the longitudinal beams; 3) changing the pillars to 45 steel.

The stress and strain after optimization are shown in figure 5 and 6.
As can be seen in the figure the maximum stress value is 545MPa, which exists at the connection between the horizontal and vertical bars. The connection is welding in actual however, it is point contact in the model the value of stress is high. The stress of bolt hole and connection between former shovel and latter shovel is 121 MPa to 181 MPa. The value decreases compared with mechanism before optimization, and mechanical performance meets the requirements because of replace of material. Even the numbers of parts increases, the quality of reduces by 5.18% compared with that of mechanism before optimization because of optimization of parts in size.

3. Conclusion
(1) The digging mechanism of onion harvester was studied and optimized using finite element simulating technology. The parameters and shape of digging mechanism were researched and determined according to the work conditions firstly, and the digital model was constructed. Further, the finite element simulating process of digging for above new-type of mechanism was performed. On the basis of above study, the new-type of digging mechanism was analyzed and optimized.

(2) Research has shown that the stress value of digging mechanism decreases, also the weight of digging mechanism reduces by 5.18%, which can cut short the cost of onion harvester and promote the advance speed effectively.

(3) The digging mechanism is the key part of onion harvester. This study can provide theoretical guidance and a good reference for designing onion harvester.

Acknowledgment
This research was financially supported by the following Foundation items: Agricultural Machinery Equipment Research and Development Innovation Project of Shandong Province (Grant No. 2017YF011); Major Science and Technology Innovation Project of Shandong Province (Grant No. 2017CXGCD222).

Reference
[1] KF Li. (2015) Research on key technology of self-propelled carrot combine harvester. Chinese academy of agricultural mechanization sciences.
[2] Chinese academy of agricultural mechanization sciences. (2007) Agricultural machinery design manual. China agricultural science and technology press, Beijing.
[3] T Wang, YL Liao, Y Yang. (2015) Design and mechanical analysis of multi-level digging shovel of cassava harvester. Research on agricultural mechanization.,37(10):50-54.
[4] MF Liu. (2011) Handbook of mechanical properties of metal materials. Machine PRESS, Beijing.
[5] AH Zhu, GZ Chai. (2004) Optimization design using finite element analyzing software. Mining machinery., (01):15-17.
[6] Fujii Y, Ohnishi M, Tsuga K. (2014) Farmers' satisfaction and preference assessment of a Welsh onion harvester. Engineering in Agriculture, Environment and Food., 7(2):70-77.