RESEARCH ON DESIGN AND EXPERIMENT OF MULTIFUNCTIONAL VEGETABLE FIELD MACHINE
/
多功能蔬菜田间作业机械设计与试验研究

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ABSTRACT
Vegetable industry occupies a significant position in the world agricultural production, China has been the largest vegetable producing country in the world. However, the mechanization of vegetable production is still in the initial stage. There are many problems such as complex environment, non-uniform agronomy, various kinds of agricultural machinery etc. In order to meet the varied requirements of vegetable field work, in this paper, a new type of high-efficiency vegetable field operation power equipment was developed by adopting the idea of "frame-type", and the key components are developed. They include ground gap adjusting mechanism, wheel spacing adjusting mechanism, inter-axle hitch mechanism, the rear hitch mechanism and frame. The vibration modal analysis and stiffness analysis of the frame are carried out by ANSYS, which proves that the frame design is reasonable and meets the use requirements. Finally, a prototype was made and field experiments were carried out. The results showed that the maximum running speed of the multifunctional vegetable field machine was 16 km/h, the maximum operating speed was 8 km/h, the maximum gradient was 20, and the adjustable range of ground clearance was 400~800 mm. The adjustable range of wheel spacing was 1600-2000 mm.

摘要
蔬菜产业在世界农业生产中占有重要地位,中国已成为世界上最大的蔬菜生产国。然而，蔬菜生产机械化程度仍旧很低，存在着田间环境复杂、农艺不统一、农机具种类繁多等诸多问题。为满足蔬菜田间作业农艺需求多样化的要求，本文采用"框架式"结构设计思想，开发了一种新型多功能高效蔬菜田间作业动力设备，并对其关键部件进行设计，包括地隙调节机构、轮距调节机构、轴间悬挂机构、后悬挂机构和车架。利用 ANSYS 对车架进行振动模态分析和刚度分析，证明车架设计合理，能够满足使用要求。最后，试制样机并进行田间试验。结果表明，多功能蔬菜田间作业机的最高运行速度为 16 公里/小时；最大运行速度 8Km/h，最大坡度 20°，离地间隙可在 400 ~ 800 mm 范围内调节；轮间距可调范围为 1600-2000 毫米。

INTRODUCTION
Vegetable industry occupies a significant position in the world agricultural production. In recent years, with the development of agricultural science and technology, the yield of vegetable products has increased. According to FAO statistics, from 2009 to 2018, Asia had the largest vegetable yield and area. In the meantime, China has been the largest vegetable producing country in the world, and its output has accounted for more than half of the world's output since 2015. However, at present, the mechanization of vegetable production is still in the initial stage. The comprehensive mechanization level of the whole vegetable production process is lower than 25%, and the vegetable production efficiency is far lower than that of developed countries. At the same time, there are some problems such as insufficient productivity, high cost and low benefit, etc. *(He C.X. and Yu X.C., 2012; Xiao T.Q. et al., 2015; Li X.R. et al., 2021; Yang et al., 2020).*

At present, vegetable production can be divided into two types: one uses large fields to produce vegetables, and the other uses artificial facilities to produce vegetables efficiently. The two production modes have basically the same mechanized production process.

According to the vegetable production process, the mechanization process can be divided into three types: pre-harvest mechanization, harvest mechanization and postharvest operation. Among them, the mechanization of vegetable pre-harvest operation mainly includes: soil preparation, seedling raising, transplanting, grafting, sowing, field management and other processes; vegetable harvest mechanization mainly includes: rhizome vegetables, leafy vegetables, melon, fruit and other categories; vegetable postharvest operation mechanization mainly includes: waste film recovery, vegetable residue treatment, etc. Vegetable field machine plays a very important role in vegetable mechanization production.

For vegetable production, with the development of trenchers, graders, rotary tillers, subsoilers, rakes, two-way ploughs and other agricultural machinery, mechanized operations can basically be realized *(Mi N.H. et al., 2014)*. However, agricultural machinery usually needs to be used with tractors. *Kumar and Raheman, (2011)* developed a walk-behind type hand tractor powered 2-row fully automatic vegetable transplanter for individual paper pot seedlings by considering the power availability. *Dihingia et al. (2018)* developed a vegetable transplanter for transplanting soil block seedlings which can cooperate with local power machinery. *Raja et al., (2019)* developed a precision weed control equipment for vegetable fields with high crop and weed densities. Because of the variety of field operations, different agricultural machinery have different characteristics, and they will also change for different vegetable objects, so it is difficult to achieve universal and accurate matching between agricultural machinery and tractors to realize mechanized operation. Therefore, it is urgent to apply the operation machinery suitable for multi agricultural tools.

At present, the phenomenon of field crop damage and soil compaction caused by the operation of field power machinery is receiving widespread attention. *Materechera S., (2009),* discover that conventional tillage practices with tractors limit the performance of vegetable crops and affect the quality of water resources. *Pedersen et al., (2013),* proposed a wide span tractor which is designed to optimise the Controlled Traffic Farming (CTF) system, and *Bulgakov et al., (2019)* had determined the quantitative effect of transverse displacements of the working implements and the suitable size of the safeguard zone. However, wide span tractor can only be used in specific scenes and it is not suitable for small plots and greenhouse operations. Therefore, it is more common to design tractors with small size and light weight to reduce soil compaction.

In addition, the research on tractors now also focuses on safety reliability and hitch mechanism of the tractor. *Hui W.D. et al., (2018),* established the security frame prototype geometric model and applied with MIDAS software to verify the accuracy and effectiveness of analysis model. *Shao M.X. et al., (2019)* designed a tractor system with force adjustment function based on the traditional tractor hydraulic hitch system. *Yang Q.Z. et al., (2020)* proposed a tractor three degree of freedom of agricultural implement hitch mechanism which can be used for the operation of the tractor and farm implement set with automatic chassis levelling on the slope.

Based on previous research, in order to break through the limitation that traditional vegetable field operation power machinery uses small tractors as power machinery, this paper studies the structural design scheme of multifunctional vegetable field machine, develops the power machinery with inter-shaft hitch system and rear hitch system for different agricultural machinery, adopts frame structure to replace the traditional agricultural machinery chassis, so as to provide 100% visual inter-axle working space. In the meantime, in order to ensure reliability and reduce soil compaction, the key components are developed and improved, including ground clearance adjustment and wheel spacing adjustment mechanism, hitch mechanism and frame structure. The strength and stiffness of the frame are analysed by using ANSYS software.

MATERIALS AND METHODS

Structure design of multifunctional vegetable field machine

Multifunctional vegetable field machine is mainly used in the vegetable field production process including fertilization, weeding, sowing, spraying, intertillage, etc. There are various kinds of vegetables, complicated working environment, various kinds of supporting agricultural machinery, and different requirements in different areas. Therefore, the design should be considered from many aspects at the beginning *(Wang Z.Y., 2010)*.

According to the working characteristics and requirements of multifunctional vegetable field machine, the layout scheme of the machine structure is proposed, because the working environment of multifunctional vegetable field machine requires that the machine can withstand various bending moments and torques stably under various working conditions. In this paper, the "frame-type" structure is adopted, and the inter-shaft hitch system is developed to enable the driver have a good visual field for agricultural machinery. Therefore, the driver can operate accurately in the working process, so as to improve the final yield of vegetables. The structure of multifunctional vegetable field machine is shown in Fig.1.

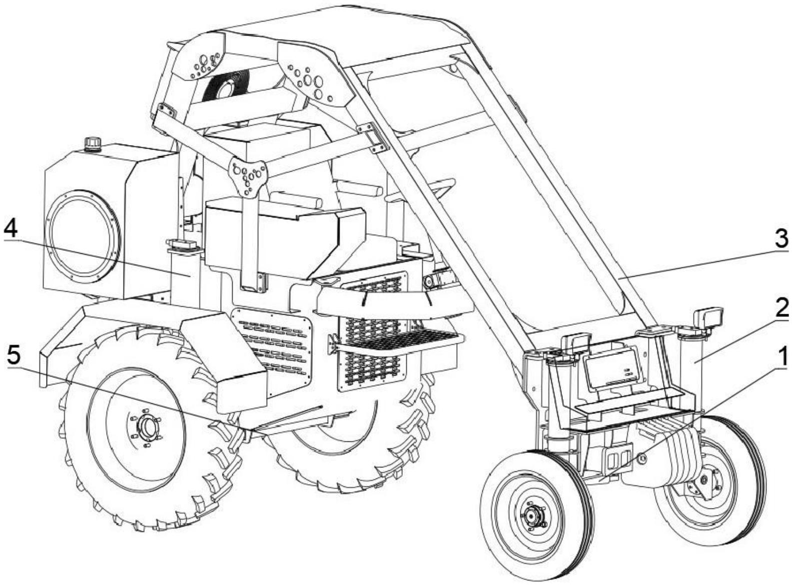

Fig. 1 – Structural design scheme of the whole machine

1. Front wheel spacing adjustment mechanism; 2. Front ground clearance adjustment; 3. Frame; 4. Rear ground clearance adjusting mechanism; 5. Rear wheel spacing adjustment mechanism

Key component design

- **Ground clearance adjustment and wheel spacing adjustment mechanism**

The ground clearance adjustment mechanism and wheel spacing adjustment mechanism work together to make the multifunctional vegetable field machine adapt to the different flatness of field, the mechanized production methods and planting agronomy of different vegetable varieties *(Du X.X., 2014; Shen T.L.F. et al., 2016)*. Combined with the actual situation and requirements, the minimum ground clearance of multifunctional vegetable field machine is selected to be 400mm, the minimum wheel spacing is 1600mm, the adjustable range of the ground clearance is 400mm, and the adjustable range of the wheel spacing is 400mm. The front ground clearance adjustment mechanism, the rear ground clearance adjustment mechanism, front wheel spacing adjustment mechanism and rear wheel spacing adjustment mechanism are shown in Fig. 2.

The ground clearance adjustment mechanism in front of the machine is composed of hydraulic cylinder block, end cap, piston rod and hydraulic cylinder block sleeve. The hydraulic cylinder block is fixed with the front wheel steering mechanism. Piston rod drives the hydraulic cylinder block sleeve move. Because the sleeve and the frame form a whole in the direction perpendicular to the ground, so it can drive the machine movement, the purpose of changing the clearance from the ground is achieved.

The ground clearance adjusting mechanism at the rear of the machine body is composed of independent hydraulic cylinder and guide device. The piston rod of the hydraulic cylinder is firmly connected to the motor cover of the wheel part, the cylinder block is connected to the guide mechanism, and the guide mechanism is connected to the spacing adjustment device of the rear wheel, so as to form a whole with the frame in the direction of the vertical ground. When the cylinder block moves, the movement of the whole machine is driven to achieve the purpose of changing the clearance from the ground.

The front wheel spacing adjustment mechanism is composed of the left and right frame, the beam sleeve and the hydraulic cylinder. The adjustment frame for single wheel spacing is composed of four 5 mm thick steel plates and 100×100×10 mm square pipes, and the beam sleeve is composed of 120×120×10 mm square pipes. The frame is fixed with the sleeve of the ground gap adjustment mechanism, and the force of vertical movement is transmitted through the beam sleeve which is fixed with the frame. The cylinder body is firmly connected with the beam sleeve. Through the connection of the hydraulic rod and the adjustment frame on both sides, the left and right motion stroke can be synchronously adjusted to avoid the vehicle centre of gravity be too high, which will lead to the increase of the vehicle risk.

The structure and working principle of the rear wheel spacing regulating mechanism is similar to that of the front wheel spacing regulating mechanism. The hydraulic cylinder is a two-way piston cylinder with a rod cavity as the working chamber when the wheel spacing is reduced.

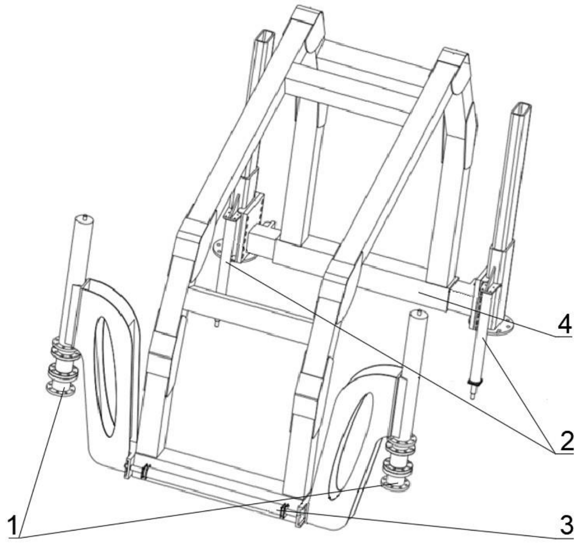

Fig. 2 – The ground clearance adjustment and wheel spacing adjustment mechanism
1. Front wheel gap adjustment mechanism; 2. Rear wheel gap adjustment mechanism;
3. Front wheel spacing adjustment mechanism; 4. Rear wheel spacing adjustment mechanism

- **Hitch mechanism design**

At present, most agricultural machinery is driven by tractors or has its own power source, and most agricultural machinery and tools used in vegetable production are hooked up by traction or three-point hitch *(Xue C.S., 2018)*. In the process of agricultural machinery operation, drivers need to constantly look back to observe the operation situation. It is difficult to ensure the accuracy of the operation and it may bring danger. Therefore, a non-standard three-point inter-shaft hitch system is developed. The height adjustment function is realized by hydraulic power, and the width of the hitch system can be adjusted manually. It can make the working state of agricultural machinery completely within the driver's visual field, thus ensuring the accuracy of the operation process and improving the driver's safety.

As shown in Fig. 3, the transverse part of the inter-shaft hitch mechanism is square sleeve beam, which is similar to the wheel spacing adjustment mechanism.

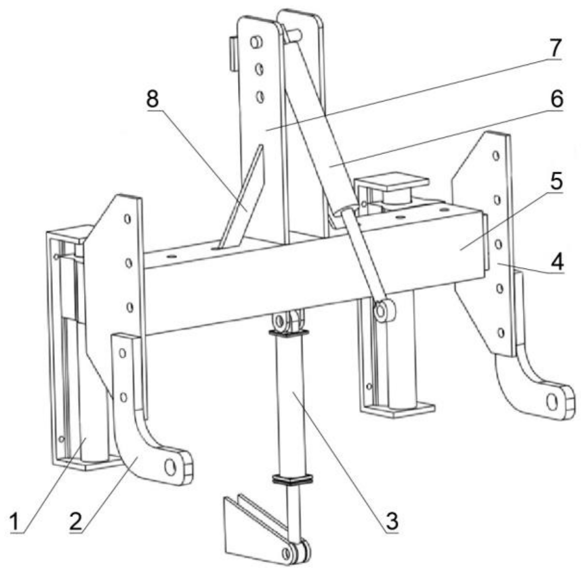

Fig. 3 – Inter-shaft hitch mechanism
1. Slide rail; 2. Lifting arm; 3. Height adjusting hydraulic cylinder; 4. Stretching beam; 5. Stretching beam sleeve; 6. Lifting hydraulic cylinder; 7. Longitudinal beam; 8. Reinforcing plate.

It adopts the structure of two telescopic sleeves, but the width adjustment here needs to be completed manually. The sliding guide rail can adjust the height of the hanging position of agricultural machinery, and the lifting arm machine can change the height of hanging agricultural tools, which can increase the height adjustment range, match more agricultural machinery and better control the working depth of agricultural machinery in the soil. The mechanism has a maximum width adjustment capacity of 300 mm and a maximum height adjustment distance of 150 mm. The rear hitch of this machine adopts the traditional three-point hitch mechanism, which can match more agricultural machinery. Because of multifunctional vegetable field machine having two hitch structures, it can install multiple machines for simultaneous operation which can reduce soil compaction and crop damage.

- **Frame mechanism design**

The frame is one of the most important parts of the multifunctional vegetable field machine, which mainly plays the following roles: connects the front and rear parts of the whole machine, bears various forces and torques brought by the front and rear wheels, reduces the vibration of the whole machine caused by uneven road surface, so that the tractor can have good driving stability *(Zhang L., 2018)*.

The multifunctional vegetable field machine adopts "frame-type" structure. The front end is welded and fixed with the crossbeam and crossbeam sleeve which can adjust the distance between front wheels, and the rear end is similar to the front end. When designing the frame, it is necessary to ensure its safe rigidity and strength.

The material selection and cross-section shape of the frame directly affect the performance of the tractor. Reasonable selection can effectively ensure the strength and rigidity of the frame, and can also help the subsequent processing and manufacturing. The main material of the frame structure use 100×100×10 mm square tube. The frame is welded by 13 square tubes with different lengths and 24 steel plates with 10 mm thickness. Its structure is shown in Fig.4, its length is 1900mm, the width is 800mm, and the height is 1534 mm. Among them, the wide steel plate can connect all parts of the frame and strengthen the moment bearing capacity.

As the main load-bearing component, the rigidity of the frame directly affects the safety performance, service performance, stability performance and service life of the multifunctional vegetable field machine. In this paper, the finite element analysis software ANSYS is used to carry out linear static analysis on the frame, so as to understand its stress and strain under the statics condition, which provides a certain theoretical design basis for the structural design and will play a certain reference role for the subsequent design improvement of related models.

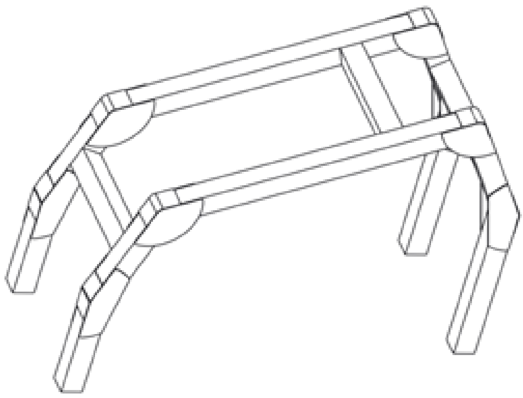

Fig. 4 – Frame

- **Frame analysis**

In this paper, CREO software is used to carry out 3D model of the frame. After simplifying some features of the 3D model that are not applicable for finite element analysis, it is converted into the available model of ANSYS. The frame is made of carbon structural steel Q345B, and its material performance is shown in Tab.1. The grid division has a great impact on the quality of analysis. In order to make the grid division reasonable, the automatic grid division application of ANSYS software is adopted in this analysis, and on this basis, the larger grid is refined, and a total of 214270 dividing nodes and 49976 body units are obtained. In order to facilitate calculation, each part is integrated into a solid, and the default SOLID186 unit type of the system is selected.

Table 1

Q345B material properties

Name of the material	Elastic modulus/(kg·cm^{-2})	Poisson's ratio	Yield strength (MPa)	Tensile strength (MPa)	Density (Kg·m^{-3})
Q345B	2.06·e^{5}	0.280	345	470~630	7.85·e^{3}

In ANSYS, Block Lanczos is used as the mode extraction method, and free boundary modal analysis is used as the analysis method. The vibration source of the frame is mainly from two different aspects. One is the vibration generated by the ground when moving. Due to the low motion speed of the machine, the frequency is generally less than 30Hz. And the other is the excitation source from the interior of the vehicle, such as the engine and internal friction, whose excitation frequency is generally less than 100Hz. Therefore, the range of calculated frequency band is determined as 0Hz-100Hz. The first 10 modes are shown in Fig.5, and the analysis results are shown in Tab.2.

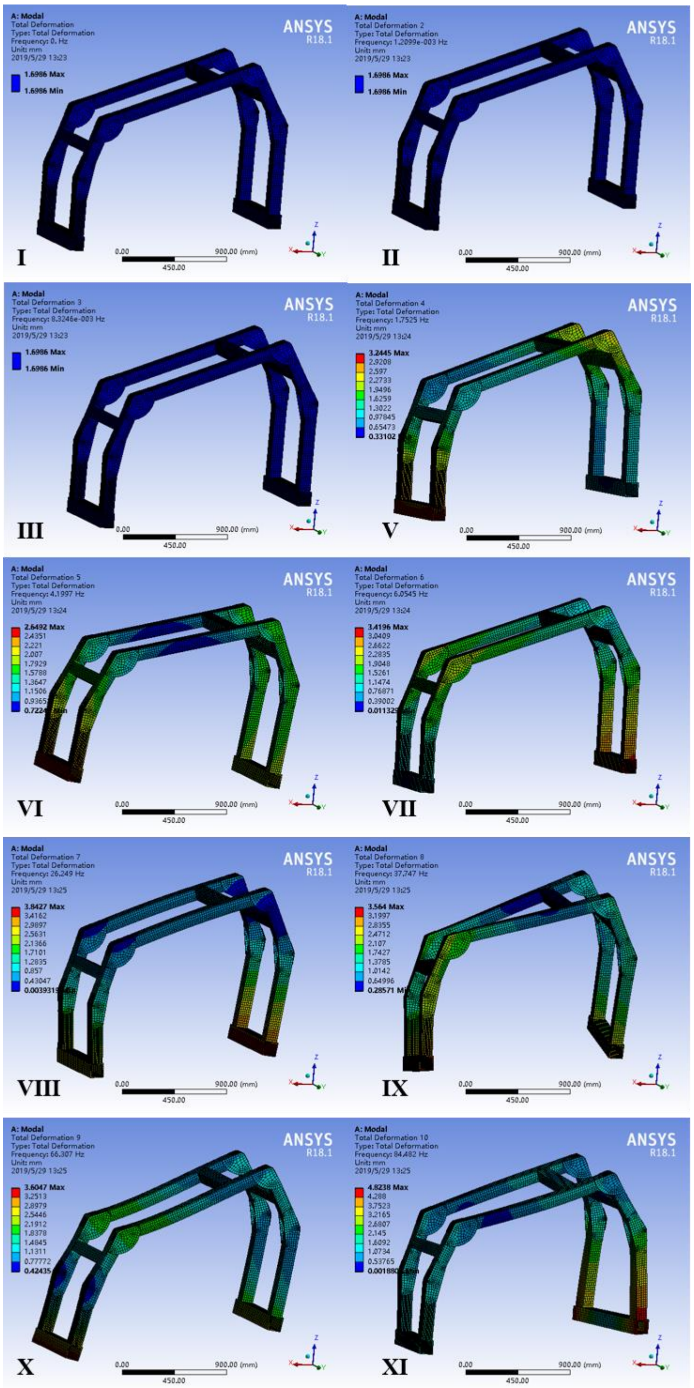

Fig. 5 – The first ten natural frequencies of the frame correspond to the mode diagram

According to the results of the frame free boundary modal analysis, the frame deformation is mainly in the form of bending, torsion and bending. From first to the third order modal of ultra-low frequency almost no effect is shown, four order shows the state of local bending vibration mode, five order modal and ten order modal show the local torsional vibration mode, the six order modal and nine order modal show the overall longitudinal bending vibration mode, combination of seven order modal show the local bending and twisting vibration mode, the combination of eight order modal show the overall bending and twisting vibration mode. The deformation of the beam is relatively small.

Table 2

The first ten natural frequencies and modes of vibration of the frame

Modal order time	Modal frequency (Hz)	Maximum displacement (mm)	Vibration performance
1	0	1.6986	No obvious vibration
2	$1.2099 \cdot e^{-3}$	1.6986	No obvious vibration
3	$8.3245 \cdot e^{-3}$	1.6986	No obvious vibration
4	1.7525	3.2445	Local bending
5	4.1997	2.6492	Local bending
6	6.0545	3.4196	Overall longitudinal bending
7	26.249	3.8427	Local bending and twisting
8	37.747	3.564	Overall bending and twisting
9	66.307	3.6047	Overall longitudinal bending mode
10	84.482	4.8238	Partially reversing

In addition, the stiffness of the frame is analysed. Taking the right front wheel of the vehicle impacted by the road as an example, the frame is deformed due to the deformation of the front axle. The dynamic load of the front axle is taken as 1.14MPa through searching literature and calculation, which simulates the impact of a single wheel on the road, and the other three tires are used as fixed in homeostatic position. The stress and strain of the frame under impact are shown in Fig.6.

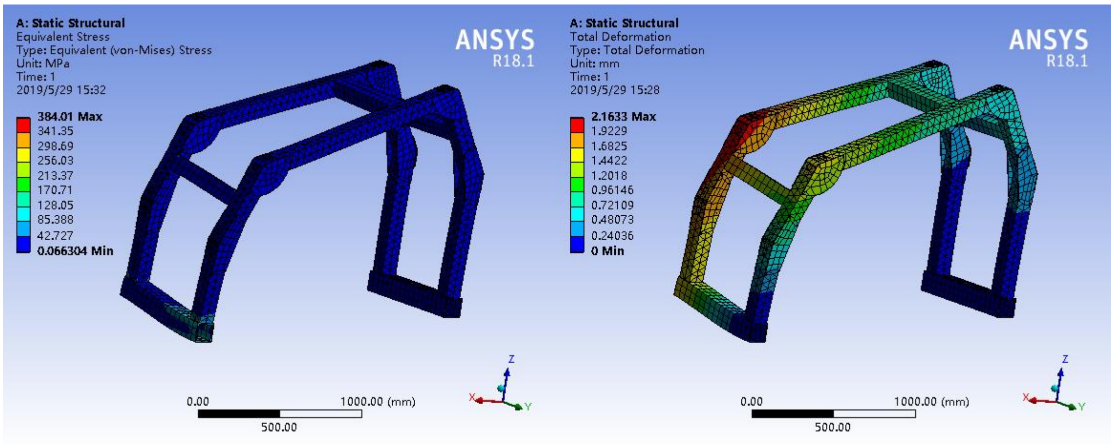

Fig. 6 – The Stress and strain of frame under impact

It can be seen from the analysis results that the maximum stress of the frame does not exceed 200 MPa under the impact action, so the frame material meets the use requirements. The maximum deformation displacement of the frame is about 2.17 mm.

RESULTS

At present, there are many problems in vegetable mechanized production, such as complex environment, non-uniform agronomy, different production processes, various kinds of vegetables, and many supporting agricultural machinery. In this paper, the multifunctional vegetable field machine is developed, and its key components are designed, including the ground clearance adjustment and wheel spacing adjustment mechanism, the inter-axle hitch mechanism, the rear hitch mechanism and the frame.

The multifunctional vegetable field machine can adapt to different production conditions, adjust chassis levelling and reduce soil compaction.

Through the finite element analysis, the vibration modal analysis and stiffness analysis of the frame are carried out, which proves that the frame design is reasonable and meets the requirements. Finally, a prototype was made and its parameters were measured in the Mechanical and Electrical College of Northwest A&F University. The prototype of multifunctional vegetable field machine is shown in Fig. 7.

Fig. 7 – Multifunctional vegetable field machine

The measure results are shown in Tab.3.

Table 3

Main structure parameters of precise and efficient vegetable field operation management machine

Name	Parameter
Length × width × height（mm）	2580×1914×2115
Wheelbase length（mm）	1800
Minimum wheel track length（mm）	1600
Minimum ground clearance（mm）	400
Quality（kg）	1600
Power source	ZN385Q Diesel engine

CONCLUSIONS

In order to realize efficient, intelligent and environment-friendly full-cycle field operation management of vegetables, a new type of high-efficiency multifunctional vegetable field machine was developed by adopting the idea of "frame-type" mechanism design.

The whole machine structure, ground clearance adjustment and wheel spacing adjustment mechanism, the inter-axle hitch mechanism, the rear hitch mechanism and frame are developed and optimized, especially the vibration modal analysis and stiffness analysis of the frame are carried out.

The trial production and experiment of the equipment have been completed. The test results show that the maximum running speed of the vegetable field machine is 16 km/h.

The maximum operating speed is 8 Km/h, the maximum gradient is 20^o, and the adjustable range of ground clearance is 400 ~ 800 mm. The adjustable range of wheel spacing is 1600-2000mm. It can improve the efficiency and quality of vegetable field operation.

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