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# Design and Experiment for Flexible Clamping and Conveying Device for Green Leafy Vegetable Orderly Harvester

**Yue Jin [1,2], Jinwu Wang [1,*], Jia Chen [2], Zhiyu Song [2,*], Renlong Zhang [2] and Ran Zhou [2]**

[1] College of Engineering, Northeast Agricultural University, Harbin 150030, China
[2] Nanjing Institute of Agricultural Mechanization, Ministry of Agricultural and Rural Affairs, Nanjing 210014, China
* Correspondence: jinwuw@163.com (J.W.); songzhiyu@caas.cn (Z.S.)

**Abstract:** Due to the advantages of improving vegetable quality and reducing labor, technology for the orderly harvesting of green leafy vegetables has always been the focus of research. The core of the technology is the clamping and conveying device. At present, technology for the orderly harvesting of green leafy vegetables has several difficult problems, such as the plugging of the clamping and conveying device, great damage caused by mechanical clamping and high transportation loss. A green leafy vegetable is essentially a viscoelastic body and plastic deformation is an important index to measure its mechanical damage. Therefore, based on vegetable linear viscoelastic characteristics, we determined the deformation and plastic damage mechanism caused by orderly clamping and conveying. A rheological constitutive model and mathematical equations of the damage deformation value were constructed for the green leafy vegetable mechanical clamping process. Viscoelastic parameters of green leafy vegetable samples were obtained by creep experiments. The elastic clamping force and clamping spacing were analyzed systematically when the flexible clamping and conveying device was clamping, conveying and collecting. Under different spring stiffness and clamping time combinations, green leafy vegetable plastic damage deformation values were calculated and the vegetable damage regularity analyzed. After comprehensive consideration, we concluded that, when the harvester forward speed was 0.6 km/h, the optimal parameter combination of the flexible clamping and conveying device was a conveying roller rotation speed of 80 r/min, and a spring stiffness combination of 2.0 N/mm and 0.6 N/mm. Finally, a bench test verified that the mechanized harvest effect was best under a combination of parameters. Thus, we proved that the method is appropriate for studying the effects of clamping and conveying devices on green leafy vegetable damage based on viscoelastic rheological characteristics.

**Keywords:** green leafy vegetables orderly harvesting; viscoelastic property; creep experiment; flexible clamping and conveying device; mechanical damage

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## 1. Introduction

The vegetable industry is important to China's agricultural and rural economy, which is vital for farmers' income and urban residents' food. Recently, the national vegetable planting area has stabilized at c.20 m ha, with an output of >700 million tons and an economic value of more than 2 trillion yuan. Vegetables have become an important cash crop in China [1,2]. With the continuous expansion of the vegetable planting scale, harvesting requires more labor and labor costs in the process of the mechanized production of vegetables. Therefore, relying on traditional manual harvesting has seriously restricted the development of the vegetable industry, and it is urgent to develop advanced and applicable vegetable harvesting technology and equipment.

Green leafy vegetables are mainly planted by type, such as bok choy, crown daisy and leek, because of their short growing period, multiple cropping characteristics and long growing season throughout the country. Systematic harvesting technology plays a vital

role in improving the quality of green leafy vegetables, increasing their production and promoting income, and reducing labor. The technology adopts a specific clamping and conveying device to guide the vegetables, gather them together, transport them, and finally load them into boxes in a neat and orderly manner. Machine harvested vegetables can be directly supplied to the market, with good product commercialization, and without the need for secondary manual finishing [3–6]. A clamping and conveying device is necessary for the systematic harvesting of green leafy vegetables, and mainly comprises vertical and twisted clamping [7,8].

At present, the RAPID leafy vegetable harvester developed by the Hortech Company in Italy and the SPH400 hand-held spinach harvester developed by the Kubota Company in Japan can achieve the orderly harvesting of multiple rows of green leafy vegetables. They mainly use the collaborative operation of band saw cutting and vertical clamping conveying [9]. The 4G-200 leek harvester of the South Korean company adopted the operation mode of disk cutting and twisted clamping and conveying to achieve the orderly harvesting of single rows of leeks [3]. In China, Jin et al. [10–12] developed two kinds of multi-row green leafy vegetable orderly harvesters. And they designed and optimized various forms of clamping conveying devices and orderly collecting devices. Tang et al. [13] developed a vertical clamping conveyor belt speed intelligent adjustment system for an orderly harvesting machine for leafy vegetables, which can adapt to the speed of the conveyor belt according to the density of the harvested vegetables. Zou et al. [14,15] designed a clamping and conveying device for a spinach orderly harvester and optimized the elastic clamping mechanism based on the viscoelastic characteristics of spinach plants to realize low-damage orderly clamping and conveying. Shi et al. [16,17] developed an orderly harvester of artemisia selengensis, which transported artemisia selengensis from the vertical flexible clamping conveyor belt to the steering device. The artemisia selengensis was tumbled out of the vertical clamping conveyor belt and dumped, and then entered the orderly collection device. The orderly harvesting technology and equipment for green leafy vegetables in foreign countries have problems such as large volume, high price and planting agronomy mismatch, which have failed to achieve large-scale promotion and application. Domestic scholars still need to conduct in-depth research on the improvement of the adaptability and reliability of orderly harvesters.

Green leafy vegetables come in many varieties, with large differences in planting patterns and growth characteristics. The green leafy vegetable sizes of the same variety vary greatly in harvest time. So, in the clamping process, the clamping conveyor belt needs to produce a certain amount of deformation, to reduce loss from conveyor falls, and to avoid the conveyor belt jamming and vegetable damage. Most fruits and vegetables, including green leafy vegetables, are essentially viscoelastic, with both elastic and viscous deformation [18–20]. Elastic deformation refers to stem and leaves that can completely recover after the withdrawal of the external force applied, while viscous deformation refers to the part of the stem and leaves that cannot recover after external force withdrawal, which is also called plastic deformation. The stem and leaf final shape is directly determined by plastic deformation; therefore, plastic deformation is an important indicator of mechanical damage in green leafy vegetables [21,22].

When green leafy vegetables are harvested in an orderly mechanized manner, the nature of the plastic deformation of the stems and leaves and resulting mechanical damage is due to the stress amplitude generated by the extrusion of the clamping mechanism exceeding the compressive limit of the stems and leaves. The stems and leaves are unable to completely recover from the deformation after leaving the clamping mechanism, and are damaged. Extrusion pressure produced by a traditional spring will increase with increasing deformation range, if the spring selection and tensioning mechanism design is inappropriate. Moreover, when the size of green leafy vegetables and the feeding amount are larger in the clamping process, it is easy for a bottleneck to occur causing plugging of the device, much vegetable damage from mechanical clamping and high transportation

loss. Therefore, the scientific design of a suitable flexible clamping mechanism is key to improving systematic harvester operation and adaptability.

## 2. Materials and Methods

### *2.1. Structure of Flexible Clamping and Conveying Device*

In the systematic harvesting of green leafy vegetables, the flexible clamping and conveying device includes a driven drive roller, wave conveyor belt, active drive roller, spring tensioning mechanism, frame, conveyor belt tensioning mechanism, and bevel gear transmission mechanism (Figure 1) [13].

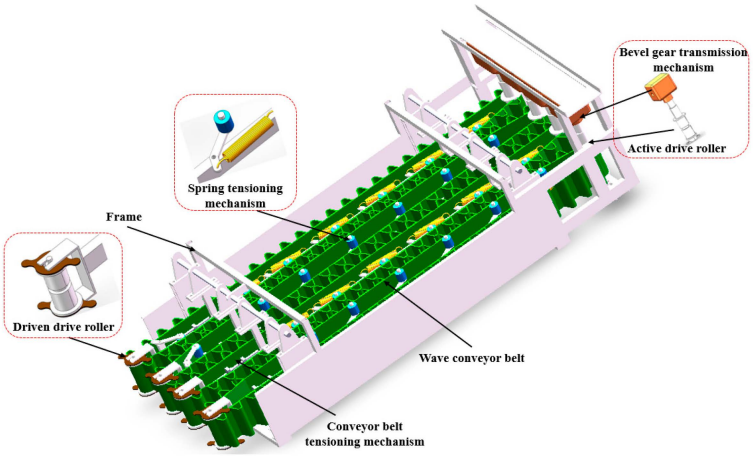


**Figure 1.** Structure of green leafy vegetable flexible clamping and conveying device.

The green leafy vegetable clamping and conveying process is divided into four stages: wave conveyor belt guiding and gathering green leafy vegetables together; green leafy vegetables located at the wave conveyor belt entrance; green leafy vegetables being completely clamped; and conveying/collecting. During the orderly harvesting of green leafy vegetables, the raised wave conveyor belt in the clamping and conveying device first touches the green leafy vegetables. The wave conveyor belt is used to straighten and gather green leafy vegetables with poor straightness or at risk of falling, and actively pushes the green leafy vegetables to the entrance of the clamping and conveying device. Then, the green leafy vegetables continue to enter the clamping and conveying device. When the green leafy vegetables are completely gripped by the belt, the green leafy vegetables are pulled out from the soil for a certain distance under the drive of the clamping and conveying device, and at the same time the roots of the green leafy vegetables are quickly cut off. Subsequently, the green leafy vegetables continue to be transported to the rear under the action of the clamping and conveying device. When the green leafy vegetables are transported to the end of the clamping and conveying device, the green leafy vegetables enter the orderly collection device from the clamping and conveying device. The whole process of the green leafy vegetable clamping and conveying is completed.

### *2.2. Force and Deformation Regularity of Green Leafy Vegetable Clamping Action*

#### 2.2.1. Green Leafy Vegetable Viscoelasticity Mathematical Model

The construction of a rheological mathematical model to describe green leafy vegetable viscoelastic properties is conducive to the analysis of their deformation characteristics under loading conditions, and the four-element Burgers model is recognized as a more accurate and complete mathematical model to characterize these viscoelastic properties (Figure 2) [14,15,20,23]. The constitutive equation is as follows:

$$D(t) = \frac{F_0}{k_1} + \frac{F_0}{c_1}t + \frac{F_0}{k_2}\left(1 - e^{-\frac{k_2}{c_2}t}\right) \quad (1)$$

where $D(t)$—deformation, mm; $t$—time, s; $F_0$—constant load, N; $k_1$—instantaneous elasticity coefficient, N/mm; $k_2$—delayed elasticity coefficient, N/mm; $c_1$—tandem viscosity coefficient, N·s/mm; and $c_2$—shunt viscosity coefficient, N·s/mm.

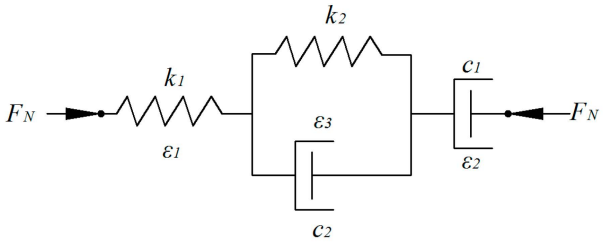


**Figure 2.** Burgers model.

2.2.2. Creep Experiments

Creep experiments can accurately obtain green leafy vegetable viscoelastic parameters of constitutive Equation (1) [24,25]. Five Shanghai Qing of Zhenpin 66 cultivars with a similar size from the right harvesting period were randomly selected. To reduce the effect of water loss on the results of the experiment, the roots of the green leafy vegetables were cut off immediately after the whole plant was pulled out of the ground. Then, the green leafy vegetables were placed horizontally on the test bench of universal testing machine, their stems were aligned with the probe, and the conveyor belts were wound on top of both the probe and the test bench to simulate the actual force of the green leafy vegetables on the clamping device, and then individual experiments were carried out. The experimental apparatus included a TA.XT plusC universal testing machine from SMS (United Kingdom), a P/1S spherical probe (one inch in ball diameter), an industrial control computer and vernier calipers.

During the constant pressure loading creep experiments, to avoid overshoot when the loading process reached set pressure for the first time, the probe loading speed was set at 5 mm/min, with a data acquisition frequency of 200 pps. Three sample points were randomly selected on each specimen, and a constant loading pressure of 6, 8 and 10 N was applied to them for uniaxial compression creep tests (Figure 3); a total of fifteen sets of experimental data were obtained (Figure 4), at a constant pressure loading time of 60 s.

**Figure 3.** Creep experiments.

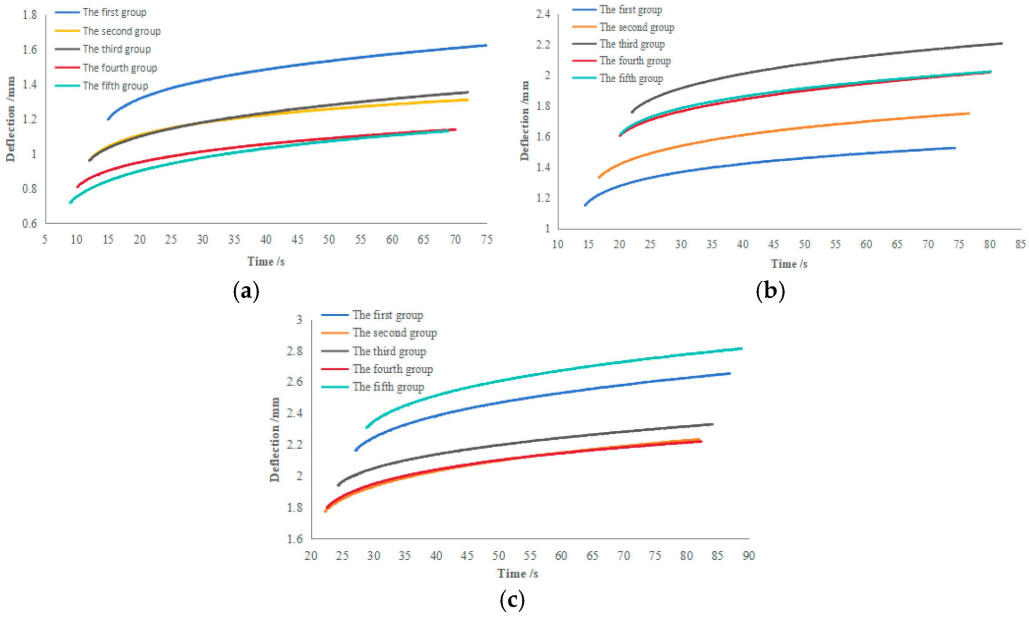


**Figure 4.** Deformation of green leafy vegetables over time under constant pressure loading: (**a**) 6 N constant pressure loading; (**b**) 8 N constant pressure loading; (**c**) 10 N constant pressure loading.

From the Figure 4 curves and data, the initial displacement when reaching the set loading pressure varied significantly for each sample tested because the gaps between each leaf were different in the whole green leafy vegetable test. These differences led to a significant difference in the initial displacement. But, from the trend of each curve, the slopes of the deformation versus time curves of similar samples under the same loading constant pressure were the same. This result indicates that the difference in the initial displacement did not affect the deformation from the point of view of the total deformation.

Using the cftool curve fitting toolbox in MATLAB 7.1 data analysis software, curve fitting of each group of green leafy vegetable creep experimental data was carried out using Formula (1) to obtain correlation coefficients in the viscoelasticity mathematical model. And average values of five groups of data with the same loading force were calculated (Table 1). The coefficients of determination $R^2$ were >0.9991, which verifies the validity of the selected model.

**Table 1.** Green leafy vegetable viscoelastic correlation coefficients.

| Loading Force $F_0$ | $k_1$/(N·mm$^{-1}$) | $k_2$/(N·mm$^{-1}$) | $c_1$/(N·s·mm$^{-1}$) | $c_2$/(N·s·mm$^{-1}$) | SSE | $R^2$ |
|---|---|---|---|---|---|---|
| 6 N | 12.72 | 9.80 | 1982.45 | 95.86 | 0.0879 | 0.9991 |
| 8 N | 17.58 | 7.19 | 2394.56 | 74.31 | 0.0880 | 0.9993 |
| 10 N | 26.86 | 5.34 | 2667.12 | 57.00 | 0.0892 | 0.9994 |
| Average | 19.05 | 7.44 | 2348.04 | 75.72 | 0.0884 | 0.9993 |

### 2.2.3. Clamping Action Force–Deformation Model

In the green leafy vegetable clamping and conveying process, the green leafy vegetables are most prone to damage in the three stages of being completely clamped, conveying and collecting. Deformation of green leafy vegetables based on characterization by the Burgers' model is shown in Figure 5.

Force and deformation expressions of green leafy vegetables during mechanical clamping are as follows:

$$\begin{cases} F(t) = F_i(t) \\ x(t) = x_1(t) \end{cases} \quad (2)$$

included among these,

$$\begin{cases} F_1(t) = k_1(x_1(t) - x_2(t)) \\ F_2(t) = k_2(x_2(t) - x_3(t)) + c_2(\dot{x_2}(t) - \dot{x_3}(t)) \\ F_3(t) = c_1\dot{x_3}(t) \\ x(t) = x_h(t) - F(t)/k_h \end{cases} \tag{3}$$

where $x(t)$—total deformation of the green leafy vegetables, mm; $x_h(t)$—total deformation, mm; $F(t)$—force on green leafy vegetables applied by the clamping belt, N; $k_h$—clamping belt stiffness, N/mm.

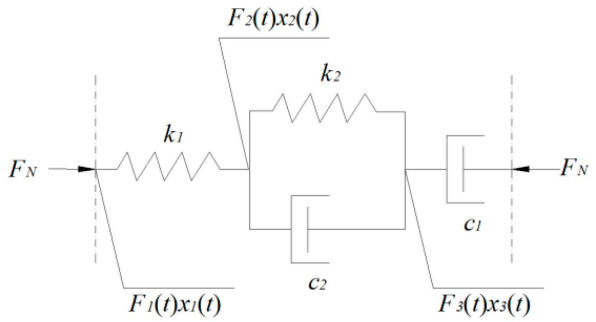


**Figure 5.** Force deformation characterization in green leafy vegetable Burgers model.

Removing $F_i$ and $x_i$, the relationship between the squeezing force on green leafy vegetables when being mechanically clamped and the resulting displacement can be modeled as follows:

$$A_2\ddot{F}(t) + A_1\dot{F}(t) + F(t) = B_2\ddot{x_h}(t) + B_1\dot{x_h}(t) \tag{4}$$

included among these,

$$\begin{cases} A_1 = \frac{k_1k_2c_1 + k_h(k_2c_1 + k_1c_1 + k_1c_2)}{k_1k_2k_h} \\ A_2 = \frac{c_1c_2(k_h + k_1)}{k_1k_2k_h} \\ B_1 = c_1 \\ B_2 = \frac{c_1c_2}{k_2} \end{cases} \tag{5}$$

We analyzed the entire process of green leafy vegetables being mechanically clamped, which included pulling green leafy vegetables out of the soil for a certain distance and then cutting their roots, wherein soil resistance required a greater clamping and pulling force. Therefore, the clamping force of the wave conveyor belt needs to be designed to meet the drawing action, and so the calculation formula for the force on green leafy vegetables under pulling action (Figure 6) is as follows:

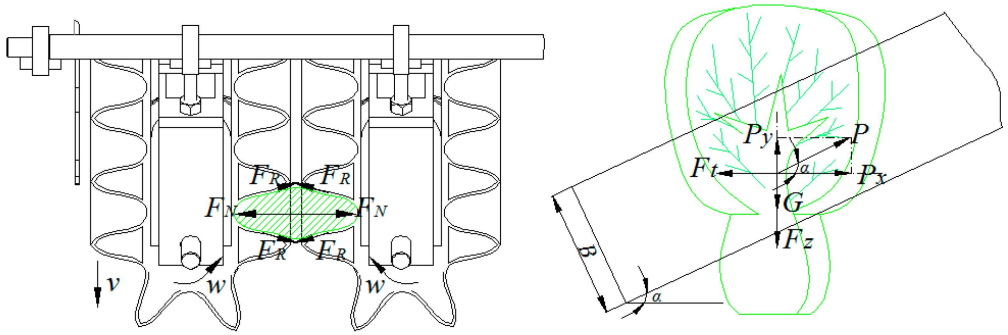


**Figure 6.** Force analysis of the complete clamping stage of green leafy vegetables.

$$\begin{cases} P_y = P\sin\alpha = \mu F_N \\ P\cos\alpha = F_t \\ P_y \geq F_Z + G \end{cases} \quad (6)$$

in which $P$—the pulling force on green leafy vegetables, N;

$P_y$—the component force of the pulling force in the vertical direction, N;

$\alpha$—horizontal inclination angle of the clamping and conveying device, (°);

$F_N$—the squeezing force on green leafy vegetables by the wave conveyor belt, N;

$\mu$—static friction coefficient between green leafy vegetables and the wave conveyor belt;

$F_t$—horizontal forward thrust of the machine on green leafy vegetables, N;

$F_Z$—soil resistance to the vertical direction of green leafy vegetables, N;

$G$—gravitational force of green leafy vegetables, N.

From literature review, combined with field measurements, we determined that the vertical pulling force $P_y$ of green leafy vegetables was 15 N, and the coefficient of static friction $\mu$ between green leafy vegetables and the wave conveyor belt was 1.9 [14], which means that the squeezing force $F_N$ on green leafy vegetables by the wave conveyor belt was 7.9 N.

#### 2.2.4. Green Leafy Vegetable Plastic Deformation Damage Value Calculation

When the clamping force exerted on green leafy vegetables exceeds the compressive limit of their stems and leaves, their stem and leaf surfaces are permanently damaged by plastic deformation. The stems and leaves have obvious crushing damage such as broken surfaces, cracks or fractures, and the plastic deformation magnitude can be used as a mathematical index for evaluating damage severity. We know from the Burgess model that plastic deformation of viscoelastic objects is mainly determined by the viscosity coefficient $c_1$ [26] and, therefore, the plastic deformation of green leafy vegetable damage is as follows:

$$X_P = \frac{1}{c_1}\int_0^T F(t)dt \quad (7)$$

where $T$—contact time between clamping belt and green leafy vegetables, s.

## 3. Analysis of Operating Parameters on Green Leafy Vegetable Damage Influence

### *3.1. Flexible Clamping and Conveying Device Damage Deformation Value Calculation*

This paper is designed utilizing the elastic tension generated by the deformation of the tensile spring to realize a flexible and low-damage clamping operation, where the clamping belt stiffness equates to the spring stiffness. As can be seen from Equation (4), the clamping belt spring stiffness $k_h$ is a key parameter affecting green leafy vegetable damage. According to green leafy vegetable quality, the actual pulling resistance in the field and belt deformation in the clamping process, the preliminary design of the spring stiffness $k_h$ of the clamping belt was 2.0 N/mm.

Because spring tensioning wheels are installed at intervals on the inner side of the flexible clamping and conveying device, green leafy vegetables are subjected to complex spring alternating forces during clamping and conveying. To simplify the force analysis and damage calculation, green leafy vegetable force and deformation during clamping and conveying can be divided into three stages (Figure 7). To analyze the effects of different spring stiffness coefficients and different action time on the amount of mechanical damage to green leafy vegetables, we calculated the green leafy vegetable damage deformation values in the whole clamping and conveying process one by one.

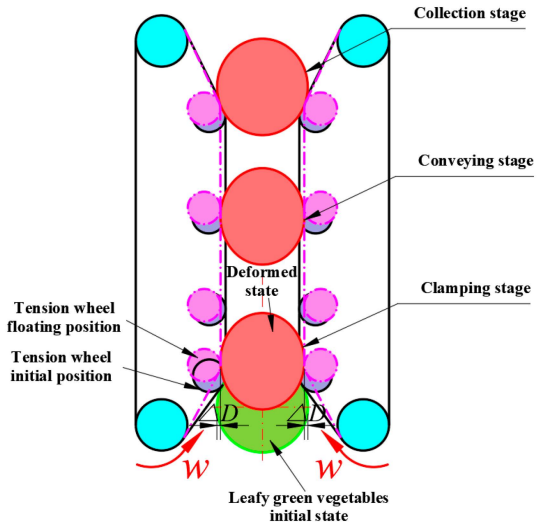


**Figure 7.** Green leafy vegetable deformation during clamping and conveying.

3.1.1. Green Leafy Vegetable Damage Value Calculation during the Clamping Stage

The spring stiffness was 2.0 N/mm and the clamping feeding speed was 1.08 km/h. Therefore, the clamping action time $t_0$ of a small green leafy vegetable was 0.1 s.

In the clamping stage, the tension spring is passively in simple harmonic motion, and green leafy vegetable deformation with time follows a trigonometric function, so the functional equation of its displacement changing with time is as follows:

$$x_h(t) = Acos(\omega t + \varphi) \tag{8}$$

where $A$ is the spring amplitude and, due to the variation in green leafy vegetable diameter being generally within 20 mm, to ensure that large green leafy vegetables could pass smoothly through the clamping and conveying device, the actual design of the amplitude $A$ was 12 mm. $\omega$ is the angular frequency, which is calculated by the formula $\omega = \sqrt{\frac{k}{m}}$, which results in $\omega$ = 2 rad/s; $\varphi$ is the phase angle, $\varphi$ = 0.

Thus, green leafy vegetable deformation under the elastic clamping force is $x_h(t) = A\cos\omega t$; then,

$$\begin{cases} \dot{x_h}(t) = -A\omega sin\omega t \\ \ddot{x_h}(t) = -A\omega^2 cos\omega t \end{cases} \tag{9}$$

The coefficient average value in Table 1 and spring stiffness are obtained by substituting them into Equation (5)

$$1.53 \times 10^4 \times \ddot{F}(t) + 1.94 \times 10^3 \times \dot{F}(t) + F(t) = -1.37 \times 10^6 \times cos2t - 6.40 \times 10^4 sin2t \tag{10}$$

Equation (10) is a second-order non-homogeneous linear differential equation with constant coefficients, belonging to the following types

$$f(x) = e^{\lambda x}\left[P_l^{(1)}(x)cos\omega x + P_n^{(2)}(x)sin\omega x\right] \tag{11}$$

where $\lambda = 0$, $P_l^{(1)}(x) = -1.37 \times 10^6$, $P_n^{(2)}(x) = -6.40 \times 10^4$; it follows from the function properties that finding the general solution to Equation (10) can be reduced to finding the general solution of the corresponding homogeneous equation and a particular solution of the non-homogeneous Equation (10) itself.

$$1.53 \times 10^4 \times \ddot{F}(t) + 1.94 \times 10^3 \times \dot{F}(t) + F(t) = 0 \tag{12}$$

The characteristic equation of Equation (12) is

$$1.53 \times 10^4 \times r^2 + 1.94 \times 10^3 \times r + 1 = 0 \tag{13}$$

There are two real roots, $r_1 = -0.12653$ and $r_2 = -0.00052$; then, the general solution of the homogeneous Equation (12) corresponding to Equation (10) is

$$Y = C_1 e^{-0.12653x} + C_2 e^{-0.00052x} \tag{14}$$

Since $\lambda + i\omega = 2i$ is not a root of the characteristic Equation (13), the particular solution $y^*$ should be the following:

$$y^* = acos\omega t + bsin\omega t \tag{15}$$

Substituting Equation (15) into Equation (10) and using the undetermined coefficient method, comparing the coefficients of the same terms at both ends we obtain

$$\begin{cases} -6.12 \times 10^4 a + 3.88 \times 10^3 b + a = -1.37 \times 10^6 \\ 6.12 \times 10^4 b + 3.88 \times 10^3 a - b = 6.41 \times 10^4 \end{cases} \tag{16}$$

This solves for $a = 22.313$ and $b = -0.371$. Thus, a particular solution to Equation (10) is

$$y^* = 22.313 \times cos2t - 0.371 \times sin2t \tag{17}$$

Based on the stabilized clamping process parameters of the conveyor belt, we determined that the initial conditions of Equation (10) are $F(0) = 0$ N, $F(0.1) = 7.9$ N, and substituting the initial conditions into equation (10) to find its general solution is

$$F(t) = -660.441 \times e^{-0.12653t} + 638.127 \times e^{-0.00052t} + 22.313 \times cos2t - 0.371 \times sin2t \tag{18}$$

Then, the plastic deformation expression corresponding to this clamping stage is given by

$$X_{P1} = \frac{1}{2348.04} \int_0^{0.1} \left( -660.441 \times e^{-0.12653t} + 638.127 \times e^{-0.00052t} + 22.313 \times cos2t - 0.371 \times sin2t \right) dt = 1.686 \times 10^{-4} \text{ mm} \tag{19}$$

3.1.2. Green Leafy Vegetable Damage Value Calculation during the Conveying Stage

When the rotational speed of the clamping and conveying roller is 60 r/min, its displacement is $x_h(t) = 2.0$ mm when it is completely clamped by the spring, and the stable clamping force of the tensioning spring is 7.9 N to ensure that the green leafy vegetables are pulled smoothly a certain distance and then cut. Subsequently, the cut vegetables are transported to the rear under the stabilizing clamping effect of the wave conveyor belt. At this time, the stabilizing clamping force of the tension spring is balanced by the gravity of the cut vegetables, the stabilizing clamping force of the tension spring is 2.5 N, the spring with a stiffness coefficient of 0.6 N/mm is selected, the distance of the whole clamping and conveying process is 1150 mm, and the calculated clamping and conveying action time is 7.3 s.

Since the green leafy vegetables are relatively immobile in the clamping band [14] and, thus, $x_h(t) = C$, where $C$ is a constant, then $\dot{x_h}(t) = 0$ and $\ddot{x_h}(t) = 0$. When the spring stiffness is 2.0 N/mm this gives the rheological model of the green leafy vegetables at this stage as

$$1.53 \times 10^4 \times \ddot{F}(t) + 1.94 \times 10^3 \times \dot{F}(t) + F(t) = 0 \tag{20}$$

Equation (20) is a homogeneous linear differential equation with constant coefficients; the initial conditions are $F(0.1) = 7.9$ N and $F(1.6) = 2.5$ N; its general solution is

$$F(t) = 31.741 \times e^{-0.12653t} - 23.443 \times e^{-0.00052t} \tag{21}$$

Then, the plastic deformation expression corresponding to this process is given by

$$X_{P2} = \frac{1}{2348.04}\int_{0.1}^{1.6}\left(31.741 \times e^{-0.12653t} - 23.443 \times e^{-0.00052t}\right)dt = 3.267 \times 10^{-3}\ \text{mm} \quad (22)$$

Similarly, the green leafy vegetable rheological model with a stiffness coefficient of 0.6 N/mm during the transport period from 1.6 s to 7.3 s is

$$4.85 \times 10^4 \times \ddot{F}(t) + 5.05 \times 10^3 \times \dot{F}(t) + F(t) = 0 \quad (23)$$

The initial conditions are $F(1.6) = 2.5$ N and $F(7.3) = 2.5$ N. The solution method is the same as above, and the general solution is

$$F(t) = -0.0075 \times e^{-0.104t} + 2.5071 \times e^{-0.0002t} \quad (24)$$

Then, the plastic deformation expression corresponding to this process is given by

$$X_{P3} = \frac{1}{2348.04}\int_{1.6}^{7.3}\left(-0.0075 \times e^{-0.104t} + 2.5071 \times e^{-0.0002t}\right)dt = 6.069 \times 10^{-3}\ \text{mm} \quad (25)$$

Therefore, the green leafy vegetable damage value during the conveying stage is $X_P = X_{P2} + X_{P3} = 9.336 \times 10^{-3}$ mm.

#### 3.1.3. Green Leafy Vegetable Damage Value Calculation during the Collection Stage

At the collection stage, the tensioning spring is still passive and in simple harmonic motion; in fact, this stage can be regarded as the reverse of the clamping stage. Green leafy vegetable deformation changes in the form of a trigonometric function, and the calculation method is the same as the clamping stage but spring stiffness is lower, so the green leafy vegetable damage value is $X_{P1} < 1.686 \times 10^{-4}$ mm, which is negligible.

### *3.2. Study on Damage of Green Leafy Vegetables by Spring Stiffness and Clamping Time*

When the clamping and conveying device speed remains unchanged, the spring stiffness design is divided into two types. The first design is to ensure that the clamping device can provide a fixed initial clamping force. Then, spring tensioning of the flexible clamping conveyor device, and the spring amplitude and angular velocity also need to be designed accordingly. The second design is to maintain the initial distance between the wave conveyor belts of the clamping device the same; then, and only then, replace the spring with one of a different stiffness. To analyze the mechanical damage of differently sized green leafy vegetables under different spring stiffness (Table 2), we applied the damage deformation calculation method outlined in Section 3.1.

**Table 2.** Three types of spring stiffness combination.

| Combination | 1 | 2 | 3 |
|---|---|---|---|
| Spring stiffness/N·mm$^{-1}$ | 1.5 and 0.4 | 2.0 and 0.6 | 3.0 and 0.9 |

In addition, the effect of clamping and conveying action time on green leafy vegetable damage should not be ignored; this paper calculated the mechanical damage value of green leafy vegetables under three different clamping conveying roller speeds, that is, three action times, as shown in Table 3.

**Table 3.** The corresponding relationship between clamping/conveying stage time and roller speed.

| Item | 1 | 2 | 3 |
|---|---|---|---|
| Clamping stage time/s | 0–0.08 | 0–0.1 | 0–0.11 |
| Conveying stage time/s | 0.08–5.5 | 0.1–7.3 | 0.11–11 |
| Clamping and conveying roller speed/r·min$^{-1}$ | 80 | 60 | 40 |

### *3.3. Bench Tests Study*

To verify the theoretical analysis correctness of green leafy vegetable deformation in the clamping process, as well as the reasonableness and applicability of our flexible clamping and conveying device, we constructed a clamping and conveying test rig at a test location in the Wuxi Dingjun Mechanical Science and Technology Co., Ltd. (Wuxi, China) plant on 5 January 2024 (Figure 8). Fifty green leafy vegetables of the appropriate harvesting period were selected for testing.

**Figure 8.** Bench tests.

According to DG/T 249-2021 "Leafy vegetable harvester" and other national standards, the operation performance of the clamping conveying device was tested [27].

#### 3.3.1. Loss Rate

After each clamping and conveying experiment, we picked up the fallen green leafy vegetables and green leafy vegetables in the collection box, weighed them, and calculated the loss rate according to Formula (26):

$$T_l = \frac{W_l}{W_Z + W_l} \times 100\% \tag{26}$$

where $T_l$ is the loss rate; $W_l$ is the quantity of green leafy vegetables not collected, kg; and $W_z$ is the total mass of green leafy vegetables in the collection box, kg.

#### 3.3.2. Damage Rate

After each clamping and conveying experiment, samples of green leafy vegetables in the collection box were randomly selected and weighed. Green leafy vegetables with obvious extrusion, crack and fracture damage were selected and weighed, and the damage rate was calculated according to Formula (27):

$$T_s = \frac{W_s}{W_d} \times 100\% \tag{27}$$

where $T_s$ is the damage rate; $W_s$ is the quantity of damaged green leafy vegetables in the sample, kg; and $W_d$ is the sample quantity of green leafy vegetables, kg.

## 4. Results and Discussion

### *4.1. Analysis of the Effect of Different Spring Stiffness on the Damage to Green Leafy Vegetables*

The calculation results for the values for mechanical damage to green leafy vegetables caused by different spring stiffnesses of the clamping and conveying device are shown in Figure 9. $S_1$ is the same initial force of the spring installed in the wave conveyor belt, $S_{1min}$ is the amount of mechanical damage when the smallest-diameter green leafy vegetables enter the wave conveyor belt and $S_{1max}$ is the amount of mechanical damage when the largest-diameter green leafy vegetables enter the wave conveyor belt (Figure 9). $S_2$ is the same initial distance of the spring installed in the wave conveyor belt, $S_{2min}$ is the amount of mechanical damage when the smallest-diameter green leafy vegetables enter the wave conveyor belt, $S_{2max}$ is the amount of mechanical damage when the largest-diameter green leafy vegetables enter the wave conveyor belt and $\Delta S$ is the damage value increment of the largest- and the smallest-diameter green leafy vegetables in the same condition.

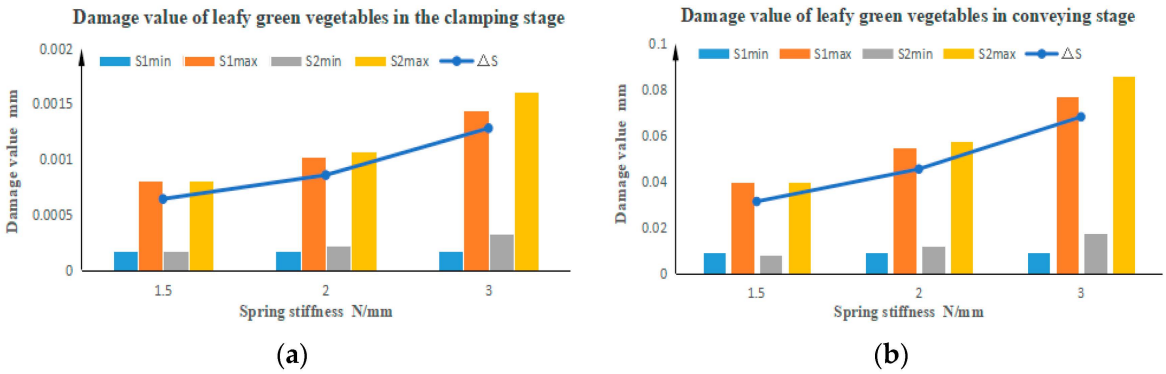


**Figure 9.** Changes in values of mechanical damage to green leafy vegetables at different action stages. (**a**) Clamping stage and (**b**) conveying stage.

Under the same initial spring force, different spring stiffnesses produce the same amount of mechanical damage to the smallest-diameter green leafy vegetables (Figure 9). But with increasing green leafy vegetable diameter, the greater the spring stiffness, the greater the amount of mechanical damage. Under the initial spring spacing, mechanical damage to green leafy vegetables increased with increasing diameter and increasing spring stiffness. By analyzing the damage increment trend, in the same threshold range of the same species of green leafy vegetables under premise conditions, the greater the spring stiffness, the greater the incremental damage to green leafy vegetables, indicating that spring stiffness is more obvious for large-vegetable mechanical damage. Therefore, when designing the green leafy vegetable orderly harvester flexible clamping conveyor device, an appropriate spring stiffness of the tensioning mechanism should be selected in combination with green leafy vegetable diameter and the actual operational situation, to reduce mechanical damage to different vegetables. Combined with the actual clamping tension of the conveyor belt and the threshold range of green leafy vegetable diameter, the conventional spring stiffness of 1.5 N/mm and 0.4 N/mm provides insufficient clamping tension to support the reliable operation of the conveyor belt. So, we selected a combination of spring stiffness of 2.0 N/mm and 0.6 N/mm.

The amount of damage to different green leafy vegetables for different spring stiffnesses was within the range of $1.686 \times 10^{-4}$–$1.614 \times 10^{-3}$ mm in the clamping stage and in the conveying stage was within the range of $9.336 \times 10^{-3}$–$8.585 \times 10^{-2}$ mm (Figure 9). Conversely, the damage amount in the clamping stage had a negligible effect on the whole clamping and conveying process. Similarly, damage in the collection stage on the entire clamping and conveying process was also negligible. This is due to the green leafy vegetable clamping and collection stages being relatively short, so clamping time damage impact cannot be ignored, but, based on the premise of faster feeding speed, spring stiffness size can be ignored. It can also be concluded that in the future the design and analysis of

leafy green vegetable flexible clamping/conveying devices should consider spring stiffness combinations affecting the damage to different green leafy vegetables sizes in the conveying stage (Figure 9).

### *4.2. Analysis of the Effect of Different Clamping Times on the Damage to Green Leafy Vegetables*

The calculation results for values for mechanical damage to green leafy vegetables caused by action times of different stages of the clamping and conveying device are shown in Figures 9 and 10, even though the clamping stage is short and incurs minimal mechanical damage, which was further verified (Figure 10). $S_{min}$ is the amount of mechanical damage when the smallest-diameter green leafy vegetables enter the wave conveyor belt and $S_{max}$ is the amount of mechanical damage when the largest-diameter green leafy vegetables enter the wave conveyor belt (Figure 10). Green leafy vegetable damage increases with increased clamping time, when the initial spring force is the same; damage to green leafy vegetables of different diameters and varying spring stiffnesses under different clamping action times is within the range of $1.345 \times 10^{-4}$–$1.593 \times 10^{-3}$ mm. Conversely, when the initial spring distance is the same, the damage to green leafy vegetables of varying diameters and different spring stiffnesses under different clamping action times is within the range of $1.345 \times 10^{-4}$–$1.777 \times 10^{-3}$ mm. The amount of damage over the entire clamping and conveying process was negligible.

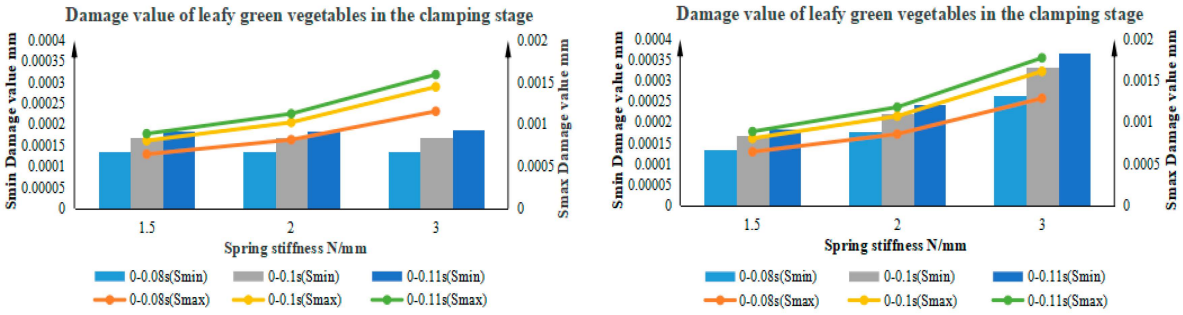


**Figure 10.** Effects of clamping stage action time on green leafy vegetable damage. (**a**) Same initial spring force and (**b**) same initial spring spacing.

Figure 11 shows the amount of damage to green leafy vegetables with different diameters and different spring stiffness under different conveying stages action times; $1 - S_{min}$ indicates that the smallest-diameter green leafy vegetables in combination with one spring stiffness enter the wave conveyor belt and $1 - S_{max}$ indicates that the largest-diameter green leafy vegetables in combination with one spring stiffness enter the wave conveyor belt. The longer the action time in the conveying stage, the greater the amount of mechanical damage to green leafy vegetables. When the initial spring force is the same, the amount of damage to green leafy vegetables of different diameters and different combinations of spring stiffnesses under different conveying action times was in the range 0.007–0.116 mm. When initial spring spacing is the same, the amount of damage for different diameters of green leafy vegetables and different combinations of spring stiffness at different conveying action time was in the range of 0.007–0.130 mm. Therefore, to reduce green leafy vegetable mechanical damage in the conveying stage, the conveying operation time should be as short as possible, i.e., the wave conveyor belt speed should be increased, under the premise of guaranteeing smooth orderly harvester operation, effectively halting the cutting device and ensuring no cutting table congestion. Considering the performance of each device and the whole machine from a system integration perspective, conveying speed should be aligned with the forward speed of the harvester and the cutting speed of the band saw, to achieve the best harvesting effect. In our design, the harvester forward

speed was 0.6 km/h, the wave conveying belt speed generally 1.2 times the harvester forward speed [28], and the clamping and conveying roller rotation speed was 80 r/min.

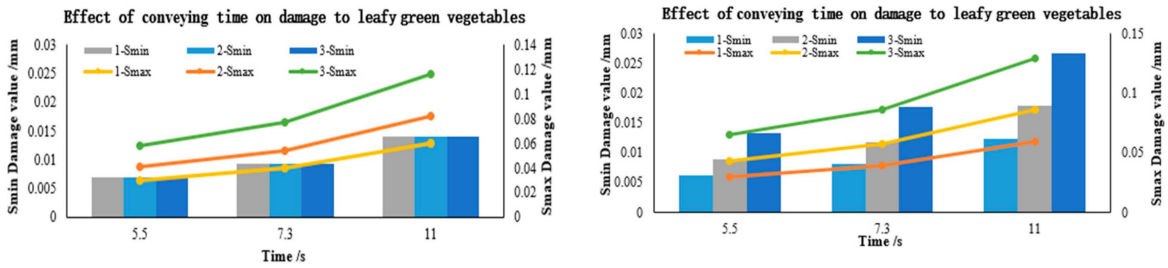


**Figure 11.** Conveying time effects on green leafy vegetable damage. (**a**) Same initial spring force and (**b**) same initial spring spacing.

Additionally, by comparing the range of the two sets of data, we see that the initial spring distance is the same as the initial spring force when the maximum green leafy vegetable damage is only 0.014 mm higher. Considering the degree of difficulty in designing and installing the flexible clamping conveyor device and adapting it to small-diameter green leafy vegetables, and ultimately selecting the same initial spring distance to carry out the device design, we could still calculate the amount of mechanical damage.

### *4.3. Analysis of Bench Test Results*

According to the analysis results in Sections 4.1 and 4.2, the parameters of the test stand were adjusted to change the spring stiffness combination and conveying speed for the test, respectively (Figure 12).

**Figure 12.** Bench tests results comparison. (**a**) Spring stiffness combination 3.0 N/mm and 0.9 N/mm, rotation speed 60 r/min; (**b**) spring stiffness combination 2.0 N/mm and 0.6 N/mm, rotation speed 80 r/min.

Since green leafy vegetables stems are very brittle, the occurrence of damage during the test was obvious. It is not difficult to see that, when the selected spring stiffness was high and the clamping time long, green leafy vegetable stems were subjected to higher extrusion pressure and longer extrusion, which produced greater damage, mainly manifested as pressure injuries and stem fractures (Figure 12). Moreover, the larger the diameter of green leafy vegetables, the more serious the damage. These experimental results are consistent with the conclusions of the previous analyses, which verified the reasonableness of our flexible clamping and conveying device, and also illustrates the feasibility of analyzing the effect of operating parameters on green leafy vegetable damage using vegetable rheological properties.

When the spring stiffness combination of the clamping and conveying device is 2.0 N/mm and 0.6 N/mm, and the rotation speed of the transmission roll is 80 r/min, the

mechanical damage of the device to green leafy vegetables is small. At the same time, to further verify the applicability of our flexible clamping conveying device, fifty plants of four types of green leafy vegetables, namely Shanghai Qing, spinach, celery and Hang cabbage, were selected for the experiment. The test results are shown in Table 4 and the test process is shown in Figure 13. The experimental results showed that the mechanical clamping action damage rate to the four different types of green leafy vegetables was lower than 2.15% and the loss rate was lower than 1.22%. It was proved that the parameters selected were reasonable, and the flexible clamping and conveying device designed was highly applicable in this paper.

**Table 4.** Clamping and conveying device bench test results.

| Types of Green Leafy Vegetables | Shanghai Qing | Spinach | Celery | Hang Cabbage |
|---|---|---|---|---|
| Loss rate/(%) | 0.95 | 0.87 | 1.22 | 1.05 |
| Damage rate/(%) | 1.88 | 1.36 | 1.14 | 2.15 |

(**a**) (**b**) (**c**)

**Figure 13.** Bench test of different types of vegetables. (**a**) Spinach bench test; (**b**) celery bench test; (**c**) Hang cabbage bench test.

## 5. Conclusions

The aim was to solve the green leafy vegetable orderly harvester problems of plugging of the clamping and conveying device, much damage through mechanical clamping and high transportation loss. Based on the viscoelastic characteristics of green leafy vegetables, the clamping and conveying device of the orderly harvester was designed and optimized. Specific conclusions are as follows:

(1) The creep experiments on green leafy vegetables were carried out on a TA.XT plusC universal testing machine. The viscoelastic parameters were obtained by fitting the deformation variation curves for green leafy vegetables with time. We constructed a rheological constitutive model of viscoelastic green leafy vegetables during mechanical clamping based on the Burgers model and established mechanical clamping plastic damage deformation equations. This provided a theoretical basis for calculating the value of mechanical damage to green leafy vegetables.

(2) The plastic deformation of green leafy vegetables under mechanical action was taken as an evaluation index to measure the damage. The damage deformation of green leafy vegetables under three spring stiffness combinations and three clamping times was theoretically calculated at the clamping stage and conveying stage. The results showed that the larger the spring stiffness and the longer the clamping time, the greater the damage increment and the more obvious the mechanical damage to large green leafy vegetables. The optimal spring stiffness combination of the clamping and conveying device was 2.0 N/mm and 0.6 N/mm, and the rotation speed of the transmission roll was 80 r/min.

(3) Bench experiments were carried out with the damage rate and loss rate as indexes, and the results showed that, under the action of the clamping and conveying device, for

four types of green leafy vegetables, including Shanghai Qing, spinach, celery and Hang cabbage, the damage rate was lower than 2.15% and the loss rate was lower than 1.22%. This meets the design requirements of the clamping and conveying device and proved that the method of optimizing the clamping and conveying device based on the viscoelastic characteristics of green leafy vegetables was feasible.

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