Mechanized Blossom Thinning in Orchards

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Orchard thinning can avoid biennial bearing and improve fruit quality, which is a necessary agronomic section in orchard management. The existing methods of artificial fruit thinning and chemical spraying are no longer suitable for the development of modern agriculture. With the continuous acceleration of the construction process of modern orchards, blossom thinning mechanization has become an inevitable trend in the development of the orchard flower and fruit management.

orchard thinning mechanism

1. Introduction

China has an orchard area of over 12 million hectares and a total output of nearly 300 million tons, making it the largest fruit producer and consumer in the world [1][2][3]. With the continuous expansion of the orchard planting area and the increasing requirements for large-scale management, the importance of mechanized orchards is becoming increasingly prominent. However, the research on related technologies started late and had a poor foundation, resulting in an orchard comprehensive mechanization rate of less than 30% [4][5]. Especially in some agronomic sections with a high labor demand, high labor intensity, and tight agricultural seasons, mechanization has not been achieved. Moreover, China is facing an aging population of orchard farmers [6]. The lack of efficient and labor-saving agricultural equipment has become a bottleneck that restricts the development of the fruit industry.

Thinning can avoid biennial bearing and improve fruit quality, which is a necessary agronomic section in pear orchard management [7][8]. The existing methods of artificial fruit thinning and chemical spraying are no longer suitable for the development of modern agriculture. Artificial fruit thinning consumes labor and time, wastes tree nutrients, and has a high-risk factor for tree-top operations [9]. The application of chemical thinning pollutes the environment, and the agents are easily affected by factors such as the spraying time, preparation concentration, and working site environment [10][11][12]. As a result, they are rarely used in actual field operations. Orchard thinning, as a key step in increasing orchard yields, still relies on manual operations. Manual operation is time-consuming and inefficient, and the experience requirements for agricultural operators in blossom thinning work are still high. With the continuous acceleration of the construction process of modern orchards, blossom thinning mechanization has become an inevitable trend in the development of orchard flower and fruit management.

Based on relevant reports in the past 20 years, the current level of development of mechanized blossom thinning technologies and equipment in orchards from three aspects: mechanism research, machine development, and intelligent upgrading are discussed. Combining the advantages and disadvantages of the research, the authors propose thoughts and prospects on orchard mechanized blossom thinning.

2. Mechanism Research

2.1. Thinning Force

The process of striking is complicated, which is the dynamic impact, friction, and vibration behavior of a flexible rope interacting with branches, inflorescences, and young fruits of fruit trees. It is difficult to estimate the impact force of the thinning rope on branches and inflorescence, and the damage degree of non-target parts such as branches and leaf buds is also difficult to estimate. Scholars have carried out relevant research on the flexible impact mechanism.

Hu et al. used a universal materials tester to measure the tensile and shear forces of apple branches' pedicel node and receptacles corolla node [13]. After repeated tests, the results showed that the average maximum tensile and shear force of the branches pedicel node in full bloom period were 3.5 N and 2.82 N, respectively. The average maximum tensile force that the receptacles corolla nodes can bear is 1.6 N. Combined with the ADAMS multi-body dynamics simulation, Hu's team also designed a performance test bench for the end actuator of the thinner. They tested the impact force of three kinds of thinning ropes made of a solid rubber strip, hollow vinyl strip, and nylon braid under different lengths, wire diameters, and speeds of the thinning shaft [14][15][16][17][18]. The optimal parameters of the actuator are as follows: the material of the thinning rope is solid rubber, the length is 20 cm, the linear diameter is 5 mm, the rotational speed of the spindle is 960 r/min, and the impact force of the thinning rope on the test branch is 5.39 N. Starting from the mechanical characteristics of peach branches, Yuan et al. obtained the stress curve of the branches and the shear strength of the branches is 6 MPa. Meanwhile, they established a rigid–flexible coupling multi-body dynamics model for the striking force of branches, analyzed the striking force of the thinning rope on branches at different rotational speeds, and concluded that the striking force range of the thinning rope is 3.3–7.6 N when the rotating speed of the spindle is 240–480 r/min [19][20][21]. Assirelli A. et al. studied the thinning power of young peach fruit, when the fruits were 20–40 mm in size and different angles were evaluated to simulate the various ways in which the thinner hits the fruits [22]. The analysis of the different angles showed that, on average, the fruits are detached more easily if the force is applied with a 90° angle, respective to the fruit position on the branch. On the other hand, if the force is applied with an angle of 0°, the average force required is three times higher.

2.2. Thinning Agronomy

The research of the thinning mechanism should not only solve the problem of flexible hitting, but should also solve the problem of thinning agronomy. Due to the different species of fruit trees, the number of flower buds contained in their inflorescence is different, and their agronomic requirements for thinning are also different. The apple, pear, and grape belong to a mixed inflorescence and there are multiple flower buds on one inflorescence, while the peach and nectarine belong to a single inflorescence and there is only one flower bud on one inflorescence. Is the effect of thinning better in the bud stage or in the full bloom stage? Is removing the side flower better than the center flower when thinning the apple tree? What is the appropriate setting for the proportion of inflorescence thinning? Relevant scholars have conducted research on such thinning agronomic issues.

Sidhu et al. compared artificial bud extinction and blossom thinning in the 'Scilate' Apple; the results demonstrated that artificial bud extinction consistently outperformed blossom thinning in terms of an improved fruit set, return bloom, and fruit weight. The fruit quality parameters, such as flesh firmness, total soluble solids, dry matter content, malic acid content, and fruit shape, were also improved under the artificial bud extinction regime [23]. Oliveira et al. evaluate the effect of shoot heading and of thinning in different development stages of flowers and fruits on the fruit production and quality of the 'BRS Kampai' peach. The results showed that thinning during flowering and at the beginning of fruit growth increases the fruit size, and that shoot heading reduces plant production, but does not significantly increase the fruit size [24]. Szot et al. evaluate the effect of the crop load, thinning practices, and position in the tree crown on the quantity and quality of the 'Szampion' apple [25]. The thinning treatments were performed at the pink bud stage and full bloom stage, leaving only the king flower or lateral flower. The best results in terms of the regularity of yielding and high-quality fruits after thinning at the pink bud stage to the king flower were obtained. Han et al. studied the effects of berry thinning on bunch compactness, grape sugar accumulation, and subsequent wine quality in the Vitis vinifera L. Cabernet Sauvignon [26]. Based on the decreasing proportion of berries in one bunch, the treatment was designated as a 25% decrease and a 50% decrease. The results showed that the different berry thinning treatment lowered bunch compactness accordingly; the content of sugar, anthocyanins, total phenols, and the mass of mature berries were all significantly enhanced with a decreasing compactness at the same harvested time. Nie et al. studied the effects of blossom thinning on the fruit setting rate and fruit quality of apple inflorescences at different periods [27]. The test results showed that the thinning technique had a better fruit setting rate of apple inflorescences, fruit weight per fruit, color index, finish index, and soluble solid content than the traditional technique. Hua et al. took the Tainong No. 1 mango tree, aged 6 to 8 years, as the test material to study the optimal date of blossom thinning of the mango. The test results showed that the blossom thinning effect was better at the early bloom stage [28].

2.3. Thinning Model

In order to study the relationship between thinning and fruit yield, relevant scholars established the fruit tree growth model and theory. Iwanami et al. developed a theoretical model using the 'Fuji' apple to explain the relationships among the timing of thinning, crop load, fruit weight, and bloom return [29]. The rate of flower-bud formation in the current year could be explained by a regression model of the timing of the thinning, crop load, and rate of flower-bud formation in the previous year. The fruit weight in the current year could be explained by a regression model of the timing of the thinning, crop load, rate of flower-bud formation, and shoot length in the current year and the previous year. Pellerin et al. proposes that thinning is a partial transfer of potential flower buds from one year to the next year and estimates the maximum repeatable sequence of flower buds without biennial bearing [30]. Manfrini et al. investigate the feasibility of a spatial analysis in apple orchards to assist growers with decision making [31]. A variation in the spatial distribution of the fruit load prior to the thinning was observed, indicating a possibility to spatially and differentially manage the orchard. No spatial variation in the fruit number was observed prior to the harvest, indicating that thinning had removed the previously-observed spatial variation in the crop load. Reginato et al. assessed the relationship between crop load and fruit size or crop load and yield efficiency by a regression analysis for nectarines and cling peaches [32]. With this methodology, the predicted crop value can be established for different growing conditions leading to an improved crop load management. This will permit growers to optimize the net return that can be obtained for a specific orchard. Understanding how crop value is affected by crop load for different cultivars can lead to better decisions in the design and establishment of new orchards.

3. Machine Development

3.1. Hand-Held Thinner

The hand-held thinner belongs to the semi-mechanized orchard management equipment, which is mainly composed of an energy supply device, operating lever, and thinning action actuator. According to the operating principle of the thinning action actuator, it can be divided into three kinds: an impact type, finger brush type, and vibration type. During the operation, the operator holds the operation lever and thins the target's inflorescences, or vibrates the canopy branches according to the agronomic requirements of the fruit tree to reduce the blossoms and fruits. The operator determines the percentage of inflorescences and young fruits that need to be removed by subjectively judging. Because of the small structure and portability, operators can directly carry the work in hand. The hand-held thinner is mainly suitable for traditional old orchards with a messy canopy structure, especially in the interior and top of the canopy.

The string type thinner is widely used, and there are many marketable products. It is controlled by a DC motor to control the speed of the spindle, so as to control the hitting force of the rope on the target inflorescence. The electric hand-held blossom thinner made by Infaco Co. Ltd. (Cahuzac sur Vère, France) has a rotary head with a five-finger comb and is powered by a 48 V electric motor; it was equipped with a portable battery bag which facilitated worker mobility in the field [33]. The orchard blossom thinner made by Cinch Co. Ltd. (Shelby Township, MI, USA) has two types of electric and manual for customers to choose; the installation hole on the spindle is reserved for the rope and is used to adjust the density of the rope according to the flower intensity. It is used on peach, cherry, apple, plum, apricot, and nectarine varietals [34]. The AF 100 electronic blossom/young fruit thinner made by Lakewoodproducts Co. Ltd. (Wellington, New Zealand) is particularly effective with stone fruit, such as nectarines, apricots, peaches, and plums. Its loop is made from high strength flexible rubber fitted on a shaft and the rubber loops will adapt to the location to remove the blossom without damaging the leaves or bark [35]. For the electric finger blossom/young fruit thinner, the rotation of the finger dial was controlled by the motor, and the target blossom/young fruit falls off in the friction and impact action with the finger brush. The Giulivo-plus electric finger thinner, made by Volpi Co. Ltd. (Casalromano, Italy), had a head with six rotating fingers and was powered by a 12 V electric motor; electricity was supplied by a 12 V, 75 Ah car battery, which remained on the ground, and a 15 m long electric extension cord [36]. For the shaking thinning device, the vibration was formed by the CAM mechanism action, acting on the branches of fruit trees, which is used for picking and thinning small fruit by acting on the branches of fruit trees. The hand-held shaker made by Campagnola Co. Ltd. in Italy is an air compressor which provided pressure between 1.0 and 1.2 MPa. The mobility of this device was limited due, in part, to the presence of the flexible hose that fed the compressed air to the shaker [37].

Relevant scientific research institutions have also designed their own hand-held thinners. Most of them are improved designs of market products and exist in the form of patents. Fruit varieties include citrus, apple, pear, peach, grape, kiwi, grape, etc. The example patent of the hand-held thinner is shown in **Table 2** [38][39][40][41][42][43][44][45][46][47]. Researchers also carried out field tests on the performance of the hand-held thinners. Lei et al. developed a hand-held electric rotating rope blossom thinner for the ‘Cuiguan’ pear orchard: its spindle speed is from 0–900 r/min and extension rod length range is from 0.95 to 1.6 m. Compared with the hand thinning, the thinner can shorten the thinning time of the small canopy layer orchard by 30.71% and the Y-trellis orchard by 48.68%, respectively [48][49]. Wang et al. developed a hand-held mechanical thinning device suitable for the apple, stone fruits, and sweet cherry, with its spindle speed from 500 to 3000 r/min. Field test results indicated that the test device could remove 61.1%, 30.8%, and 18.0% of flowers on a single branch with a swipe of around 0.5 m/s under high, medium, and low speed settings, respectively [50][51]. Martin et al. tested the Giulivo-plus electric finger thinner and the Campagnola hand-held shaker on a peach tree. The results indicated that the finger thinner reduced the time by 46% and the shaker reduced the time by 28%; two thinners reduced the crop load by 38% and increased the mass of the fruit by 47% at harvest compared to non-thinned trees [52]. After that, Martin et al. developed a hand-held fruit thinner prototype: it had a rotating cylinder with 10 flexible cords, placed at the top of a pole 2 m in length. They carried out a field test with the Infaco and Giulivo-plus thinner in peach orchards; there is no differences among them in terms of thinning time and the number of fruits per cm^2 of the trunk cross-sectional area at harvesting. Hand thinning took 385 h/ha, and mechanical thinning reduced this time by 89%. The cost of hand thinning was 4.8 €/tree, whereas the cost of mechanical thinning ranged from 0.4 to 1.1 €/tree [53][54]. Spornberger et al. tested the portable thinner and manual thinning in organically managed cherry orchards at the stage of a pea size; the portable thinner showed a high thinning effect, and because of lower costs, it is more suitable for farmers than the hand thinning of flowers or fruits [55].

3.2. Tractor-Mounted Thinner

The tractor-mounted thinner belongs to the mechanized blossom and fruit management equipment. The whole machine is operated by the tractor and the rotating power of the spindle is provided by the tractor hydraulic mechanism. The marketable productions are divided into three kinds according to the structure of the thinning arm: the single spindle, multiple spindles, and horizontal rotary spindle. The working mechanism between the thinning rope and the inflorescence is that of the hitting, rubbing, and vibrating. According to the fruit species, crown type, and other agronomic parameters, operators adjust the tractor advancing speed, the spindle operation angle, the spindle rotational speed, and the density of the thinning rope, so as to reasonably select the thinning intensity. The tractor-mounted thinner is mainly suitable for orchards with the same crown structure, such as the hedge type, trunk type, and V-type.

At present, the Darwin series orchard single spindle string blossom thinner made by Fruit Tec Co., Ltd. is the mainstream one in the market. The Darwin S is mounted on the front of the tractor, so a better view of the spindle is ensured and thus, the operator can guide the spindle more easily on the tree canopy. The spindle rotational speed can be comfortably and continuously adjusted with buttons on the control unit in the driver's cabin to be optimally adapted to the driving speed. The Darwin PT is attached to a front loader directly and is designed to work mainly in the V-type canopy tree. The spindle has a tilt angle of 180°; this allows it to be lifted to the height of the tree-tops and work horizontally over the trees. If the vase trees are very wide, there is also the possibility of tilting the spindle into the tree's interior. The Darwin SmaArt replaces the subjective estimation of the blooming strength with the eye with objective detection by camera. To do this, a camera in front of the thinning spindle detects the blossom density of each individual tree and passes on the data to the on-board computer in real time. Using a thinning algorithm, the computer then calculates the optimum spindle speed and controls the thinning unit. As an option, the system can be combined with a GPS receiver. Using the GPS system, it is possible to detect each individual tree and to assign the data, such as the number of blossoms and the spindle speed, to the tree and to compare it later with the yield data.

In recent years, scholars have carried out a large number of tests in apple, peach, and plum orchards with the Darwin series thinner. The range of the optimal working speed is 6 to 18 km/h, and the range of the spindle rotation speed is 150 to 450 r/min. Accurate working parameters need to be obtained in the field according to the fruit tree species, the shape of the canopy, and the period of blossom thinning. Wallis et al. evaluated the risk of fire blight development and spread after Darwin 300 blossom thinning in apple orchards. The results demonstrate that the use of the thinner should, therefore, be limited to orchards with no history of disease in the last 3 years and on days when predicted weather is not suitable for tree infection; there is a low risk for fire blight development and spread by mechanical thinning under an early blossom stage, especially when paired with a subsequent bactericide application [56][57]. Penzel et al. translated the Darwin 250 spindle rotational frequency to average kinetic energy. At a high flower set, thinning treatments of 0.23 J and 0.33 J were adequate settings to reduce crop load in 'Elstar' and 0.33 J in 'Gala' without yield loss [58]. Lordan et al. evaluated the working performance of Darwin 250 in 'Gala', 'Golden Delicious', and 'Fuji' apple orchards; two prediction models were developed to adjust the right tractor and spindle rotational speeds depending on the initial number of flower clusters [59]. Theron et al. evaluated chemical thinning with the Darwin thinner during the plum blossom stage; the method increased the fruit drop, fruit size, and fruit weight [60]. Cline et al. tested the Darwin 300 and hand thinning in apple and peach orchards; the result showed that mechanical thinning represents a viable method for initial crop load reduction, coupled with hand thinning after fruit, set to reach a final optimal production [61][62]. Baugher et al. tested the Darwin 300 in V-shaped and open-center trained peach orchards; they demonstrated that the mechanical thinner reduces labor requirements and improves fruit size [63][64][65][66][67].

Other companies also make related productions, such as the Eclairvale series orchard thinner made by La Canne Vale Co., Ltd. (Narbonne, France) [68]. The machine can be adopted to be both semi-mounted and mounted, to perform the thinning operation adequately: the total mass of the tractor with or without front ballast must guarantee the stability of a 3 m rear overhang. It has a freely rotating rotor onto which semi-rigid rods are attached. Its rotation occurs through the penetration of the rods into the canopy and the advancement of the tractor, which induces a slow rotation and rubbing of the rods against the branches, which causes some of the blossom or green fruit to fall. Rods are made of flexible glass fibers with a soft plastic end cap; it is the only wearing part and each rod can be easily replaced in less than one minute. Assirelli et al. tested the Eclairvale thinner in apricot and peach orchards [69][70][71]. In the apricot, the machine removed 20.8% of flowers and 43.6% of fruit, allowing 48% time-saving in the follow-up fruit manual thinning as compared with the hand thinning. In the peach, mechanical thinning at blooming time removed 63% of flowers, allowing 42.4% time-saving in the follow-up fruit manual thinning as compared with the hand thinning. Fruit damages always remained below the economic thresholds to marketable production or to the plant.

The FLEXITREE three-arm blossom thinner made by Clemens Co. Ltd. (Wittlich, Germany), which is linked in front of a tractor [72]. Three arms are installed flexibly in different positions of the vertical rod and its structure can be changed by adjusting, which has the advantage of more penetration into the canopy. The device is flexibly configurable and can be perfectly adapted to the crown structure and different tree heights by means of various adjustment options. Lei et al. designed a three-arm tractor-mounted flower thinner named TTBT-300 for ‘Y’ trellis and trunk-type pear orchards; the field test showed that the thinner can save at least 60% of artificial fruit thinning time and the profitable area was 0.58 hm^2 [73][74]. Blanke et al. designed a three-arm tractor-mounted flower thinner named Bonner for plums and apples. In the plum orchard, the yield of Class one fruits increased per tree from 47% in the un-thinned controls up to 69%; the fruit mass was enlarged from 28 g in the un-thinned control to 30–32 g [75][76]. In the apple orchard, the portion of Class one fruits bigger than 70 mm was increased by 10% without yield loss and it reduced the subsequent hand thinning by, respectively, 32.5% [77][78]. They also proposed an integrated coefficient of thinning (ICT) to develop the critical parameters of the machine. The optimum values are 10–40, where an ICT > 50 led to tree damage and ICT < 8 led to sub-optimum thinning efficacy [79][80].

The spiked-drum shaker made by the United States Department of Agriculture consisted of several panels of radially spaced nylon rods bolted to plates on a central spindle. Schupp et al. evaluated the double spiked-drum shaker on the peach; it reduced peach crop load by an average of 36%, decreased follow-up hand thinning time by 20% to 42%, and increased fruit in higher market value size categories by 35% [81]. Miller et al. evaluated the single and double spiked-drum shaker on the peach to reduce the cost and time required for hand thinning peaches. At the 60% full blossom stage, the double-spiked drum shaker reduced crop load by 27% and the single spiked-drum shaker reduced crop load by 9%; they removed an average of 37% of the green fruit [82].

The one-rotor orchard horizontal rotary thinner made by Phil Brown Welding Co. Ltd. can be carried on a standard forklift tractor [83]. The rotor was driven by a hydraulic with a variable speed, and the ropes can be easily replaced when worn. Aasted et al. developed a system using an LIDAR to sense the canopy and automatically control the position of a modified Darwin string thinner position to maintain engagement [84]. They found that the laser control system performed similarly to the joystick control for the blossom counts. Though the laser system was slightly less engaged on the lower canopy, the overall scaffold performance was much closer. Lyons et al. developed a visual blossom thinning system [85]. It consisted of kinematic targeting and heuristic programming, a robotic arm, and a pomologically designed end-effector. The robotic arm had a consistent range of −1.26 cm to +1.57 cm vector magnitude per target location, and the end-effector brushes had a consistent range of −2.97 cm to +3.04 cm per target location. Li et al. developed a profiling control system for the litchi blossom thinner; the spatial position of the spindle could be adjusted by the translational screw and profile adjusting screw. The test results show that the dynamic mean errors of the translational screw and profile adjusting screw were 0.17 and 0.07 cm, respectively; the actuators have good position-adjusting accuracy and the proposed profiling control system can meet the requirements of real-time control [86][87]. Wouters et al. established a set of multi-spectral camera systems for the detection of pear inflorescence, which can identify pear inflorescence in six bands of visible and near infrared spectra [88]. The test results show that approximately 87% of the visible floral buds were detected correctly with a low false discovery rate (<16%).

There are mainly four kinds: the single spindle string thinner has an angle adjusting device, multi-arm profiling thinner, multi-sensors automatic thinner, and machine vision intelligent thinner. The blossom thinner angle adjusting device is designed for the single spindle string thinner, aiming at adjusting the spindle angle to adapt to different tree canopies. The multi-arm profiling thinner is a pure mechanism innovation model, which realizes fruit tree canopy profiling through mechanism deformation. The multi-sensors automatic thinner adds sensors such as the radar, infrared probe, and ultrasonic probe to the existing blossom thinning equipment to realize the operation of the spindle angle and rotation speed adjusting. The machine vision intelligent thinner is a kind of intelligent blossom thinning equipment, which replaces human eyes with a high-definition camera, replaces the human brain with a deep learning convolutional neural network, and replaces the human hand with a mechanical flower thinning arm. At present, most of the patented products are a conceptual design, which has a certain theoretical basis. Some prototypes have been successfully developed, but there is still a certain distance to commercialization.

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