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Kinematic model for mechanical apple blossom thinning

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Abstract

The international apple trade requires apples with diameters of over 70 mm. Left untouched, apple trees tend to produce many apples of small diameter. To increase apple size, the number of blossoms can be reduced in their early growth stage, leaving fewer apples that will grow larger because of access to a greater portion of nutrients. Over the past few decades this has been mainly accomplished through chemical means, but recent demand for sustainable fruit production with fewer chemicals requires means of blossom thinning using, *e.g.*, mechanical methods, *i.e.*, a machine with rotors and brushes. The goal of this project was to perform kinematic analysis on such a mechanical thinning machine to model the motion and behavior, both mathematically and graphically, as well as offer recommendations of operating parameters to maximize the machine's efficiency. The project involved creating and assembling a three-dimensional model of the machine in Pro/ENGINEER, performing kinematic analysis on the model, using the output to produce a mathematical formula, and using that formula to both analyze and predict the operation of the machine. The mathematical model was verified successfully against field test data. It was then used to provide tractor and rotor speeds for a range of desired percentage of blossoms removed. It also accomplished the reverse, predicting the percentage of blossoms removed for a series of chosen tractor and rotor speeds.

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Introduction

Fruit trees cannot support all the flowers and fruits until harvest in terms of photosynthesis, photoassimilates and carbohydrate and nutrient supply (Untiedt & Blanke, 2001). Hence, removal of excess flowers or fruit is a prerequisite for regular yields of high-quality fruit (size, diameter, coloration, firmness and sugar) and relevant in preventing or breaking alternate (biennial) bearing, *i.e.* the sequence of years with high and low yield (Krasniqi *et al.,* 2013). The international apple market requires dessert apple fruit to be 70 mm or above in diameter (Seehuber *et al.,* 2011); the vast majority of apples from an uncontrolled, *i.e.*, un-thinned fruit tree will be much smaller than 70 mm. One effective solution to this problem is to reduce the number of apple blossoms at an early developmental stage, resulting in each apple fruit having access to a larger share of the tree's carbohydrates. While thinning can reduce the yield of the tree in terms of numbers of apples, even with a lower number of apples the portion of fruit larger than the critical 70 mm diameter provides a substantial increase in financial returns (Seehuber *et al.,* 2011).

The use of thinning chemicals is often unwanted, as some of them can be classified as 'hormones' and alert negative consumer awareness (Netsawang *et al.,* 2023). The efficacy of some chemical thinning agents is temperature dependent (Costa *et al*., 2013), thereby excluding locations or years with a cold spring and may also depend on tree age and variety. Mechanical thinning has long been used with young fruits *e.g.*, olives, using simple manual tools like whips. Automated mechanical thinning at the flowering stage by a machine appears as an alternative to chemical thinning, which may be a suitable sustainable practice with minimal damage to the tree for both integrated fruit production and organic farming. The current emphasis in agriculture is on sustainability, the implementation of the EU Green Deal (2023). In the United States, the ban on carbaryl is expected (Hehnen *et al*., 2012), an insecticide with critical use at flowering at a time, when pollinators are required. The combination of such a mechanical thinning device with additional hand-thinning after June drop is a further possibility for increasing the number of acceptably sized, high-quality apple fruits. Apple was used here as a model crop, but the same system can be used for a wide range of other fruit trees such as pear, peach, apricot and plum. In order to achieve high-quality large fruit, the first aim of this study was to mechanical thin flowers evenly from all parts of the tree canopy, particularly the inner, poorly illuminated parts. As a consequence, the inner shaded canopy receives fewer photo-assimilates from leaf photosynthesis, resulting in fruits of smaller size, less coloration, more firmness, and less sugar. The second aim was to analyze test data taken from field experiments to develop a 3D model to simulate its kinematic behavior and then correlate the two results with an equation.

Materials and Methods

Device description

This thinning device was developed at the University of Bonn, patented and under trial at horticultural research stations (Damerow and Blanke, 2009; Seehuber *et al*., 2011). It is comprised of a ca. 3.0 m tall, vertical square beam with three horizontal arms and variable angle (alpha) rotors arranged vertically on top of one another (Figure 1).

Each of the rotor arms can be adjusted vertically from a height of 0.50-2.30 m (attachment points), measured from the ground, allowing for adaptation on the type of fruit tree and for a vertical coverage of the tree canopy ranging from 0.25-3.25 m. Radiating from four sides of each rotor at right angles are forty 0.35 m long 3 mm diameter, stiff plastic tines (duroplast) that act as whips when passing through the trees. The device was mounted on the front hitch of a tractor and the rotors are actuated by the tractor's hydraulic system. The device fits the majority of horticultural tractors (narrow track) with a front three-point hitch and hydraulic capacity of 100 L/h.

A spring mechanism is built in to allow the rotor arms to retract if the rotors encounter immovable objects like tree trunks or tree stakes. Because of variable field and tree conditions, many settings on the device were designed to be changeable. A top view of the design of the device is shown in Figure 2.

Field evaluation and data analysis

The mechanical blossom thinning device was tested during three growing seasons at the University of Bonn Research Center Campus Klein-Altendorf, Germany on an eleven-year-old apple cv. 'Braeburn' trees with a tree spacing of 1.2 m × 3.5 m during flowering at growth stage BBCH 60-65 (first flower open to full bloom).

Programming of the kinematics of the rotors and brushes in the tree canopy

A three-dimensional model of the apple blossom thinning machine was designed using the computer-aided design and analysis software Pro/ENGINEER™ (CAD-Schroer Ltd, Moers, Germany). The program code provides kinematic analysis and visualizations such as 2D projections *e.g*., the rotor motion of this thinning device. The model was calibrated using test data collected when removing apple blossoms with the thinning machine. Subsequently, the model output was used to evaluate numerical results such as thinning efficacy and provided recommendations as to input variables such as rotor speed. This is to thin apple flowers more selectively in various parts of the tree canopy and optimize tractor and rotor speed.

The kinematics of moving robots (Hiraoka *et al.,* 2023) or rotors and brushes in the tree are symbolized using cycloids (Eckhardt, 1998). The objective of this project was to analyze test data taken from field experiments to develop a 3D model to simulate its kinematic behavior and then correlate the two results with an equation. The model was created in Pro/ENGINEER Wildfire 2.0 with the built-in 'Mechanism' sub-utility, which allows the model to be animated and analyzed kinematically. The model allowed the visualization of the movement of the tine tips in the form of cycloid diagrams to show their 2D projected motion. Once the equation and cycloid output graphs from the Pro/E model were

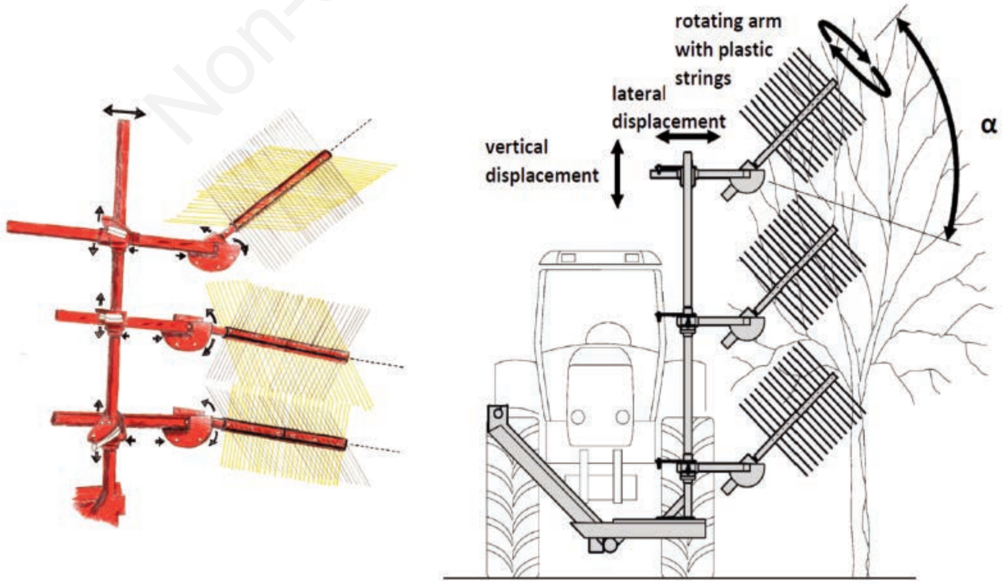

Figure 1. Front view of the mechanical thinning device showing the position of the device with its arms mounted at the front hitch of the tractor and the vertical variable angle alpha.

verified against the field test data, the prediction of further scenarios, not covered in field testing, became possible.

Parameters

Each rotor shaft has two degrees of freedom - rotation about its own axis to allow the plastic tines to strike the blossoms and angular translation with respect to the vertical (alpha, Figure 1) horizontal (beta, Figure 2) plane. These two degrees of freedom were left unconstrained and the other four were fixed, making the rotor behave realistically.

The suitable feature of Pro/E in terms of this project was its numerical and graphical output from the 'Mechanism' subroutine. The trajectories of the endpoint of the tines were modeled. The model was programmed to record the three-dimensional position of the trajectory marker throughout the duration of each analysis test; an example of the analysis is shown in (Figure 3). Projected onto a two-dimensional graph, with the direction of the tractor's travel on the horizontal axis and vertical dimensions of the track on the vertical axis, this trajectory visualized a series of cycloids.

Results

Correlation equation

To evaluate the percentage and location of apple blossoms removed for a range of rotor speeds, the *in-situ* field results were correlated with the cycloid graphs from the modeling. These field data showed a linear relationship (Figure 3) within the employed range from 300 rpm to 420 rpm between the input (rotor speed) and output (percentage flower blossoms removed). The implied linear correlation is expressed as equation 1.

$$C = m \cdot n + d \tag{1}$$

In equation 1, C (removed blossoms) is the dependent variable on the y-axis, m is the slope, n is the independent variable on the x-axis (rotor speed), and d is the constant y-intercept value. The output C and y-intercept d were desired to be in percentage blossoms removed and the input n in rotor rpm. The slope m therefore had to have the units of percentage blossoms removed per rpm. In modifying the equation for use in this project, the y-intercept term d is zero. In order to take both the field results and theoretical Pro/ENGINEER model's results into account to form equation 1 as well as to obtain the correct units of m, the slope m in equation 1 was further refined as equation 2.

$$C = (d/v)(A \cdot K) \cdot n \tag{2}$$

where C = percentage of removed flowers (maximum <55%)
d = constant = 2.5 (we leave d at =1 (=omit) or d=1.5, or d=2.0)
v = tractor speed or velocity (minimum 2.5 km/h)
A = slope of the curve from field data (from equation 4)
K = slope of the desired curve (from equation 3)
n = rotor speed (maximum 500 rpm)

In equation 2, C remains the output in percentage blossoms removed and the input remains n in units of rpm. The slope m is replaced by the term $(d/v)(A \times K)$. The term (d/v) is for calibration purposes, where d is a constant and v remains a variable that takes the value of the particular tractor speed being modeled. Since the variable v is in the denominator, the percentage of blossoms removed will decrease as tractor speed increases. This is in contrast to the variable n (rotor speed), which, when increased, causes an increase in the number of blossoms removed.

The constant K is the slope of the linear relationship within the theoretical model between the number of data points taken and the input rotor speed with units of data points per rpm. The constant A originates from the field test results and the Pro/ENGINEER model and is in units of percentage blossoms removed per data point. The model was programmed to take one data point, or tracing coordinate, every 10 degrees of angular rotation by the rotor with one full rotation by the rotor corresponding to 36 data points.

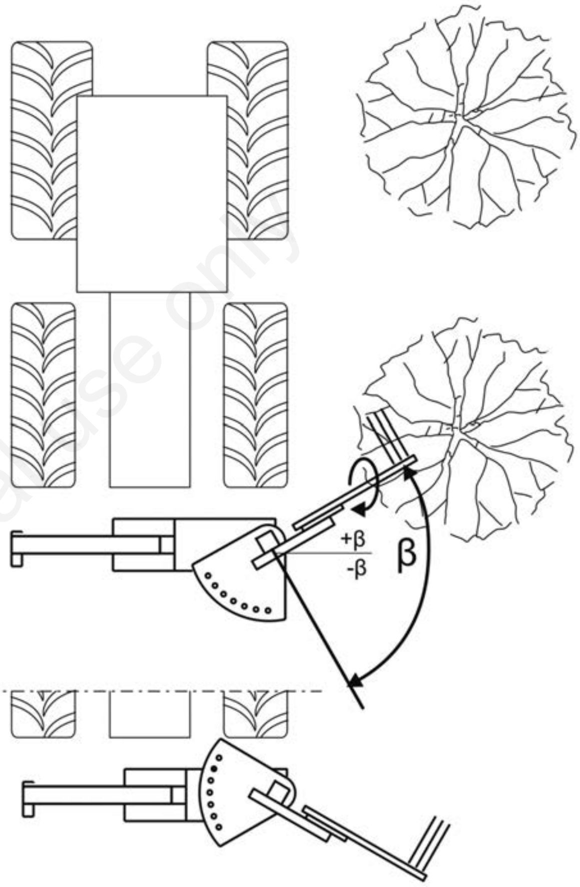

Figure 2. Top-view of the mechanical blossom thinner and horizontal variable beta angle.

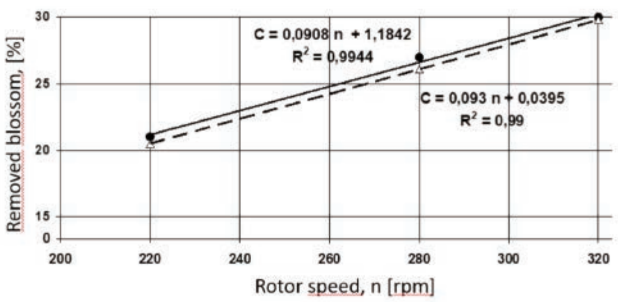

Figure 3. Graphical comparison of theoretical (dotted) and field (continuous) data at 2.5 km/h, where 'C' is % buds removed and 'n' is rotor input speed.

The number of data points varies directly with the input rotor speed. This calculation is shown in equation 3.

$$K = \frac{p_2 - p_1}{n_2 - n_1} \qquad (3)$$

K is the desired slope in data points (p) per rpm (n) and only requires two data points to be calculated. The subscripts 1 and 2 denote any two sets of data run through the theoretical model, provided test 2 has a higher input speed than test 1 to obtain a positive slope.

A represents the component of the slope coming from the field data testing and is shown in equation 4.

$$A = r_i/p_i \qquad (4)$$

A is calculated by dividing the percentage blossoms removed (r) by the number of data points p; an average value of A was used by finding the average of all A_i values (one for each input rpm).

The product of A and K then provides the correct units for the slope, percentage blossoms removed per number of hits, and takes into account data from both the cycloid graphs and field tests. It is important to note that for any set of field data, A and K do not change, which allows the model to predict the output values in percent of blossoms removed for any input rotor speed and any tractor speed. With A and K set, equation 2 thus describes the behavior the machine in the field based on the theoretical Pro/ENGINEER model.

Model correlation constants

To provide the basis for the model's output, the field data shown in Table 1 was used.

The thinning machine was operated at 2.5 km/h with rotor speeds of 220, 280, and 320 rpm. The percentage of flower buds removed was counted manually, with an absolute counting error of +/- 5%. The next step in obtaining a correlation equation was to run the Pro/E model using the same speed parameters from the field test results, *i.e.*, a constant tractor speed of 2.5 km/h and a fixed angle alpha of 60 degrees between the rotor and the ground and perpendicular to the direction of travel. To explore the K for 2.5 km/h, the model was run at 220 rpm and 280 rpm, the first two speeds of field testing. Each test lasted 8.64 seconds, corresponding to 6 meters of distance traveled by tractor, and resulted in 1142 data points for 220 rpm, 1452 data points for 280 rpm and 1662 for 320 rpm.

K was calculated by using these two data sets and equation 3 and resulted in 5.17 data points per each rotation. The values were combined through equation 4 to obtain an average value of A (Table 1).

Since all these points were taken at a tractor speed of 2.5 km/h, the variable d becomes 2.5 km/h. Inserting these three constants into equation 2, a new formula, equation 5, becomes the model for the mechanism at any tractor speed and any rotational speed.

$$C = \frac{0.233 \cdot n}{v} \qquad (5)$$

Verification of model-to-field results

With the correlation equation (equation 5) defined, the verification of the theoretical results against field testing results could be carried out. The field results were measured for rotor speeds of 220, 280, and 320 rpm and those n values and a common speed v of 2.5 km/h were substituted into equation 5. The theoretical results obtained are compared to the field data results in Table 2 At a rotor speed of 220 rpm, the field value of the percentage of buds removed was 33.5%, while the model predicted 39.4%. The absolute error between the two, 5.9%, was the highest at this value. At 280 rpm the field value was 55.5% and the model's was 50.1%, giving a 5.4% error. At 320 rpm the field value was 60.0% and the model's was 57.3%, yielding the smallest error of the three results at only 2.7%. Figure 3 shows these field points plotted on the same graph as the correlation curve. As the error in field data was given as +/- 5% (absolute) of buds removed, the theoretical curve was deemed a valid fit, because points at 220 rpm and 280 rpm both lie less than 1% outside of that range. The value at 320 rpm, 2.7% absolute error, lies comfortably within that range. This also confirms the assumption that the output of the process could be modeled linearly.

The Pro/E model is not only able to output the number of points produced, but also an exact trace (trajectory) of a single point defined at the end of one of the rotor strings. The trajectory of this point, as if viewed from the side and watching the tractor pass in front of the viewer from left to right, is shown in Figure 4. The cycloid plots for 280 and 320 rpm were both similar to Figure 4 (result not shown). The cycloid of the lower rotor

Table 1. Tabulated field test results (percentage blossoms removed) and correlation A between flower buds removed and data points.

Rotor speed [rpm]	Percentage blossoms removed*	Flower buds removed/ data points
220	33.5	0.0293
280	55.5	0.0382
320	30	0.036

*Uncertainty +/- 5% of buds removed average A value 0.0346.

Table 2. Tabulated field test results (percentage blossoms removed) and correlation A between flower buds removed and data points.

Rotor speed [rpm]	Theoretical buds removed, %	Field tested bud removal, %	Difference (absolute)	Difference (relative)
220 rpm	39.4	33.5	5.9	17.6
280 rpm	50.1	55.5	5.4	9.7
320 rpm	57.3	60.0	2.7	4.5

(Figure 4) ranged from a low of 0.82 m to a high of 1.24 m, covering a height of 0.42 m. Even though the tractor traveled a distance of exactly 6 m, because of its position at the end of one of the strings, the trajectory point traveled a horizontal distance of 6.6 m. To show the effect of all three rotors being in operation, Figure 5 includes data for a trajectory point of the three rotors at three different heights at 220 rpm and 2.5 km/h.

A more complete operating range of the machine is evident. The range now extends from 0.82 m as the lowest point being worked to 2.08 m at the highest point. Each rotor accounts for one third of the range, with a negligible overlap of 0.02 m. Since each rotor is rotating at the same speed, all three cycloids are in phase and differ only in their relative height from the ground. Any angle or distance variable in the setup of the machine could be varied to provide the operator with an exact picture of the working range. Since tree heights vary from orchard to orchard, graphs such as Figure 5 may be used as a guide to machine mount settings without requiring pretesting. Also, this would make the machine easily adjustable to different tree training (slender spindle, tall spindle, fruit wall), or other fruits such as plum (Lammerich *et al.,* 2020) or peach (Schupp *et al.,* 2008).

Manipulation of rotor and tractor speed

With the model now calibrated and successfully verified against field data, it was possible to use it to explore the effects of changing both rotor and tractor speeds. The tractor speed parameters were chosen as 2.5, 4.0 and 5.5 km/h and the rotor speed parameters as 200, 300, 400, and 500 rpm. The goal was to obtain the theoretical percentage of buds removed at each combination of tractor and rotor speed, yielding 12 total values. Again, employing equation 5, the results are presented in Table 3. For a tractor speed of 2.5 km/h, the percentage of buds removed ranged from 35.8% at 200 rpm up to 89.4% at 500 rpm. At 4.0 km/h, the range was from 22.4% to 55.9%. At 5.5 km/h, the highest tractor speed, the range was from 16.3% to 40.6%.

The trends show that in all cases, an increase in the rotor's rotational speed corresponded to an increase in the percentage of buds removed. This makes physical sense as the rotor speed increases, the number of cycloids per meter traveled will increase and the speed at which the tines hit the branches and buds will also increase, causing more violent collisions and increasing the number of buds removed. The relation between tractor speed and percentage of buds removed, however, was inverse. As the tractor speed increased, there was a decrease in the percentage of buds removed. This is because the faster the tractor travels, the fewer cycloids will be created per meter and therefore the less time a particular area can be worked. This interesting property that various combinations of tractor and rotor speed can produce the same percentage of buds removed, is worth examining further in field testing to correlate with this model's results. The advantage of this

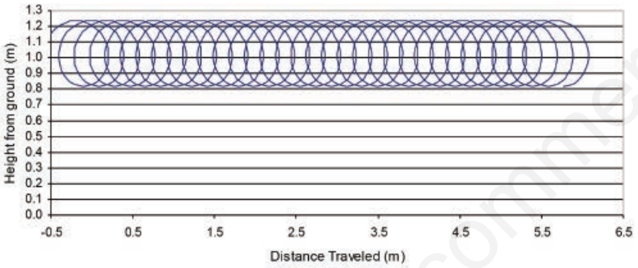

Figure 4. Plot of cycloid trajectories for lower rotor at 220 rpm, tractor speed of 2.5 km/h, yielding 39.4% buds removed.

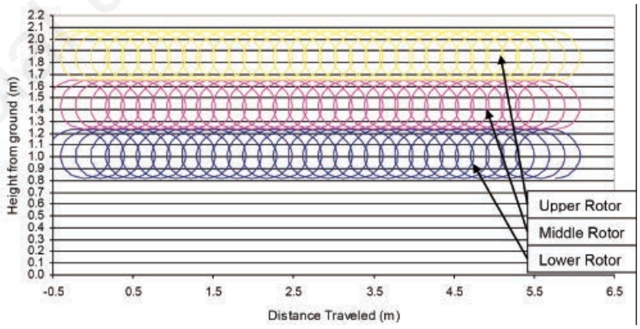

Figure 5. Plot of cycloid trajectories of all three rotors at 2.5 km/h, yielding 39.4% buds removed.

Table 3. Parameter study, relative buds removed at various tractor and rotor speeds.

Rotor speed [rpm]	2.5 km/h, %	4.0 km/h, %	5.5 km/h
200 rpm	35.8	22.4	16.3%
300 rpm	53.6	33.5	24.4%
400 rpm	71.5	44.7	32.5%
500 rpm	89.4	55.9	32.5%

Table 4. Correct rotor speeds (in rpm) for desired percentage of buds removed.

Rotor speed [rpm]	2.5 km/h, %	5.0 km/h, %	7.5 km/h
10% removed	56	89	123
20% removed	112	179	246
30% removed	168	268	369
40% removed	224	358	492
50% removed	280	447	615

model can be shown by further parameter studies. As a practical matter, the operator might be interested in knowing how fast to run the rotor speed needs to be to achieve a particular percent reduction in blossoms. Equation 5 can be used for that purpose by substituting two known variables and simply solving for the third. From experience over two growing seasons, the optimal percentage of buds removed for a good combination of apple diameter and tree yield was found to be 30%. Therefore, a testing range including percent of buds removed of 10, 20, 30, 40, and 50% and tractor speeds of 2.5, 5.0, and 7.5 km/h were chosen. The resulting rpm values are shown in Table 4.

A tractor speed of 2.5 km/h yielded a rotor speed range from 56 to 280 rpm over the 10-50% range. The 5.0 km/h speed yielded a rotor speed range from 89 to 447 rpm. The 7.5 km/h tractor speed yielded speeds from 123 to 615 rpm. For the ideal removal of 30%, the corresponding rotor speed for 2.5 km/h was 168 rpm, for 5.0 km/h was 268 rpm, and for 7.5 km/h was 369 rpm.

There are two important realistic considerations an operator will have to make when interpreting Table 4 and when choosing tractor speed and rotor speed parameters. These are the effects on potential tree damage due to excessive rotor speed. The highest rotor speed tested in the field was 320 rpm and it caused 8% leaf damage; it can be speculated that rotor speeds of up to 500 rpm may cause leaf damage of ca. 10%. The benefit of Table 4 is that more tractor speeds could be easily calculated, giving the operator virtually unlimited options for choosing tractor speeds and rotor speeds that are within known safe regions of operation.

Relation between flower buds removed and the yield and final apple fruit size

The content of this paper thus far concentrated on the interaction between tractor and rotor speed and the corresponding output of percentage of buds removed. As was stated in the introduction, however, the end goal is to produce a large portion of apples of acceptable diameter (class I; fruit >70 mm) for economic returns, to satisfy consumer and trade demands, and to avoid alternate bearing. The total process of a deciduous tree, starting from a bare tree in the winter to the harvest in the fall, is composed of many steps. The purpose of this report was to study and analyze the only step where the apple harvest is directly influenced by a mechanical machine, the process of removing a percentage of apple blossoms in the spring. Many other processes occur after this step to influence the harvest, but they are all natural, such as hail and frost as abiotic examples. For example, after the blossom removal, the tree undergoes a June drop for a natural biotic phase in the tree's yearly life cycle where it loses, or aborts, the weakest and smallest fruitlets. This is essentially nature's equivalent process to what the machine accomplishes, ensuring that blossoms with little chance of producing a healthy fruit are jettisoned and no longer take up nutritional resources.

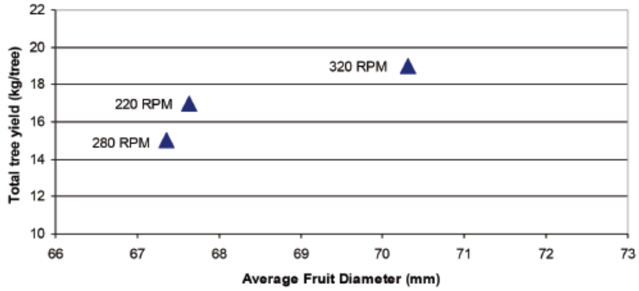

Figure 6. Tree yield versus fruit diameter for field testing at 220, 280, and 320 rpm at 2.5 km/h.

The following information was not modeled by the Pro/E machine but was taken from field data in the first year and does relate the importance of percent of buds removed to apple size. The data in Figure 6, taken from the field results, show the relationship between rotor speed and tree output.

The horizontal axis shows fruit diameter while the vertical axis represents yield per tree (the values at each of the three tested speeds are shown next to the data points). There is very little difference between the average diameter of apples between 220 and 280 rpm as they differ by less than half of a millimeter. The yield for both is also very close, with 220 rpm giving 17 kg/tree and 280 rpm giving 15 kg/tree. For 320 rpm, the yield was ca. 18 kg/tree near the optimum crop load for spindle-trained apple trees (Krasniqi *et al.*, 2013) and an average apple diameter of 70.5 mm.

While tree yield is a factor, the most important outcome is the fruit diameter. Of the three speeds in the graph, the 320 rpm point was highest in both tree yield and fruit diameter and was the sole speed, which yielded a fruit size over the desired 70 mm diameter.

Discussion

As there is no comparative simulation of any mechanical thinning device to our knowledge, discussion of the kinematic model and its trajectories does not apply.

However, two constraints arise from the interactions between the tree and the machine. During the blossom thinning process, these two possible concerns are damage to the machine and damage to the tree. The design of the machine includes safety features like spring releases on the rotors to allow the rotor arms to bend around immovable objects. Thus, there is relatively little worry about damage to the actual machine structure, and with the considered rotor speeds to the operator and people in the orchard, as the operator controls the device in his view angle in the front the tractor. The rotor tines are made of tough, flexible plastic that are in no immediate danger of being damaged while passing through the tree branches and can be replaced on wear. The main concern in the apparatus therefore is the health of the blossoms and first leaves that remain on the tree. The ideal would be to remove a certain percentage of blossoms and leave the remaining blossoms and these primary leaves with absolutely no damage so they can produce the best and healthiest apples possible. However, slight leaf, blossom, and branch damage are inevitable so a possible constraint is to keep the tractor and rotor speeds at levels where the damage is acceptable. During field tests, a combination of a tractor speed of 2.5 km/h and a rotor speed of 320 rpm produced leaf damage of 8%, *i.e.*, below the acceptable 10% damage to these primary leaves supplying the first photoassimilates after bud break meaning that combination of tractor and rotor speed values is nearing the upper limit. On the lower end, since the field data run at 220 rpm already produced only marginally effective results, no speeds under 200 rpm were evaluated. Overall, the final range of inputs for rotor speed was chosen to be 200-500 rpm with tractor speeds of 2.5, 4 and 5 km/h.

Conclusions

The major objective of this project was to create a working kinematic model of the apple tree thinning device, whose output could be used to create an equation, which then models the percentage of buds removed during the thinning operation. This equation was verified and validated against field data and agreed with an absolute error of less than 6% in buds removed for all field data test points. It was then used to predict the percentage of buds removed at three different tractor speeds and four different rotor speeds. As a practical guide for farmers, the equation was further refined to provide the machine operator with information about which combinations of tractor and rotor speeds could be used to produce the desired percentage of buds removed.

From the data taken used for this project, it was determined that a tractor speed of 2.5 km/h and a rotor speed of 320 rpm delivered an average fruit diameter of the correct diameter of over 70 mm. The kinematic analysis can provide the percentage of buds removed for any tractor and rotor speed combination.

The device is easy to handle, economical and environment-friendly but restricted to the time between flower bud and the end of flowering.

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