DESIGN AND EXPERIMENT OF A SELF-PROPELLED CRAWLER-POTATO HARVESTER FOR HILLY AND MOUNTAINOUS AREAS

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丘陵山区履带自走式马铃薯收获机设计与试验

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DOI: https://doi.org/10.35633/inmateh-64-14

***Keywords:** hilly and mountainous area, self-propelled, potato harvester, finite element analysis*

ABSTRACT

A self-propelled crawler and potato harvester was designed, with the terrain characteristics of both hilly and mountainous areas considered, to address the low degree of mechanization, markedly low potato harvesting rate, and high labor intensity of potato harvesting in hilly and mountainous areas. The harvester could complete the tasks of digging potatoes, separating them from the soil, transporting potatoes, and collecting them in a single operation. Finite element analysis was conducted on major parts, such as the digging shovel and the frame, based on the overall structure and working principle of the harvester. A field experiment was then conducted. The results of the finite element analysis showed that the maximum stress of the digging shovel was 37.969MPa, the maximum strain was 1.846×10^{-4}, and the total deformation was 0.8041mm. These measurements were within a safe range. The field experiment results showed that potato harvesting rate, bruising rate, and damage rate were 98.54%, 1.51%, and 1.31%, respectively that is, higher than the national standards for potato harvesters. The potato harvester exhibited reliable walking performance and harvesting performance, which could provide a reference for research on the mechanization of potato harvesting in hilly and mountainous areas.

摘要

针对丘陵山区马铃薯收获的机械化程度低、明薯率低和劳动强度大的问题，结合丘陵山区地形特点，设计了一种履带自走式马铃薯收获机。该收获机能够一次性完成丘陵山区单垄双行马铃薯的挖掘、薯土分离、输送和集薯装箱的工作。在阐述收获机整体结构和工作原理的基础上，完成对挖掘铲和机架等关键部件的有限元分析，并进行了田间收获试验。有限元分析结果表明，挖掘铲的最大应力为 37.969MPa，最大应变为 1.846×10^{-4}，总变形为 0.8041mm，均在安全范围内。田间试验结果表明，该收获机明薯率为 98.54%，破皮率为 1.51%，伤薯率为 1.31%，各项数据指标均符合马铃薯收获机国家标准的要求。该马铃薯收获机通过性能和收获性能良好，为丘陵山区复杂地形马铃薯全程机械化收获的研究提供参考。

INTRODUCTION

Potatoes are cultivated worldwide, and China has a long history of potato cultivation *(Xu et al., 2018; Zaheer et al., 2016)*. Potatoes present several advantages, such as fast growth, high yield, and high nutritional content *(Darooghegi et al., 2020; Tian et al., 2016)*. With the development of the potato staple food strategy in China, potato planting area and yield have increased year by year *(Li et al., 2020; Zhou et al., 2021)*. The two data points currently rank first globally. In 2019, the potato planting area in China exceeded 5.3×10^5 hectares, and fresh potatoes output exceeded 1.1×10^9 kilograms. However, relative to that of agriculturally developed countries, the technical skills of potato harvesters remain relatively backward *(Li et al., 2020; Wei et al., 2019)*. The mechanization degree of potato harvesting in major potato-producing areas in China, particularly hilly and mountainous areas, is considerably lower than that in plain areas *(Liu et al., 2020)*.

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Numerous studies have been conducted on potato harvesters locally and globally *(Novikov et al., 2018; Uspenskiy et al., 2018; Yang et al., 2020)*. Potato harvesting can be divided, depending on the planting terrain, into the combined harvesting mode and segmented harvest mode *(Tseplyaev et al., 2018)*. The combined harvesting mode is mainly promoted in large and medium plain areas. Combined potato harvesters are not suitable for hilly and mountainous areas because of complex terrain and narrow land plots; moreover, they are generally costly. Therefore, the segmented harvesting mode is currently the primary mode adopted for hilly and mountainous areas *(Wei et al., 2019; Zhang et al., 2021)*. That is, potatoes are first dug out and then picked up. Mechanized operation in potato excavation has been realized. Various excavators, including self-propelled potato excavators and traction excavators, have been developed in many universities *(Baybulatov et al., 2020; Wan et al., 2019; Yang et al., 2016).* However, potato picking mainly relies on manual work. In hilly and mountainous areas, the application of the segmented harvesting mode is impeded by low efficiency and high costs, directly affecting the healthy and sustainable development of the potato industry *(Hrushetsky et al., 2019; Zhao et al., 2016)*.

To address the aforementioned problems, a harvester that can complete the tasks of digging and collecting potatoes in a single operation was designed. The size limit and functional requirements for the harvester were determined by assessing the potato planting environment in hilly and mountainous areas. In this study, the overall structure of the harvester was designed, the key components were analyzed, the harvester prototype was processed, and the field experiment was performed.

MATERIALS AND METHODS

Overall structure and working principle

As shown in Figure 1, the potato harvester mainly consists of the following: a cab, a frame, a crawler chassis, a depth limiting wheel, a digging shovel, a wave chain rod, a baffle, a transmission chain, and a collecting box. The wave chain rod, baffle, and transmission chain comprise the conveying device. The digging shovel and the depth limiting wheel are fixed in front of the conveying device. The cab, conveying device, and collecting box are fixed above the crawler chassis via the frame. The overall structure of the potato harvester provides advantages, including a moderate size and compact arrangement.

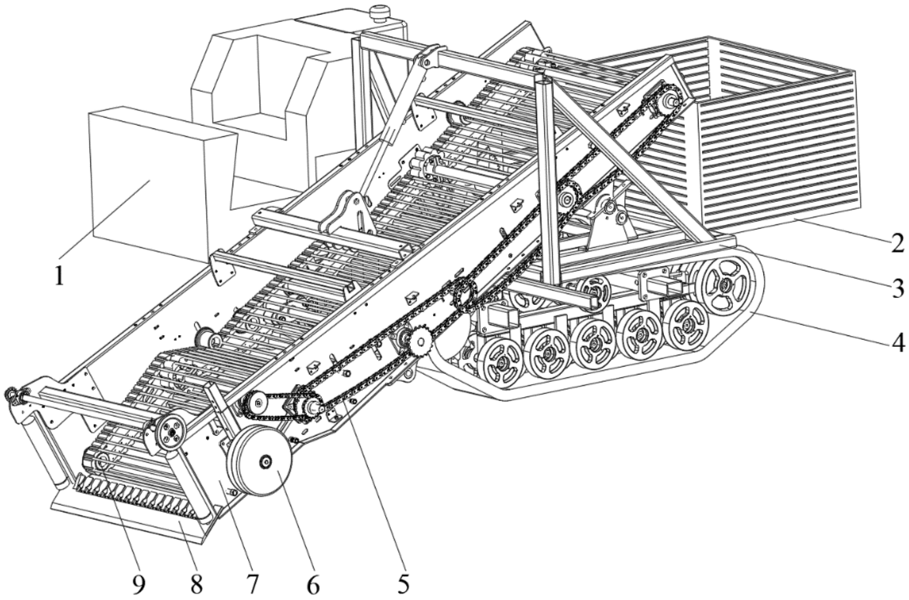

Fig. 1 - Diagram of the self-propelled crawler-potato harvester
1) cab; 2) collecting box; 3) frame; 4) crawler chassis; 5) transmission chain; 6) depth limiting wheel; 7) baffle; 8) digging shovel; 9) wave chain rod

The driver controls the potato harvester to move forward steadily, and the crawler chassis runs smoothly. Potatoes are dug out of the soil by using a digging shovel. The depth limiting wheel can ensure that the digging shovel is in the appropriate depth. The transmission chain drives the wave chain rod to rotate. Owing to vibration, the soil block progressively decreases. When the soil block is smaller than the gap of the wave chain rod, it falls back to the ground, prompting the separation of potatoes and the soil block. Potatoes are then transported in the back. When the collection box is filled with potatoes, it requires replacement.

The aforementioned process is repeated until the entire harvesting process is completed. The main technical parameters of the potato harvester are listed in Table 1.

Table 1

Main technical parameters of the self-propelled crawler-potato harvester

Technical parameters	**Value**	**Units**
Overall dimensions (length× width× height)	5200×2750×2750	mm
Overall weight	2970	kg
Auxiliary power	74	kW
Digging depth	100-300	mm
Working width	800	mm
Working speed	0.5-0.7	m·s^{-1}

Finite element analysis

Finite element analysis is often used in the analysis of the stress and strain of the research object to improve reliability *(Issa et al., 2020)*. The solution process of finite element analysis typically includes the pre-processing, load-solving, and post-processing modules *(Yu et al., 2015)*. The main function of the pre-processing module is to define the material properties and divide the grid cells. The main function of the load-solving module is to add load constraints and displacement constraints. The solution is then completed computationally. The post-processing module mainly views the stress and strain analysis results. The weak structure of the design can be identified by finite element analysis. The design is then optimized in size and material. The aforementioned procedure is repeated, ultimately enhancing the design.

The digging shovel, one of the principal parts of a potato harvester, generally penetrates the soil at an angle of 20°-25° *(Fan et al., 2019)*. As the harvester moves forward, the potatoes and the soil are dug out together. The reliability of the digging shovel directly affects the working efficiency of the harvester. Consistent with the previously described steps, a finite element analysis of the digging shovel was conducted, and the software used was ANSYS 2020. Defined as 45 steel, the material of the digging shovel was evaluated; the results are listed in Table 2. As shown in Figure 2, the grid cell size of the digging shovel is 5mm, the number of nodes is 3.7778×10^4, and the number of cells is 2.0012×10^4. Figure 3 shows that the maximum stress value of the digging shovel is 37.969 MPa, which is considerably less than 355 MPa (yield strength of 45 steel). Figures 4 and 5 show that the maximum strain of the digging shovel is 1.846×10^{-4}, and the total deformation is 0.8041 mm, which fall within the safe range. Therefore, the design of the digging shovel can ensure its continuous and stable work.

Table 2

Main material properties of 45 steel

Parameters	**Value**	**Units**
Elastic modulus	2.09×10^5	MPa
Poisson's ratio	0.269	-
Mass density	7.89×10^3	kg·m^3
Yield strength	355	MPa

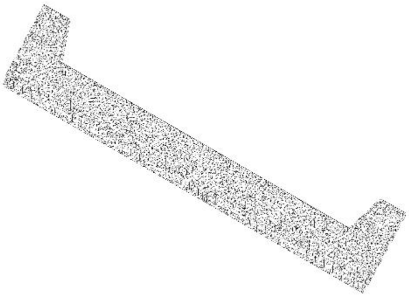

Fig. 2 - Mesh generation of the digging shovel

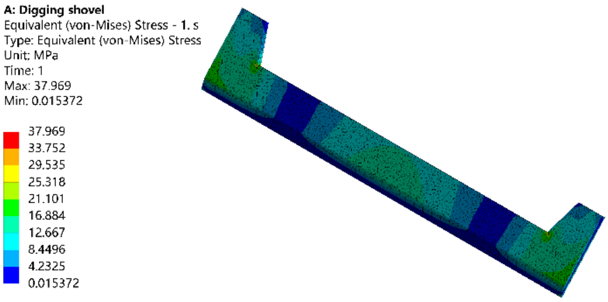

Fig. 3 - Stress nephogram of the digging shovel

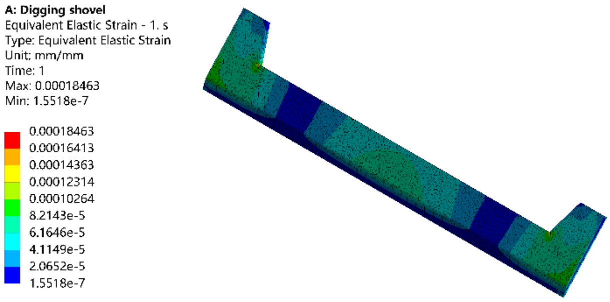

Fig. 4 - Strain nephogram of the digging shovel

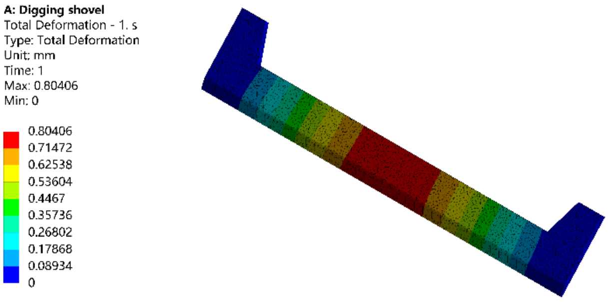

Fig. 5 - Total deformation nephogram of the digging shovel

The frame is also one of the principal components of a potato harvester *(Shen et al., 2020)*. A cab and a collection box are usually fixed above the frame, and a crawler chassis is connected below the frame. The reliability of the frame structure directly affects the stability of the whole harvester. As shown in Figure 6, the frame has a symmetrical structure to facilitate processing. The frame material was also 45 steel. The finite element analysis results of the frame are presented in Figures 7-9. The following characteristics of the frame were within the safe range: maximum stress, 13.946 MPa; maximum strain, 6.836×10^{-5}; and total deformation, 4.887×10^{-3} mm. Therefore, the frame can ensure a reliable connection.

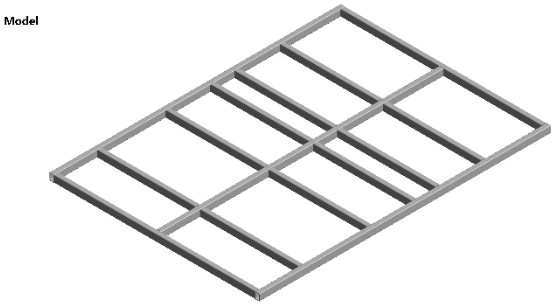

Fig. 6 - Schematic of the frame

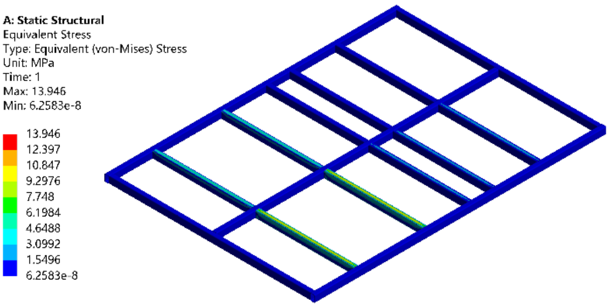

Fig. 7 - Stress nephogram of the frame

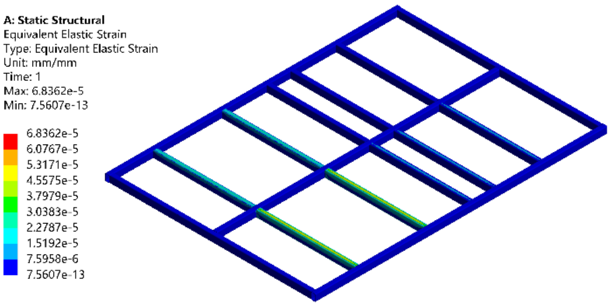

Fig. 8 - Strain nephogram of the frame

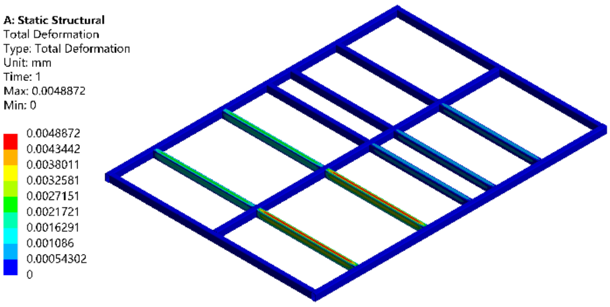

Fig. 9 - Total deformation nephogram of the frame

Performance evaluation

In accordance with relevant standards for the NYT648-2015 potato harvester, the performance of the harvester was evaluated by calculating the harvesting rate, bruising rate, and damage rate *(Chen et al., 2020; Qi et al., 2017)*. The experiment was designed as follows: five areas of the experimental field were randomly selected, with each field measuring 30 m in length. Five plots were randomly selected from each field, with each plot measuring 3 m in length. One plot was randomly selected from each field for harvesting experiments repeated five times. The evaluation indexes were then calculated based on the following formulas:

$$L_1 = \frac{M_1}{(M_1 + M_2)} \times 100\% \tag{1}$$

$$L_2 = \frac{M_3}{(M_1 + M_2)} \times 100\% \tag{2}$$

$$L_3 = \frac{M_4}{(M_1 + M_2)} \times 100\% \tag{3}$$

where:

L_1 is potato harvesting rate, %; L_2 is potato bruising rate, %; L_3 is potato damage rate, %; M_1 is the quantity of excavated potatoes, kg; M_2 is the quantity of potatoes that have not been excavated, kg; M_3 is the quantity of potato with broken skin, kg; M_4 is the quantity of the damaged potatoes, kg.

RESULTS AND ANALYSIS

Field experiment

To verify whether the self-propelled crawler-potato harvester can meet the requirements, a field experiment was conducted in Xiji County, Guyuan City, Ningxia on October 25, 2020. As shown in Figure 10, the experimental field is a hilly and mountainous area where a large number of potatoes are planted. The experimental field was located at 105.73° E and 35.96° N. The rainfall was 0.0 mm and the soil water content was 20%.

Fig. 10 – The experimental field

Qingshu No.9 is planted in the experimental field from April to May and harvested from September to October every year. The experiment equipment and instruments mainly included a self-propelled crawler-potato harvester, a stopwatch, a tape measure, a digital vernier caliper, a digital display platform scale, and a record book. The process of the field experiment is illustrated in Figures 11 and 12.

Fig. 11 - Potato harvester in motion

Fig. 12 - Potato harvester at work

Data analysis

The experimental data are listed in Table 3. The results of the field experiment showed that potato harvesting rate was 98.54%, the bruising rate was 1.51%, and the damage rate was 1.31%. All harvester indexes met the requirements for national harvester quantity evaluation. The effect of the harvester operation is shown in Figure 13.

Table 3

Data and results of the field experiment

Serial number	Harvesting rate (%)	Bruising rate (%)	Damage rate (%)
1	98.58	1.45	1.28
2	98.59	1.53	1.31
3	98.35	1.52	135
4	98.53	1.55	1.27
5	98.65	1.48	1.34
Average value	98.54	1.51	1.31

Fig. 13 – Potato harvester operation effect

CONCLUSIONS

(1) A self-propelled crawler-potato harvester was designed for potato harvesting in hilly and mountainous areas, which could complete the excavation and collection of potatoes in a single operation.

(2) The results of finite element analysis showed that the maximum stress and strain of the digging shovel and the frame met the safety requirements. The results of field experiments showed that the harvesting rate was 98.54%, the bruising rate was 1.51%, and the damage rate was 1.31%, which were superior to the national standards for potato harvesters.

(3) It is of great significance to improve the degree of potato harvesting mechanization and promote the sustainable and healthy development of the potato industry in hilly and mountainous areas.

ACKNOWLEDGEMENT

This research was supported by the Foreign Science and Technology Cooperation Special Project of Ningxia Hui Autonomous Region Key Research and Development Program (No. 2019BFF02003).

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