MECHANICAL RASPBERRY HARVESTING

BY

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ABSTRACT

Raspberry growers in the lower mainland of British Columbia are contending with increasing production costs and are facing problems in obtaining seasonal labour for fruit picking. Since cost of hand harvesting represents a large proportion of the total production cost, the purpose of this research was to investigate the feasibility of mechanical raspberry harvesting and to design a mechanical harvesting system suitable for the lower mainland of British Columbia.

A systematic design procedure, oriented toward design and testing of a bio-machine system, was employed and the selected design was based upon the physical and mechanical properties of the raspberry plant and its fruit. An economic analysis, comparing the mechanical harvesting system to present hand harvesting methods was used to determine the necessary relationships among machine cost, machine capacity and machine efficiency. The selected design for a mechanical raspberry harvesting system included tools for feeding, cane orientation, selective harvesting, fruit collection, fruit conveying and fruit storage. Mathematical models for these tools were constructed, based on a series of tests determining pertinent physical and mechanical properties of the raspberry plant and fruit. In addition, tests to define fruit quality were undertaken and the relationships among fruit quality and selective harvesting parameters were investigated. The use of chemical growth regulators to alter fruit retention force was also investigated.
Force-deformation moduli, resulting from flat plate compression tests of raspberry fruit, were found to be good indicators of fruit quality. Correlations among force-deformation moduli and fruit properties indicated that either fruit retention force or F/W ratio could be used as control variables for a selective harvesting tool. Prototype units for feeding, cane orientation and selective harvesting tools were designed and fabricated. The selective harvesting tool was a fixed displacement shaker designed to apply equal maximum acceleration to all fruiting portions of the plant, independent of plant properties. F/W ratio was used as the control variable for selective harvesting.

Limited field testing indicated that the tools for feeding, cane orientation and selective harvesting could satisfactorily be used in a mechanical raspberry harvesting system. Results also indicated that mechanical harvesting could be substantially more profitable than hand harvesting.

The Willamette variety of raspberries as commonly grown in British Columbia was found not especially suitable for mechanical harvesting. Due to the high ratio of fruit retention force to fruit stem strength in the Willamette variety, the quality of machine harvested fruit must be lower than the quality of hand harvested fruit. Since fruit retention force is dependent upon fruit variety, investigation of physical properties of other suitable raspberry varieties should be undertaken in order to find a variety having properties more compatible with mechanical harvesting methods.
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TERMINOLOGY

Abscission layer.- The region on the fruit stem at which natural abscission occurs.

Aggregate fruit.- A fruit formed by the ripening together of a number of separate ovaries, all belonging to a single flower and adhering as a unit on a common receptacle.

Amplitude.- The maximum displacement of an oscillating motion as measured from the mean position.

Analysis of covariance.- The analysis of covariance as used in this study applies to a method of comparing regressions in multiple classifications. If the relation between $Y$ and $X$ is obtained for two individual treatments, the model for the regressions is

$$Y_{ij} = \alpha_i + \beta_i X_{ij} + \xi_{ij}$$

where $i = 1, 2$ denotes the two treatments. The method compares the residual variances $\sigma_1^2$ and $\sigma_2^2$, compares the slopes $\beta_1$ and $\beta_2$, and compares the elevations of the lines $\alpha_1$ and $\alpha_2$. The procedure used is outlined on page 432 of reference (33).

Analysis of variance.- A process by means of which the total variance in a composite sample is apportioned among the different factors responsible for its gross value. See, for example, pages 278 to 436 of reference (28).

Angle modulus.- The angle between the deformation axis and the initial linear portion of the force-deformation curve for raspberry fruit compressed between parallel flat plates at a rate of 2 cm/min.

Base motion.- The type of motion imparted by a vibratory harvesting tool at its point of contact with a plant.

Break-even point.- The minimum necessary fruit removal efficiency, in percent of gross fruit yield, which must be achieved by a mechanical harvesting machine, in order to obtain the same gross income from mechanical harvesting as is presently obtained from hand harvesting.

Bruising.- Damage to plant tissue by external forces causing change in texture and/or eventual chemical alteration of color, flavour and texture. Bruising does not break the skin. In this study, bruise damage was evaluated one-half hour after loading and was reported in terms of the maximum depth and mean width of the bruised tissue.
Cane.- The woody, productive, second-year growth of the raspberry plant.

Cane taper.- When considering a specific length of cane, cane taper is defined as the mean radius of the cross-section of the small end of the cane divided by the mean radius of the cross-section of the large end of the cane.

Coefficient of determination.- In simple regression, the quantity, \( r^2 \), representing the fraction of the corrected sums of squares that is attributable to simple linear regression. See, for example, page 225 of reference (28).

Coefficient of multiple determination.- In multiple regression, the quantity, \( R^2 \), representing the fraction of the sums of squares of the deviations of \( Y \) from its mean that is attributable to the regression. \( R^2 \) is defined as the sum of squares due to regression divided by the sum of squares about the mean. See, for example, page 402 of reference (33).

Core.- The receptacle on the end of the fruit attachment stem, around which the raspberry fruit grows.

Drupelets.- The individual raspberry fruitlets, each of which are formed from the ripening of separate ovaries. The raspberry fruit consists of a number of loosely bound drupelets attached to a central core.

Field efficiency.- The ratio of effective field capacity to theoretical field capacity.

Fixed displacement shaker.- A vibratory harvesting tool in which the amplitude of the applied base motion is constant.

Fruit firmness.- The resistance to deformation offered by a fruit under compressive load. In this study, the tangent modulus of the force-deformation curve, resulting from compression of the fruit between parallel flat plates at a rate of 2 cm/min, was used as an indicator of fruit firmness.

Fruit retention force.- The tensile force required to remove a raspberry fruit from its core.

Fruit rigidity.- In this study, rigidity was defined as the ability of fruit to transmit mechanical vibrations. The intensity of vibrations transmitted through an individual fruit, compressed with a force of ten grams between two parallel diaphragms, the lower diaphragm being excited at a frequency of 250 Hz, was used as an indicator of fruit rigidity.
Growth regulator.- An organic compound which, when introduced into a plant in a relatively small quantity, induces effects on the growth pattern of the plant.

Inertia shaker.- A vibratory harvesting tool in which the maximum force exerted by the applied base motion is constant.

Linear limit.- The minimum load at which the force-deformation curve, resulting from compressing raspberry fruit between parallel flat plates at a rate of 2 cm/min, becomes non-linear.

Mean.- The arithmetic mean \( \mu \), of a random sample of independent observations.

Multiple correlation coefficient.- The square root, \( R \), of the coefficient of multiple determination.

Picking efficiency.- The percentage of mature fruit on a plant which is removed by a harvester. This is also called the fruit removal efficiency.

PPM.- Parts per million.

Random sample.- A sample consisting of independent observations which are drawn from a population.

Raspberry.- Raspberry, as used in this study, refers to the American red raspberry (family: Rosaceae, genus: Rubus, species: Strigosus, variety: Willamette).

Shoot.- The succulent, non-productive, first year growth of the raspberry plant.

Simple correlation coefficient.- The square root, \( r \), of the coefficient of determination.

Standard deviation.- The standard deviation \( \sigma \), of a random sample of independent observations \( x_i \), defined as

\[
\sigma = \sqrt{\frac{\sum(x_i-\mu)^2}{n-1}}
\]

where \( n \) = the number of observations
\( \mu \) = the sample mean

Stem.- The member attaching a raspberry fruit to an intermediate limb. (See figure 5)

Stroke.- The maximum displacement imparted by the base motion. The stroke is twice the amplitude of the motion.

Tangent modulus.- The tangent of the angle modulus.
Tool. - A device which performs a basic process function.

Trellis. - A supporting framework within a raspberry row.
The purpose of the trellis is to prevent the plants from lodging.
NOMENCLATURE

A Machine purchase price, dollars

$A_p$ Projected fruit area normal to direction of motion

B Number of men required to operate a mechanical harvesting system

C Fruit color index

$[C]$ Flexibility matrix

$C_d$ Overall drag coefficient

$[D]$ Dynamic matrix

$E$ Modulus of elasticity

F Fruit retention force

$F_a$ Force applied to fruit

$F_d$ Minimum force to damage fruit support system or to remove immature fruit

$F_m$ Upper limit of fruit retention force of mature fruit

$F_r$ Drag force

$F/W$ Ratio of fruit retention force to fruit weight

$I_o$ Moment of inertia of cane cross section at soil surface

$I(x)$ Moment of inertia of cane cross section per unit of length

$K$ A modulus relating fruit deformation to compressive load. For this study, $K = 20 \gamma$

$L$ Cane length from soil surface to point of load application

$N_{h}$ Numbers of fruit on one plant in a one-half-foot-thick vertical slice

$N_{v}$ Numbers of fruit on one plant in a one-foot-thick horizontal slice

$O_f$ Annual machine overhead cost, dollars

$O_o$ Hourly operating cost, dollars
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<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Probability level, ((1-\beta)), where (\beta) is the level of significance. (P) is also the type II error.</td>
</tr>
<tr>
<td>(P_c)</td>
<td>Static compressive load applied to fruit</td>
</tr>
<tr>
<td>(P_a)</td>
<td>Concentrated horizontal load applied to a cane</td>
</tr>
<tr>
<td>R</td>
<td>Multiple correlation coefficient</td>
</tr>
<tr>
<td>(R^2)</td>
<td>Coefficient of multiple determination</td>
</tr>
<tr>
<td>S</td>
<td>Forward speed, miles per hour</td>
</tr>
<tr>
<td>(S_y)</td>
<td>Standard error of the estimate</td>
</tr>
<tr>
<td>([S_1])</td>
<td>Sweeping matrix devoid of the fruit mode</td>
</tr>
<tr>
<td>T</td>
<td>Time, days</td>
</tr>
<tr>
<td>V</td>
<td>Relative velocity between falling fruit and surrounding fluid</td>
</tr>
<tr>
<td>(V_a)</td>
<td>Maximum allowable impact velocity of fruit striking a rigid surface</td>
</tr>
<tr>
<td>(V_c)</td>
<td>Upward velocity of air supplied by an air cushioning system</td>
</tr>
<tr>
<td>(V_g)</td>
<td>Forward velocity of machine</td>
</tr>
<tr>
<td>(V_t)</td>
<td>Terminal velocity of falling fruit</td>
</tr>
<tr>
<td>W</td>
<td>Weight of a single fruit</td>
</tr>
<tr>
<td>Y</td>
<td>Dependent variable</td>
</tr>
<tr>
<td>Z</td>
<td>Mode of vibration of a raspberry cane</td>
</tr>
<tr>
<td>({Z_1})</td>
<td>Column matrix of mode shape for the fundamental mode of vibration</td>
</tr>
<tr>
<td>({Z_2})</td>
<td>Column matrix of mode shape for the second principal mode of vibration</td>
</tr>
<tr>
<td>a</td>
<td>Intercept of simple regression equation</td>
</tr>
<tr>
<td>(a_f)</td>
<td>Acceleration of fruit relative to cane</td>
</tr>
<tr>
<td>b</td>
<td>Slope of simple regression equation</td>
</tr>
<tr>
<td>c</td>
<td>Cane taper, ((r_1/r_0))</td>
</tr>
<tr>
<td>d</td>
<td>Fruit diameter</td>
</tr>
</tbody>
</table>
\( d_c \)  
Fruit deformation under compressive load

\( e_b \)  
Maximum impact energy which a fruit can absorb without bruising

\( g \)  
Acceleration due to gravity

\( h \)  
Fruit length

\( h_a \)  
Maximum allowable free full distance without bruising

\( i \)  
Matrix row

\( j \)  
Matrix column

\( k \)  
Ratio of crank arm length to connecting rod length

\( l \)  
Fruit stem length

\( m \)  
Mass of a single fruit

\( m(x) \)  
Mass of cane per unit of length

\( [\cdot m\cdot] \)  
Diagonal mass matrix

\( n \)  
Sample size

\( n_r \)  
Feed roll speed, revolutions per minute

\( q \)  
\( P_a f^2/\epsilon I_0 \)

\( r \)  
Simple correlation coefficient

\( r^2 \)  
Coefficient of determination

\( r_f \)  
Feed roll radius

\( r_s \)  
Crank arm length

\( r_o \)  
Radius of cane cross section at soil surface

\( r_l \)  
Radius of cane cross section at point of load application

\( r_{0.01} \)  
Minimum significant value of \( r \) for \( P \leq 0.01 \)

\( r_{0.05} \)  
Minimum significant value of \( r \) for \( P \leq 0.05 \)

\( s \)  
Base motion displacement

\( \dot{s} \)  
Base motion velocity

\( \ddot{s} \)  
Base motion acceleration

- xx -
$s_0$ Base motion amplitude

$t$ Time, seconds

$x$ Height above soil surface at which cane deflection is measured

$x_h$ Distance from the center of the fruit row, outward, feet

$x_v$ Distance above ground, feet

$y$ Horizontal cane deflection at height, $x$, above soil surface.

$z$ Horizontal distance (inches) behind the front of the feed rolls at which cane contact occurs

$\alpha$ Angle between fruit stem and intermediate plant stem (figure 21)

$\beta$ Level of significance

$\gamma$ Tangent modulus

$\theta$ Angle of inclination of feed rolls

$\mu$ Mean of a sample of independent observations

$\rho_f$ Mass density of fluid

$\rho_p$ Mass density of fruit

$\sigma$ Standard deviation of a sample

$\phi$ Angle Modulus

$\omega_b$ Base motion frequency

$\omega_n$ Natural frequency of fruit attachment system

$\omega_f$ Angular velocity of feed rolls

$\omega_1$ Fundamental (first) natural frequency of a raspberry cane

$\omega_2$ Second natural frequency of a raspberry cane
ACKNOWLEDGMENTS

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The author wishes to thank the following people for advice and assistance. Dr. J. P. Duncan and Dr. V. J. Modi, Mechanical Engineering Department; Professor T. L. Coulthard, Professor E. L. Watson and Mr. W. Gleave, Agricultural Engineering Department and Dr. G. W. Eaton, Plant Science Department, all at the University of British Columbia.
INTRODUCTION

Present Status of Raspberry Production in British Columbia

Raspberry production in Canada is a small industry when compared to other types of farming but, nevertheless, it is an important industry in the lower mainland of British Columbia. The output value of raspberries from British Columbia exceeds that of the other Canadian provinces (12)\(^1\) and 95 percent of this output comes from the lower Fraser Valley. In 1967 the lower mainland production of raspberries was 16.1 million pounds from 2150 acres under cultivation representing an estimated gross value to the growers of 2.3 million dollars (5).

Favourable environmental conditions and proximity to markets in Vancouver and the United States make the lower Fraser Valley especially suitable for raspberry production. The industry has obtained a reputation for high quality fruit and efficient methods of production, processing and marketing.

The need for harvest mechanization

Raspberry growers are contending with increasing production costs which are disproportionately high when compared to market prices and are facing problems in obtaining suitable seasonal picking labour. Each year the growers find it increasingly difficult to attract competent pickers at wage rates allowing profitable returns. Approximately 10,000 pickers are required in the lower Fraser Valley during the month long harvest season. The cost of obtaining and maintaining this

---

1 Numbers in parentheses refer to references listed in the literature cited.
labour force represents up to 80 percent of the total cost of production. Unless a more reliable and efficient method of harvesting can be found many growers may be forced out of production. Mechanization of the harvesting process may be a solution to the problem.

**Scope and Purpose of this Research**

The purpose of this research project was to investigate the feasibility of mechanical harvesting of raspberries and to design a prototype harvesting system which would be suitable for conditions prevailing in the lower mainland of British Columbia. Since over 65 percent of the lower mainland raspberry acreage is planted to the Willamette variety (12), only this variety was considered.

**Review of Previous Work**

During the past decade much emphasis has been placed on mechanization of fruit and vegetable production (3). In this period over 500 papers have been written on different aspects of harvest mechanization. At present over 200 North American firms (4) are engaged in manufacturing specialized harvesting machines and harvesting aids for various crops. Research on mechanical harvesting of cane fruits has, however, been limited and little data are available on the engineering properties of cane fruits necessary for design of a harvesting system. Several attempts (6, 15) have been made at designing machines for harvesting cane fruits. This work has been largely on a trial and error basis, using existing tools designed for other crops, and results are not well documented.
Experiments on other types of crops, however, yield useful information for the initial planning stage of a cane fruit harvesting system.

**Categories of harvesting systems**

Existing fruit and vegetable harvesting systems may be categorized on the basis of the physiological and morphological characteristics of the plant being harvested:

(i) Once-over system (regenerative plant): The fruit matures uniformly at one time during the growing season. The plant supporting the fruit attachment system regenerates itself each year. In harvesting such crops the complete plant may be removed from the soil to facilitate processing under controlled conditions within the harvesting machine. This is the easiest type of harvesting system to design since damage to the plant and fruit support system can be tolerated. Such machines have long been used for harvesting small grains and recently have been designed for harvesting delicate fruits such as tomatoes (21, 34) and cucumbers (35).

(ii) Once-over system (non-regenerative plant): The fruit matures uniformly at one time during the growing season; however, the plant does not regenerate itself annually and hence plant damage must be within acceptable levels not to adversely affect yield in following years. The plant may not be removed from the soil for processing within the harvesting machine. Such machines
have been designed for harvesting cherries (16), nuts (13) and many other tree fruits.

(iii) Selective system: The fruit matures non-uniformly over a prolonged period. The harvesting machine must be able to discriminate between mature and immature fruit, removing the mature fruit and leaving the immature fruit for subsequent passes of the harvester. The harvester must not damage the fruit support system or the immature fruit. Such machines have been designed to satisfactorily harvest cotton, cucumbers (18), cantaloupe (17), mushrooms (29) and other unevenly maturing plants.

Methods of fruit removal

To accomplish fruit removal, a force greater than the fruit retention force must be applied to the fruit or the fruit attachment stem must be severed. Four main methods of fruit removal are used in existing harvesting machines:

(i) Fruit removal by impact: The fruit is struck, usually by a rotating drum with such impact that the energy imparted to the fruit is greater than the energy required for fruit removal. This method is suited to tough fruits and has been successfully used for hundreds of years in grain harvesting. Although initial designs were by trial and error, Kolganov (19) indicates that such systems have recently been analyzed based on the physio-mechanical properties of grain.
(ii) Fruit removal by inertial force: Some type of base motion is applied to the plant stalk or fruit limb. If the inertial force developed in the fruit due to acceleration exceeds the fruit retention force, fruit removal occurs. This method depends upon the vibrating limb structure to transfer a sufficient portion of the base motion amplitude to the fruit attachment system to cause detachment. Much work has recently been conducted on the modes of vibration of various plant structures, the effects of type of base motion and points of application of base motion, and time-dependent properties of live plant material. This work has primarily been concentrated on tree fruits (coffee, cherries, olives, apples, nuts). Phillips et al. (31) recently simulated the response of tree limbs with secondary branches to forced vibration by use of finite element analysis.

(iii) Fruit removal by tensile force (stripping): A direct tensile force greater than the fruit retention force is exerted on the fruit. This method is satisfactorily used in the harvesting of ear corn and some types of cotton. Relative motion of the plant with respect to stationary stripping bars or rotary strippers causes fruit removal if the exerted force is greater than the fruit retention force. An experimental auger-type picking head for oranges (20) and a selective mechanical cantaloupe harvester (17) are both based on
this principle.

(iv) Fruit removed by shear: The stem attaching the fruit to the secondary limbs is cut with a shearing device and the stem does not separate from the fruit at the abscission layer. The feasibility of such a device depends on whether separation at the abscission layer is essential for acceptable fruit. Such devices are used for harvesting of some vegetables (cabbage, lettuce) but could not be used for raspberries since removal of the core from the fruit is essential for an acceptable grade of fruit.
SYSTEMATIC DESIGN PROCEDURE

The design and development procedure used in this study follows that developed by Persson (29,30) which is oriented toward design and testing of a machine system handling biological materials. The steps in this procedure are outlined in figure 1.

The study is initially carried out at two levels. In the first stage, flow charts (figure 2) of possible sequences of operations between initial and final conditions are constructed and the most appropriate sequence is selected on the basis of economic considerations, mechanical limitations and other pertinent criteria. The second stage is a detailed description of the phenomena occurring on each treatment device (tool) outlined in the flow chart. The input conditions, output conditions and operational requirements of each tool in the process are determined and preliminary tool analysis is undertaken.

The tool analyses probably cannot be completed at this stage due to lack of information on the engineering properties of the material being processed. This leads to the third step in the procedure which is determination of the physical and mechanical properties of the material, necessary to complete the tool analyses. This allows the mathematical models of the individual tools to be completed.

The final steps involve design, fabrication and testing of the individual tools and incorporation of the tools into a machine for which control mechanisms and powering systems are selected as based on material properties and operational requirements. The
Figure 1  Systematic design procedure
machine may now be field tested to evaluate durability and functional performance.

This research project followed the outlined procedure; however, functional and durability evaluations were limited to trials in one location on one raspberry variety during a single harvest season. The remaining sections of this thesis follow the steps as outlined in figure 1.
ANALYSIS OF THE PROCESS

Flow Chart

The flow charts (figure 3) compare hand harvesting with a proposed mechanical harvesting system. The initial condition for both flow charts is fruit at various stages of maturity on the plants; the final condition is harvested fruit delivered to the processor. The flow chart for mechanical harvesting is broken into elementary functions (tools) each of which are analyzed in the following sections of the thesis by the procedure outlined in figure 1. The proposed mechanical system contains two machines, one for harvesting and one for transporting fruit to the processing plant. Only the harvesting machine is considered in this study.

Operational Requirements of the Harvesting Machine

Initial condition

The initial analysis of the process must include a description of the morphology and physiology of the plant, the cultural practices necessary for production and the plant environment. The machine must be designed to operate within this framework.

Figure 4 shows a typical row of raspberries of the Willamette variety. The raspberry plant has a perennial root system with biennial stalks. During the first year, the growth is nonproductive shoots, growing up to eight feet in height. The shoots which are pruned to four feet in the spring of the second year now become known as canes. The canes grow to approximately six feet and bear fruit during the second year.
Figure 3  Flow charts for hand harvesting and for the proposed mechanical harvesting system
At the end of the second year, the canes die and it is common practice to remove the dead canes from the new shoots before the third year. Although the plants are productive in all succeeding years, yield decreases when the plants pass a certain stage of development. It is therefore necessary to destroy plants after eight to twelve years and plant new stock.

Raspberries are planted in parallel rows spaced at ten feet. Individual plants are spaced in the rows at a distance of two and one half feet, resulting in hedge rows (figure 4) once the plants mature. Due to rank growth, weak and flexible canes, weak root systems and a heavy load imposed on the canes by fruit and leaves, an artificial support system is necessary to prevent the plants from lodging. Most growers use a trellising system composed of wooden posts and steel support wires placed within the plant rows. The harvesting machine must be designed to cope with this necessary cultural practice.

The raspberry fruit (figure 5) is an aggregate fruit composed of loosely bound drupelets attached to a central core. As the fruit matures, attachment to the core weakens and the fruit may be removed from the core. Fruit retention force decreases as the fruit ripens and when the fruit becomes overmature it falls from the plant. Raspberries mature unevenly over a thirty day period. The most productive period is the first twenty days of the harvest season. Picking is required at least once every three days throughout the harvest season to avoid overmature fruit. The harvesting machine must therefore be of the selective
Figure 4  A typical row of Willamette raspberries

Figure 5  The raspberry fruit
type with the capability of removing fruit of desired maturity without appreciable plant damage. Each plant must be harvested at least ten times during the harvest season.

Final condition

An acceptable final condition or end product of the harvesting machine depends upon the available market for different grades of fruit. High quality fruit may be marketed fresh or may be processed prior to marketing. Fruit of lower quality must be processed as jam, canned fruit or frozen fruit to prevent deterioration. As is shown in Table 1, over 95 percent of the raspberry production in the lower mainland (12) is sold for processing rather than for direct consumption. This indicates that even if a machine is incapable of harvesting fruit suitable for the fresh market, it can still serve 95 percent of the industry. The fruit must, however, be acceptable at the processing plant.

TABLE I  RASPBERRY PRODUCTION IN THE LOWER MAINLAND OF BRITISH COLUMBIA

<table>
<thead>
<tr>
<th>Year</th>
<th>Fresh Fruit (lbs)</th>
<th>Processed Fruit (lbs.)</th>
<th>Processed as Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>350,000</td>
<td>6,886,000</td>
<td>95</td>
</tr>
<tr>
<td>1964</td>
<td>300,000</td>
<td>13,595,000</td>
<td>98</td>
</tr>
<tr>
<td>1965</td>
<td>300,000</td>
<td>14,671,000</td>
<td>98</td>
</tr>
</tbody>
</table>

Economic Analysis of Raspberry Harvesting

Cost of hand picking

The cost of hand picking in 1967 was five cents per pound of fruit while in 1969 it varied from seven to ten cents per
pound. These figures represent only the wages paid to the pickers. Additional expenses are also incurred by way of incentives to retain experienced pickers. For example, many growers provide daily transportation to and from the urban center (Vancouver) or appropriate living quarters on the farm.

Yields and market price

In the period from 1962 to 1967 average annual yields of raspberries marketed in the lower mainland varied from 6450 to 8660 pounds per acre (12). In trials on the efficiency of hand picking (6) it was shown that only 80 percent of the fruit is actually harvested. This indicates that the potential average annual yield may be over 10,000 pounds per acre.

Large fluctuations occur in the selling price of raspberries depending upon market conditions. For example, in 1967 the price of fruit sold to processing plants was thirteen cents per pound while in 1969 it ranged from twenty-seven to thirty cents per pound.

Estimated cost of mechanical harvesting

Since the total cost incurred by using a mechanical harvesting system results from overhead cost and operating cost, both these costs were estimated in order to determine design limits for machine price and machine capacity. Machine life was estimated as ten years, with depreciation computed on a straight line basis over this period. The total repair cost for the ten year period was estimated as thirty percent of the purchase price while charges for interest on investment for the same period were taken as six percent of the average investment. Annual insurance
costs were estimated as one-half percent of the machine purchase price. The resulting annual overhead cost in dollars was

\[ O_f = 0.165 A \]  \hspace{1cm} [1]

where \( A \) = machine purchase price, dollars.

Estimating the cost of fuel and oil at $0.50 per hour and the cost of labour at $1.50 per hour, the resulting hourly operating cost in dollars was

\[ O_o = 0.50 + 1.50 B \]  \hspace{1cm} [2]

where \( B \) = the number of men required to operate the machine.

Based on these approximations, the cost of mechanical harvesting was determined over a range of machine prices, machine capacities, picking efficiencies and fruit yields. Table II presents the results of this analysis for the upper and lower limits of the ranges considered. Since this table is based on a labour force of two men operating the machine for six hours per day for a thirty day period, the annual operating cost is $630 for any of the combinations presented. Annual overhead costs vary from $250 for the $1,500 machine to $1900 for the $11,500 machine.

The machine capacities presented in table II are for a single row machine operating with 100 percent field efficiency in fruit rows spaced at ten feet. On this basis, a machine operating at one-quarter mile/hour can harvest five acres per season, while one operating at three miles/hour can harvest sixty acres.
TABLE II  

ESTIMATED COST OF MECHANICAL HARVESTING

<table>
<thead>
<tr>
<th>Machine Purchase Price (dollars)</th>
<th>Forward Speed (mile/hour)</th>
<th>Capacity (acre/hour)</th>
<th>Picking Efficiency (percent)</th>
<th>Fruit Yield (lb./acre)</th>
<th>Picking Cost (cents/lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,500</td>
<td>0.25</td>
<td>0.3</td>
<td>40</td>
<td>6,000</td>
<td>7.4</td>
</tr>
<tr>
<td>1,500</td>
<td>0.25</td>
<td>0.3</td>
<td>40</td>
<td>10,000</td>
<td>4.5</td>
</tr>
<tr>
<td>1,500</td>
<td>0.25</td>
<td>0.3</td>
<td>100</td>
<td>6,000</td>
<td>3.0</td>
</tr>
<tr>
<td>1,500</td>
<td>3.00</td>
<td>3.3</td>
<td>40</td>
<td>6,000</td>
<td>0.6</td>
</tr>
<tr>
<td>1,500</td>
<td>3.00</td>
<td>3.3</td>
<td>100</td>
<td>6,000</td>
<td>0.2</td>
</tr>
<tr>
<td>1,500</td>
<td>3.00</td>
<td>3.3</td>
<td>100</td>
<td>10,000</td>
<td>0.1</td>
</tr>
<tr>
<td>11,500</td>
<td>0.25</td>
<td>0.3</td>
<td>40</td>
<td>6,000</td>
<td>21.5</td>
</tr>
<tr>
<td>11,500</td>
<td>0.25</td>
<td>0.3</td>
<td>40</td>
<td>10,000</td>
<td>12.9</td>
</tr>
<tr>
<td>11,500</td>
<td>0.25</td>
<td>0.3</td>
<td>100</td>
<td>6,000</td>
<td>8.6</td>
</tr>
<tr>
<td>11,500</td>
<td>3.00</td>
<td>3.3</td>
<td>40</td>
<td>6,000</td>
<td>1.8</td>
</tr>
<tr>
<td>11,500</td>
<td>3.00</td>
<td>3.3</td>
<td>100</td>
<td>6,000</td>
<td>0.7</td>
</tr>
<tr>
<td>11,500</td>
<td>3.00</td>
<td>3.3</td>
<td>100</td>
<td>10,000</td>
<td>0.4</td>
</tr>
</tbody>
</table>

1 The picking costs in this table are based on overhead and operating costs as determined by equations [1] and [2]. It is assumed that two men are required to operate the machine. The results are for a single-row machine operating at 100 percent field efficiency, six hours each day for a thirty day period, with each plant being picked once every three days.
The break-even point

The machine picking costs as presented in table II represent the machine cost per pound of harvested fruit for each combination of machine factors. These figures cannot be directly compared to the per-pound-cost paid to hand pickers since hand picking efficiency and fruit market price must also be considered. Machine picking costs were compared to hand picking costs by use of a break-even point (figures 6 and 7). The break-even point was defined as the necessary machine picking efficiency (percent of gross fruit yield) which must be achieved to obtain the same gross income from machine harvesting as is presently obtained from hand harvesting.

For this comparison, it was assumed that the only difference in cost for the two harvesting methods occurred during the actual harvest operation. Other production costs were assumed to be constant. The cost of hand picking was considered to be ten cents per pound of harvested fruit while hand picking efficiency was estimated as 80 percent of the gross fruit yield. It was further assumed that machine harvested fruit had the same market value as hand harvested fruit.

Figure 6 shows the effect of machine purchase price on the break-even point for a machine capacity of one acre per hour. At this machine capacity, break-even point is not strongly dependent upon purchase price for the range of fruit yields expected in the lower mainland. Break-even point for fruit market price of thirty cents per pound is approximately 55 percent, while for a market price of 20 cents per pound it is approximately 42
Figure 6 The effect of machine purchase price on the break-even point for a machine capacity of one acre per hour.
Figure 7  The effect of machine capacity on the break-even point for a machine purchase price of $3,500.
percent. As is shown in figure 7, break-even point is strongly dependent upon machine capacity for capacities below one acre per hour. For capacities above one acre per hour the break-even point is nearly constant for the range of yields expected in the lower mainland. Figure 7 is based on a machine purchase price of $3,500; however, nearly similar results can be expected for all machines within the cost range presented in figure 6.

Summary of Machine Requirements

Based on plant characteristics and economic considerations, as outlined above, the following factors should be considered in design of a harvesting system:

(i) Individual plants must be picked at least ten times during the harvest season. Plant damage must be controlled so that the cumulative damage for the whole harvest season is within acceptable limits.

(ii) Fruit trellising systems are necessary in the lower mainland. The machine must be designed to operate within the trellising framework.

(iii) A machine which harvests fruit suitable only for processing will serve over 95 percent of the lower mainland raspberry industry.

(iv) Machine capacity should be at least one acre per hour. This represents a forward speed of at least one mile per hour. A machine with a capacity of one acre per hour can harvest approximately twenty acres per season.

(v) For the range of yields expected in the lower
mainland and for machine capacities above one acre per hour, the break-even point is not strongly dependent upon machine purchase price within the price range of $1,500 to $11,500. It must be noted that for low fruit yields and low machine capacities, break-even point is strongly dependent upon machine purchase price.

(vi) Although a machine with gross seasonal picking efficiency of 40 to 60 percent may be economically feasible, much higher profits than are presently obtained are possible with a machine of high picking efficiency.
TOOL ANALYSES

Mechanization of the Process

The individual components of the flow chart for mechanical harvesting (figure 3) represent the basic process functions. One or more tools may be required to perform a given function. Conversely, a single tool may have more than one function. In the following section of the design procedure, the tools selected to mechanize the process are outlined; operational requirements, input conditions and output conditions for each tool are stated; preliminary tool analysis is conducted and the unknown plant and fruit properties, necessary for tool design, are listed.

Tool for Feeding and Cane Orientation.

Function

This tool mechanizes the first two basic process functions on the flow chart. Its requirements are as follows:

Input condition.- Rows of raspberry plants contained within a trellising support structure.

Output condition.- Plants delivered to the selection tool with the canes suitably supported and with the fruit positioned to allow the selection tool to function.

Operational requirements.- Cumulative damage to the canes, shoots, foliage and fruiting portions must be within acceptable limits after at least ten successive passes of the tool, spaced at three day intervals. The tool should be capable of functioning within a range of forward speeds above one mile per hour and its design must be compatible with a suitable trellising system.
Proposed design

The selection tool must scan all fruit bearing portions of the plant. Since fruit is distributed throughout most of the plant, the primary requirement of the feeding and cane orientation tool is to concentrate the fruiting portions within fixed limits, thereby determining the size of the selection tool and its positioning on the machine. A proposed tool for feeding and cane orientation which meets this requirement is illustrated in figure 8. Inclined, aggressive rolls, rotating in opposite directions, are positioned on each side of the raspberry row. As the machine passes down the row, the rolls gather and compress the plant. Roll velocity is synchronized with forward speed in order to hold the canes upright as the rolls pass the plants.

**Figure 8** Tool for feeding and cane orientation.
Front and rear roll spacing is adjustable to accommodate variation in plant dimensions, to obtain the desired concentration between the rolls and to permit the rolls to pass the trellising support posts.

**Analysis**

For synchronization of roll velocity with speed of forward travel, the horizontal component of the tangential roll velocity must be the same magnitude as the forward velocity but of opposite sign. Assuming that no slipping occurs between the feed rolls and canes and using consistent units of measurement, the necessary angular velocity of the feed rolls (figure 8) is

\[ \omega_f = -\frac{V_g}{r_f} \sin \theta \]  \[ \text{[3]} \]

where

- \( V_g \) = forward velocity of harvesting machine
- \( r_f \) = feed roll radius
- \( \theta \) = feed roll inclination

The reaction force between the canes and the feed rolls may be estimated based on the flexural characteristics of the canes. Assuming a cane to be elastic, considering it as a vertical tapered cantilever beam with circular cross section (figure 9) and applying simple beam theory with a consistent set of units, the equation of flexure is

\[ \frac{d^2y}{dx^2} = \frac{Pa}{EIo} \left( \frac{L - x}{L} \right) \left( 1 - \frac{x}{L} \right)^4 \]  \[ \text{[4]} \]

where

- \( E \) = elastic modulus of cane material
- \( Io \) = moment of inertia of cane cross section at soil surface
- \( Pa \) = horizontal load applied to cane at distance, \( L \), above soil surface
\[ c = \text{cane taper} \]
\[ = \frac{\text{radius of cane cross section at load point}}{\text{radius of cane cross section at soil surface}} \]
\[ y = \text{horizontal cane deflection at distance, } x, \text{ above soil surface} \]

Integrating equation [4] and applying boundary conditions satisfying a cantilever beam, the resulting expression is

\[
y = \left( \frac{P_a L^3}{EI_0 (1-c)^3} \right) \left[ \frac{1}{2[1-\frac{X}{L}(1-c)]} - \frac{c}{6[1-\frac{X}{L}(1-c)]^2} - \frac{x(1-c)}{2L} + \frac{cx(1-c)}{3L} + \frac{c}{6} - \frac{1}{2} \right] \tag{5} \]

where the nomenclature is as previously defined.

The total reaction force between the feed rolls and the compressed canes can be estimated by successively applying equation [5] to all the canes in contact with the rolls at one instant. Cane deflection, point of load application and cane taper differ for each cane due to the inclination of the feed rolls.

![Diagram of a raspberry cane idealized as a tapered vertical cantilever beam of circular cross section.](image)

Figure 9 A raspberry cane idealized as a tapered vertical cantilever beam of circular cross section.
Unknowns

The following plant characteristics must be determined before analysis of the feeding and cane orientation tool can be completed:

(i) Mean plant dimensions.
(ii) Fruit distribution on canes.
(iii) Mean cane dimensions and cane density per plant.
(iv) Elastic modulus of cane material.
(v) Susceptibility of plants to mechanical damage.

Tool for Selective Harvesting

Function

This tool mechanizes the fruit selection function and the fruit picking function on the flow chart and has the following requirements:

Input Condition.- Plants held by the feed rolls.
Output Condition.- Mature fruit of acceptable quality.
Operational Requirements.- This tool must select and pick mature fruit while leaving immature fruit on the plant. The rate of selection and picking must be high enough to allow machine speeds over one mile per hour. The harvested fruit must be of acceptable quality while damage to immature fruit, canes and foliage must be within acceptable limits. Although the picking tool should remove all of the mature fruit at each harvest date, economic analysis indicates that harvesting efficiencies as low as forty percent may be acceptable.

Proposed design

The tool for selective harvesting must scan the plants in
the region directly above the feed rolls, selecting and removing the mature fruit as the plants are delivered by the feed rolls. Since fruit quality, fruit color and fruit retention force are all a function of fruit maturity it is assumed that the desired quality of harvested fruit may be obtained by selecting fruit within certain limits of color or fruit retention force. Although selective hand picking is based primarily on fruit color, the density of foliage makes mechanical color sensing difficult. Selection based on fruit retention force is readily mechanized and has the added advantage of combining the selection function and picking function into one tool. Figure 10 illustrates the proposed design of a selective harvesting tool which operates on the basis of fruit retention force. A vibratory motion is imparted to the plants in the region directly above the feed rolls. By controlling the frequency and amplitude of the applied base motion, a desired level of inertial force is developed in the fruit. Fruit removal occurs if the developed inertial force exceeds the fruit retention force.
Analysis

The force applied to the fruit support system must be within the following limits:

\[ F_m \leq F_a \leq F_d \]  \hspace{1cm} [6]

where

\( F_m \) = upper limit of fruit retention force of mature fruit
\( F_a \) = applied force
\( F_d \) = force required to remove immature fruit or to damage the fruit support system.

Using Newton's second principle, with a consistent set of units, the inertial force developed in the fruit as the result of applied base motion is

\[ F_a = \frac{W a_f}{g} \]  \hspace{1cm} [7]

where

\( a_f \) = acceleration of the fruit
\( W \) = fruit weight
\( g \) = acceleration due to gravity

Since for fruit removal the inertial force must equal fruit retention force, the necessary acceleration is

\[ a_f = \left( \frac{F}{W} \right) g \]  \hspace{1cm} [8]

where \( F/W \) = fruit retention force/fruit weight

Applying simple harmonic base motion to the canes above the feed rolls and assuming that all the base motion displacement is imparted to the fruit, the displacement, velocity and acceleration of the fruit are, respectively

\[ s = s_0 \sin (\omega_b t) \]  \hspace{1cm} [9]
\[ \dot{s} = s_0 \omega_b \cos (\omega_b t) \]  \hspace{1cm} [10]
\[ \ddot{s} = -s_0 \omega_b^2 \sin (\omega_b t) \]  \hspace{1cm} [11]
where

\[ s_0 = \text{base motion amplitude} \]
\[ t = \text{time, seconds} \]
\[ \omega_b = \text{base motion frequency, radians/second} \]

As can be seen from comparison of equations [9], [10] and [11] the acceleration is maximum when the base motion is at maximum displacement and zero velocity. If the base motion is applied to the canes so that no relative displacement can occur between the base motion mechanism and the canes, the maximum acceleration of the fruit relative to the canes is \( s_0 \omega_b^2 \). This is true only for fruit close to the feed rolls. Cane displacement at points distant from the point of base motion application will be diminished due to internal and external damping and the flexural strength of the canes. Conversely, amplitude magnification can be expected if applied frequency is at the resonant frequency of the canes and base motion is applied to an antinode.

Unknowns

The unknown physical and mechanical properties necessary for design of the selective harvesting tool are:

(i) The statistical distribution of fruit weight
(ii) The statistical distribution of fruit retention force.
(iii) The statistical distribution of F/W ratio
(iv) The modes of vibration and natural frequencies of both the canes and the fruit attachment system
(v) Susceptibility of the fruit attachment system to mechanical damage
(vi) The relationships among fruit color, fruit retention force, fruit maturity and fruit quality
(vii) A basic definition of fruit quality is required. Present standards for fresh raspberries (8) as set by the Canadian Government Specifications Board are:

"Raspberries shall be freshly picked, clean, sound, mature, ripe but firm, of good color, and free from mold, mildew or other decay, cores, stems, leaves, dirt or other foreign material, green or dried fruit, and shall be whole and fairly uniform in size and not less than one-half inch in diameter".

These standards do not adequately define fruit quality.

Tool for Fruit Collection and Conveying

Function

This tool which mechanizes the collection and conveying functions on the flow chart has the following requirements:

Input Condition.- Mature fruit which has been removed from the plant by the selective harvesting tool.

Output Condition.- Fruit delivered to the fruit storage tool.

Operational Requirements.- The collection and conveying tool must collect fruit as it falls from the selective harvesting tool and convey it to the storage tool while maintaining fruit damage at an acceptable level. Conveyor capacity must be great enough to accommodate forward speeds above one mile per hour in crops yielding up to 10,000 pounds per acre.

Proposed design

A belt conveyor or oscillating conveyor, of sufficient width and length to collect all the fruit falling from the selective harvesting tool, is placed adjacent to each feed roll. The falling fruit, which is intercepted by the conveyor, is delivered to the fruit storage tool. The impact velocity of
the fruit striking the conveyor, the depth of fruit on the con­
veyor, the conveyor material and the fruit velocity as it leaves
the conveyor must be based on the bruising characteristics of
the raspberry fruit.

Analysis

The impact velocity of the fruit striking the conveyor
surface and of the fruit entering the storage tool must be
limited to prevent fruit bruising. The maximum allowable free
fall height is

\[ h_a = \frac{e_b}{W} \]  \[12\]

where \( e_b \) = the maximum impact energy which the fruit can
absorb without bruising

\( W \) = the weight of a single fruit

Similarly, the maximum allowable impact velocity is

\[ V_a = (2 \frac{e_b}{m})^{1/2} \] \[13\]

where \( m \) = the mass of a single fruit

If fruit free fall height is greater than \( h_a \) then
provision must be made to limit the impact velocity to \( V_a \). This
could be done by allowing the fruit to fall in a more viscous
fluid than air or by supplying an air cushioning system.

As given by Mohsenin (25), the drag force on freely
falling fruit may be estimated as

\[ F_r = C_d A_p \rho_f V^2/2 \] \[14\]

where \( A_p \) = the projected fruit area normal to the
direction of motion

\( C_d \) = the overall drag coefficient, unitless

\( V \) = the velocity of the fruit relative to the
surrounding fluid
\( \rho_f \) = the mass density of the surrounding fluid

In this relationship, the overall drag coefficient is defined as

\[
C_d = \frac{2W (\rho_p - \rho_f)}{V_t^2 A_p \rho_p \rho_f} \tag{15}
\]

where \( V_t \) = terminal velocity of the falling fruit

\( W \) = the weight of a single fruit

\( \rho_p \) = the mass density of the fruit

Assuming that the raspberry fruit is spherical (\( C = 0.5 \)) and noting that at terminal velocity the drag force equals the fruit weight, the estimated terminal velocity of raspberry fruit is

\[
V_t = (W(\rho_p - \rho_f)/A_p \rho_f)^{1/2} \tag{16}
\]

The necessary upward air velocity supplied by the air cushioning system then is

\[
V_c = V_t - V_a \tag{17}
\]

where \( V_a \) and \( V_t \) are as defined in equations [13] and [16] respectively.

Conveyor dimensions must be based on fruit distribution on the canes and on the maximum expected fruit yield for a specific harvest date.

**Unknowns**

The following fruit properties are unknown:

(i) The aerodynamic properties of the raspberry fruit

(ii) The statistical distributions of fruit weight, fruit density and projected area of the fruit
(iii) The bruising characteristics of raspberry fruit
(iv) The quantity and distribution of fruit on the canes at the peak of the harvest season.

**Tool for Fruit Storage**

**Function**

This tool stores the harvested fruit on the machine to permit continuous operation of the harvester for a certain length of time. Its requirements are:

- **Input Condition.** - Fruit leaving the conveying tool.
- **Output Condition.** - Fruit containers filled to a suitable depth.
- **Operational Requirements.** - Fruit containers should be evenly filled. Filling depth must be limited by the resistance to bruising of the lower fruit layer and by the effect of in-transit vibrations on fruit damage. The tool must have sufficient storage capacity to allow continuous operation for an acceptable length of time. Down time, for removing a set of full containers and placing a set of empty containers on the machine, should be minimal.

**Proposed Design**

Individual fruit containers oscillate slowly beneath the conveyor discharge to permit uniform filling. When one container is filled to a suitable depth, it is removed from beneath the conveyor discharge and replaced with an empty container. Storage space to accommodate a suitable number of fruit containers is provided on the machine.

**Analysis**

The maximum rate of fruit entering the storage tool will
be determined in the final analysis of the fruit conveying tool. The necessary storage capacity will be determined by the rate of fruit entering the storage tool and by the allowable depth of fill of each storage container. Assuming a linear relationship between fruit deformation and compressive load, the allowable load on the bottom layer of fruit in a container is

\[ P_c = K d_c \]  

[18]

where

- \( K \) = a modulus relating fruit deformation to compressive load.
- \( d_c \) = allowable fruit deformation.

The depth of fill will be limited by the allowable fruit deformation and by the effects of in-transit vibrations on fruit damage.

**Unknowns**

The following plant and fruit properties must be determined before storage tool design may be completed:

(i) The quantity of fruit on the canes at the peak of the harvest season.

(ii) The deformation characteristics of fruit under compressive load.

(iii) The effect of in-transit vibrations on fruit damage.

**Summary**

The four tools which were described above are required to mechanize all the functions on the flow chart. Analysis of the tools is incomplete. Delimitation of the physical and mechanical properties of the raspberry plant and its fruit is necessary before the mathematical models for the tools can be completed. The next section of the thesis therefore presents the results of measurements determining these properties.
ANALYSIS OF PRODUCT CHARACTERISTICS

Scope of Investigation

This chapter presents the results of measurements determining the physical and mechanical properties of the raspberry plant and its fruit. In addition to determining the data required for completion of the tool analyses, an investigation on the control of physical properties, by the use of chemical growth regulators, was also undertaken. Due to large variability in the properties of biological materials, statistical analyses were used to interpret the data.

The following results are based on analyses of the Willamette variety of raspberries grown at the Small Fruit Substation of the Canada Department of Agriculture at Abbotsford, British Columbia. Cultural practices used on the test plots were similar to those used by commercial growers in the lower mainland.

Distribution of Fruit on the Raspberry Plant

The numbers of fruit on successive one-foot-thick horizontal slices were counted on nineteen randomly selected plants midway through the 1968 harvest. Similarly, the numbers of fruit in one-half-foot-thick vertical slices, from the center of the row outward, were counted on fourteen plants. Using the method of least squares and stepwise regression procedure, the best fit polynomials of numbers of fruit versus distance were determined. The polynomial of best fit describing the vertical fruit distribution was

$$N_v = -9.04 + 17.40x_v - 0.09x_v^4, \quad R^2 = 0.64, \quad n=114,$$

$$S_y = 11.2$$

[19]
for the range $0.5 \leq x_v \leq 5.5$

where $N_v =$ numbers of fruit on one plant in a one-foot-thick horizontal slice from $(x_v - 0.5)$ ft. to $(x_v + 0.5)$ ft.

$x_v =$ distance above soil surface, ft.

In the case of horizontal fruit distribution, the best fit polynomial was

$$
N_h = 0.67 + 42.31 x_h - 15.53 x_h^3 + 3.62 x_h^4, \quad R^2 = 0.63, \quad n = 84, \quad S_y = 8.49 \quad [20]
$$

for the range $0.25 \leq x_h \leq 2.75$

where $N_h =$ Numbers of fruit on one plant in a one-half-foot-thick vertical slice from $(x_h - 0.25)$ ft. to $(x_h + 0.25)$ ft.

$x_h =$ distance from the center of the row, outward, ft.

---

Figure 11 Cumulative distribution of fruit on a raspberry plant as measured upward from the soil surface.
Figure 12 Cumulative distribution of fruit on a raspberry plant as measured outward from the center of the row of plants.

Expressions for the cumulative distribution functions, which were obtained by integrating equations [19] and [20], are shown in figures 11 and 12. From figure 11 it can be seen that in order to obtain all of the fruit, a portion of the plant from 0.5 to 5.5 feet high must be harvested. Eighty percent of the fruit is located in a three-foot-thick slice while sixty percent is contained in a two-foot-thick slice (from 2.25 to 4.25 feet). Figure 12 shows that all of the fruit is located in a six foot wide portion of the plant. Eighty percent of the fruit is contained in two 1.5 feet-thick vertical slices on each side of the plant while sixty percent is located in two one-foot-thick vertical slices (from 0.75 to 1.75 feet on each side of the center of the fruit row).
Physical Dimensions of Raspberry Plants

The average size of raspberry plants at harvest is shown in figure 13. Plant height may depend slightly upon pruning practices and width may depend upon trellising methods. The portion of the plant above 5.5 feet in height is unproductive consisting of flexible shoots. Since these may be readily deflected as the harvester passes over them, machine clearance of less than six feet is sufficient. The plant width at the soil surface ranges from three to ten inches. Although the maximum plant width is over six feet, the portion of the plant above one foot in height may be readily compressed into a four inch thick vertical slice. Each plant contains from three to ten productive canes with a similar number of shoots.

Physical Dimensions of the Raspberry Fruit and its Attachment Stem

The physical dimensions of the raspberry fruit and the stem attaching it to the plant are given in Table III. The nomenclature used in this Table is defined in figure 14.

Figure 13 Physical dimensions of a raspberry plant

Figure 14 Nomenclature used in Table III
TABLE III PHYSICAL DIMENSIONS OF THE RASPBERRY FRUIT AND ITS ATTACHMENT STEM

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem length (L), cm</td>
<td>3.07</td>
<td>0.65</td>
</tr>
<tr>
<td>Fruit length (h), cm</td>
<td>2.17</td>
<td>0.23</td>
</tr>
<tr>
<td>Fruit diameter (d), cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- maximum</td>
<td>1.97</td>
<td>0.15</td>
</tr>
<tr>
<td>- minimum</td>
<td>1.88</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Fruit Weight, Volume and Density

Based on 124 samples and data gathered by McLeod (22) in 1967, the weight of a single fruit was $4.19 \pm 0.97$ grams.

Based on 90 samples and data collected in 1968, fruit weight was $3.52 \pm 0.97$ grams. For the 1968 data, the simple linear regression of fruit weight on time of harvest was determined as

$$W = 3.01 + 0.07T, \quad r^2 = 0.12, \quad n = 90, \quad S_y = 0.92$$

[21]

for the range $1 \leq T \leq 15$

where $T =$ time in days, $T=1$ being the first day of harvest

$W =$ weight of a single fruit, grams

In order to determine fruit volume and density, individual fruits were weighed successively in both air and water, as outlined by Mohsenin (24). Fruit volume was calculated as the quotient of the weight of water displaced by a submerged fruit and the density of the water. Fruit density was then determined as the quotient of fruit weight divided by fruit volume. Based on 124 samples

---

1 In the following pages, the results of individual determinations are reported as the mean ($\mu$) \pm the standard deviation ($\sigma$).
the volume of a single raspberry fruit is $4.07 \pm 0.97 \text{ cm}^3$, while its density is $1.04 \pm 0.12 \text{ gm/cm}^3$.

**Rate of Fruit Removal**

Based on equation [19], mean fruit weight and a spacing of 2.5 feet between adjacent plants in a row, the rate of fruit removal for one pass of a single row harvesting machine was determined. Table IV shows the number of fruit per plant at various height intervals and the resulting rate of harvesting in pounds of fruit per minute at a forward speed of one mile per hour, assuming 100 percent picking efficiency. The table is based on fruit distribution at the peak of the harvest season, and represents a yield of 1925 pounds per acre for one picking.

**TABLE IV  CALCULATED RATE OF FRUIT REMOVAL FOR A SINGLE ROW HARVESTING MACHINE.**

<table>
<thead>
<tr>
<th>Plant Height Interval (feet above soil)</th>
<th>Number of Fruit on One Plant</th>
<th>Rate of Fruit Removal (lbs/minute of fruit at forward speed of 1 mile/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 to 1.5</td>
<td>8.2</td>
<td>2.3</td>
</tr>
<tr>
<td>1.5 to 2.5</td>
<td>24.1</td>
<td>6.8</td>
</tr>
<tr>
<td>2.5 to 3.5</td>
<td>35.4</td>
<td>9.9</td>
</tr>
<tr>
<td>3.5 to 4.5</td>
<td>36.7</td>
<td>10.2</td>
</tr>
<tr>
<td>4.5 to 5.5</td>
<td>20.6</td>
<td>5.8</td>
</tr>
<tr>
<td>Total Plant</td>
<td>125.0</td>
<td>35.0</td>
</tr>
</tbody>
</table>

**Terminal Velocity of Raspberry Fruit**

The terminal velocity of raspberries in air was estimated using equation [16], with $A_p$ based on mean fruit diameter (Table
III). This value for $V_t$ was then substituted into equation [15], using the mean values of fruit weight and fruit density, to verify the choice of $C_d$. Based on these calculations, the terminal velocity and drag coefficient were 3960 feet/minute and 0.5 respectively.

**Fruit Retention Force**

Fruit retention force was determined using a Chattillon type DPPL hand dynamometer (accuracy ± 3 gm). The dynamometer (figure 15) was modified to mount on a surveyor's tripod. A spring loaded scissors clamp, having jaw surfaces coated with water proof silicon carbide paper, was used to clasp the fruit stem. A slotted ring (figure 16) with slot width of 9.5 mm was used to apply the load to the fruit. The load was applied through a screw mechanism to avoid impact loading. Since the fruit was held in a vertical position, fruit weight was added to dynamometer reading to obtain fruit retention force.

The mean value of the fruit retention force obtained in 1968 from ninety random samples was $254.0 \pm 146.5$ gm. McLeod (22) obtained a value of $162.8 \pm 100$ gm in a similar experiment in 1967. Simple regression analysis of fruit retention force on harvest time resulted in the following regression equation for the 1967 data.

$$ F = 218.4 - 6.9T, \quad r^2 = 0.16, \quad n=397, \quad S_y = 91.9 \quad [22] $$

for the range $1 \leq T \leq 16$

For the 1968 data the simple regression equation was

$$ F = 347.7 - 13.4T, \quad r^2 = 0.19, \quad n=90, \quad S_y = 132.9 \quad [23] $$

for the range $1 \leq T \leq 15$. 
where $F =$ fruit retention force, grams

$T =$ time, days, where $T=1$ is the first day of harvest.

Equations [22] and [23], which are plotted in figure 17, were compared using the analysis of covariance (33). This test indicated that slopes were significantly different at $P \leq 0.01$ and levels were significantly different at $P \leq 0.005$. A further test for homogeneity of residual variances revealed that the variances were significantly different at $P \leq 0.005$ indicating that the two distributions were from different populations and that comparison is not justified. From the above results it may be concluded that fruit retention force,
Figure 17  Fruit retention force variation over the harvest season for 1967 and 1968

Figure 18  Cumulative distribution of fruit retention force for 1968
for fruit of equal maturity, decreases as the harvest season progresses. Furthermore, fruit retention force appears to be dependent upon growth conditions in a specific year.

Figure 18 shows the cumulative distribution function of fruit retention force for the first day of the harvest season, the last day of the harvest season and for the whole harvest season, based on the 1968 data. The mean fruit retention force on the first day of harvest was $290.8 \pm 101.8$ gm while on the last day of harvest, the mean fruit retention force was $162.2 \pm 142.2$ gm, each value being based on eighteen measurements.

### F/W Ratio

F/W ratio was obtained by combining the data on fruit retention force and fruit weight. Mean F/W for 1968 based on 90 samples was $82.8 \pm 65.1$ while in 1967 it was $52.7 \pm 84.5$, based on 124 measurements. The simple regression of F/W on harvest time for the 1968 data indicated that F/W decreased significantly with increase in the time of harvest.

$$F/W = 128.0 - 6.5T, \quad r^2 = 0.22, \quad n = 90, \quad S_y = 57.8 \text{ [24]}$$

for the range $1 \leq T \leq 15$

where $F/W = \text{fruit retention force/fruit weight}$

$T = \text{time in days, } T=1 \text{ being the first day of harvest.}$

Based on the 1968 data and 18 measurements for each day, mean F/W was $96.2 \pm 44.8$ on the first day of the harvest season, and was $46.4 \pm 43.3$ on the last day of measurement ($T=15$). Figure 19 shows the cumulative distribution function of F/W for the 1968 harvest season.
Strength of Fruit Attachment System

The weakest part of the fruit attachment system occurs at the point where the fruit stem attaches to the intermediate plant stem (figure 20). Stem strength is a function of direction of load application (figure 21) being greatest when the load is applied upward ($\alpha = 180^\circ$) parallel to the plant stem and least when the load is applied downward parallel to the plant stem ($\alpha = 0^\circ$). Since the direction of load application on the fruit stem in a vibratory harvesting machine is unknown, measurement of stem strength was based on a load direction of $\alpha = 0^\circ$, resulting in determination of minimum strength. Randomly selected samples, picked at two dates during the 1969 harvest season, were loaded in an Instron testing machine. Stem strength was taken as the
Figure 20  Raspberry fruit attachment system

Figure 21  Variation of fruit stem strength with load direction

Figure 22  Cumulative distribution of fruit stem strength for $\alpha = 0^\circ$
maximum reading on the force-deformation curve in each case. Based on 132 samples, the mean and standard deviation of stem strength was 177.1 ± 164.3 grams. The cumulative distribution function for stem strength is shown in figure 22.

One further test was conducted in order to determine the significance of stem strength in mechanical harvesting. All the mature fruit on one plant was hand picked by applying a direct tensile force to the fruit while maintaining α (figure 21) at approximately 90°. In a total of 63 fruit, 70 percent were detached from the core while 30 percent failed at the stem with the result that the core and stem remained attached to the harvested fruit. In actual practice, hand picking is with a rolling motion of the fingers in order to loosen the fruit from the core. In a vibratory harvester, however, fruit removal results from application of a tensile force on the fruit. From the above test it appears that fruit stem strength may limit the effectiveness of a mechanical harvester in Willamette raspberries.

**Fruit Color**

Selective harvesting of raspberries by hand is based on fruit color. The human eye distinguishes between immature, mature and overmature fruit on the basis of color differences. Measurement of the surface color of raspberries was, therefore, conducted in an attempt to determine the relationship between color and other fruit properties.

An Hitachi Perkin-Elmer model 139 UV-VIS spectrophotometer with diffuse reflectance attachment was used for measuring fruit color. Since color measurement is a destructive test with
this instrument (crushed sample placed in a glass cell) the spectrophotometer was modified to non-destructively measure the external color of raspberry fruit. A FibroxF, non-coherent, fibre optic light pipe, 45.7 cm long x 6.2 mm diameter, was used to transmit reflected light from the fruit to the integrating sphere on the spectrophotometer. A 15 power microscope eyepiece was attached to the integrating sphere in place of the sample holder (figure 23) with the end of the light pipe inserted into the eyepiece tube at a distance so that the cone of light emerging from the light pipe completely filled the lens viewed by the integrating sphere. (The aperture angle of the light pipe was 33°).

Individual fruit were placed upright on a 1.5 inch diameter turntable (figure 24) coated with black silicon carbide paper (Behr-Manning No. 2204 tufbak durite paper). The outer end of the light pipe was placed 1.5 inches above the surface of the turntable. Originally, the internal monochromatic light source in the spectrophotometer was used to illuminate the fruit, through the light pipe. That portion of the light which was reflected from the fruit and was intercepted by the outer end of the light pipe, returned through the pipe to the integrating sphere. Even though the internal light source was adjusted to 5200 nm, the wavelength most readily transmitted by the light pipe, sensitivity of the spectrophotometer was too low to satisfactorily distinguish color differences. A 17 watt external white light source (figure 24) was therefore directed onto the fruit by means of an inclined mirror. With this
Figure 23 Spectrophotometer modification, color differences were discernible. Calibration of the spectrophotometer was by means of a standard white powder cell and the black surface on the turntable. The spectrophotometer was adjusted for a reading of 100 percent reflectance with the white powder cell rotated to intercept the light from the internal source and with no fruit on the turntable, a procedure similar to the standard calibration method for this spectrophotometer. Calibration and color measurements were conducted in a darkroom. By rotating the turntable, both maximum and minimum reflectance readings were taken for each fruit. The complete instrumentation for measuring color is shown in figure 25.

Color index was defined as the mean of the maximum and minimum reflectance readings for each fruit and ranged from 85
Figure 25  Complete instrumentation for measuring external color of raspberry fruit

Figure 26  Variation in fruit color as determined by reflectance measurements
for overmature fruit, suitable only for processing, to 105 for firm fruit, suitable for the fresh market (figure 26). As is discussed later, correlations among color and other fruit properties (Tables IX and X) were highly significant.

**Bruising Characteristics of Raspberry Fruit**

Drop tests were conducted to determine the resistance of raspberry fruit to mechanical damage. Fruit, with stem and core attached, were dropped onto a smooth rigid Formica surface from predetermined heights. The stem prevented the fruit from tumbling as it fell, making it possible to determine the point of impact. Bruising damage was assessed visually thirty minutes after the drop. Color index was used as a measure of fruit maturity in order to assess the bruising characteristics of fruit at different stages of maturity. The extent of bruising was determined by measuring the depth and diameter of each bruise.

Results of drop tests are reported in Table V. Assuming damage to one drupelet as an acceptable level of bruising, the maximum free fall height for a fruit of color index 100 was 8 cm whereas for a fruit of color index 90, it was 4 cm.

The maximum impact energy \( (e_B) \) which may be absorbed by a fruit of color index 90 may be estimated as

\[
(4)(5) = 20 \text{ gm cm}
\]

Basing the result on a mean fruit weight of 3.52 ± 0.97 gm the allowable free fall height \( (h_a) \) from equation [12] is

\[
\frac{20}{(3.52 \pm 0.97)} = 4.5 \text{ cm}
\]

Similarly, from equation [13], the allowable impact velocity \( (V_a) \) is
\[
(2(20)(981)/(3.52 + 0.97))^{1/2} = 94 \text{ cm/sec}^1
\]

\[= 187 \text{ ft/min}\]

<table>
<thead>
<tr>
<th>TABLE V</th>
<th>RESULTS OF DROP TESTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of Drop (cm)</td>
<td>Fruit Weight, including Stem and Core (gm)</td>
</tr>
<tr>
<td>8</td>
<td>5.0</td>
</tr>
<tr>
<td>8</td>
<td>5.0</td>
</tr>
<tr>
<td>15</td>
<td>5.2</td>
</tr>
<tr>
<td>15</td>
<td>5.9</td>
</tr>
<tr>
<td>30</td>
<td>5.0</td>
</tr>
<tr>
<td>30</td>
<td>5.0</td>
</tr>
<tr>
<td>75</td>
<td>4.5</td>
</tr>
<tr>
<td>75</td>
<td>5.6</td>
</tr>
</tbody>
</table>

**Force-Deformation Characteristics of Raspberry Fruit**

As was previously mentioned, quality of raspberry fruit is at present poorly defined. Force-deformation characteristics of raspberry fruit were investigated in order to more accurately define quality and to relate fruit properties to fruit color and fruit retention force. Force-deformation curves were obtained by placing the fruit upright between two flat plates on an Instron testing machine (figure 27) and applying a compressive load at a

1 \(V_a\) and \(h_a\), as determined above, are based on a fruit weight of the mean plus one standard deviation of the fruit weight distribution. Eighty four percent of the individual measures defining a normal distribution have values less than \((\mu + \sigma)\) whereas 97.5 percent have values less than \((\mu + 2\sigma)\).
Figure 27  Method of loading fruit in Instron machine

Figure 28  Typical force-deformation curve for raspberry fruit subjected to flat-plate loading at 2 cm/min.
rate of two cm/min. No attempt was made to determine the time dependent properties of the fruit; only one rate of loading was used.

A typical force-deformation curve for raspberry fruit is shown in figure 28. Three characteristic moduli were obtained from each curve: the angle modulus (the angle between the lower linear portion of the curve and the deformation axis), the tangent modulus (the tangent of the above angle) and the linear limit (the minimum load at which the curve became non-linear). Correlations among force-deformation characteristics and other fruit properties, which are presented in Table VIII, are discussed later. Based on the units of measurement which defined the force-deformation curves, the relationship between compressive load and fruit deformation was

\[ P_c = d_c \times (20\gamma) \]  \[ 25 \]

where

- \( P_c \) = compressive load, gm
- \( d_c \) = fruit deformation, mm
- \( \gamma \) = tangent modulus (Table VIII)

For these units of measurement, \( K \) (equation [18]) has a value of 20\( \gamma \).

**Fruit Rigidity**

In an attempt to measure fruit quality, an apparatus similar to that developed by Nybom and described in reference (24) was used. Individual raspberries were placed upright between the diaphragms of two earphones (figure 29). The upper earphone exerted a compressive force of ten grams on the fruit while the lower earphone was excited at a frequency of 250 Hz by a signal
generator. Vibrations transmitted through the fruit to the upper earphone generated an alternating current which was amplified by an A-C amplifier and read on an ammeter. The ammeter reading was defined as fruit rigidity. Correlations among rigidity and other fruit properties are presented in Table VIII and are discussed later. As is shown in Table VI rigidity readings were significantly correlated with fruit dimensions at $P \leq 0.01$.

Figure 29 Instrumentation for measuring fruit rigidity.
TABLE VI  SIMPLE CORRELATIONS AMONG RIGIDITY AND FRUIT DIMENSIONS

<table>
<thead>
<tr>
<th></th>
<th>Rigidity</th>
<th>Fruit Weight</th>
<th>Fruit Length</th>
<th>Maximum Fruit Diameter</th>
<th>Minimum Fruit Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigidity</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fruit Weight</td>
<td>-0.42</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fruit Length</td>
<td>-0.44</td>
<td>0.79</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Fruit Diameter</td>
<td>-0.30</td>
<td>0.72</td>
<td>0.62</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Minimum Fruit Diameter</td>
<td>-0.22</td>
<td>0.80</td>
<td>0.63</td>
<td>0.72</td>
<td>1.00</td>
</tr>
</tbody>
</table>

n = 144  \ r_{0.05} = 0.16  \ r_{0.01} = 0.21

**Sugar Content of Fruit**

In a further attempt to relate fruit properties, sugar content was measured on 141 randomly selected samples during two days at the beginning of the 1968 harvest. Sugar content was determined in the field with a Zeiss model 0/85 hand sugar refractometer, which measures sugar on the basis of differences in indices of refraction of sugar solutions. Simple correlations among fruit retention force, fruit weight and sugar content are presented in Table VII. Since sugar content measurement was a destructive test, correlations between sugar content and force-deformation characteristics were not obtained. As can be seen from the table, the simple correlation of fruit retention force on fruit sugar content was not significant at \( P \leq 0.05 \).
### TABLE VII  SIMPLE CORRELATIONS AMONG FRUIT RETENTION FORCE, FRUIT WEIGHT AND FRUIT SUGAR CONTENT

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Fruit Retention Force</th>
<th>Fruit Weight</th>
<th>Fruit Sugar Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fruit Retention Force (gm)</td>
<td>303.0</td>
<td>152.0</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fruit Weight (gm)</td>
<td>5.1</td>
<td>0.75</td>
<td>0.12</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Fruit Sugar Content (percent)</td>
<td>10.2</td>
<td>1.75</td>
<td>0.14</td>
<td>0.21</td>
<td>1.00</td>
</tr>
</tbody>
</table>

\[ n = 141 \quad r_{0.05} = 0.16 \quad r_{0.01} = 0.21 \]

Comparison of Fruit Properties in an Attempt to Define Fruit Quality

In hand grading raspberries, the grader bases his decision primarily on fruit color and on firmness of fruit as determined by feeling the fruit with his fingers. Both of these parameters influence the acceptibility of the fruit at the consumer level. An immature fruit is of light color and feels firm between the fingers while an overmature fruit is of dark color and is soft. Since a mechanical harvester must selectively harvest fruit of acceptable quality, the relationship between fruit properties was studied in order to obtain a parameter which could be used for mechanical fruit selection.

Table VIII presents simple correlations among fruit
retention force, F/W, rigidity and force-deformation moduli for a random sample of 90 fruit collected on five different days during the 1968 harvest season. As can be seen, fruit retention force and F/W are both significantly correlated with force-deformation characteristics of the fruit. The highest correlation exists with the tangent modulus. The tangent modulus may be considered as an elastic modulus indicating how firmly the individual drupelets are held together and hence is a good indicator of fruit firmness as measured by hand. As can also be seen from the table, rigidity as measured by transmission of vibration is poorly correlated with fruit retention force or other fruit properties.

TABLE VIII  SIMPLE CORRELATIONS AMONG FRUIT RETENTION FORCE, F/W, RIGIDITY AND FORCE-DEFORMATION MODULI

<table>
<thead>
<tr>
<th></th>
<th>Fruit Retention Force (gm)</th>
<th>Rigidity F/W (100^-3)</th>
<th>Angle Modulus (degrees)</th>
<th>Tangent Modulus Limit (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>254.0</td>
<td>82.7</td>
<td>440.0</td>
<td>1.32</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>146.0</td>
<td>65.0</td>
<td>190.0</td>
<td>12.2</td>
</tr>
<tr>
<td>Fruit Retention Force</td>
<td>1.00</td>
<td>0.88</td>
<td>0.15</td>
<td>0.66</td>
</tr>
<tr>
<td>F/W</td>
<td>0.88</td>
<td>1.00</td>
<td>0.15</td>
<td>0.57</td>
</tr>
<tr>
<td>Rigidity</td>
<td>0.15</td>
<td>0.23</td>
<td>1.00</td>
<td>0.17</td>
</tr>
<tr>
<td>Angle Modulus</td>
<td>0.66</td>
<td>0.57</td>
<td>0.17</td>
<td>1.00</td>
</tr>
<tr>
<td>Tangent Modulus</td>
<td>0.68</td>
<td>0.61</td>
<td>0.15</td>
<td>0.96</td>
</tr>
<tr>
<td>Linear Limit</td>
<td>0.59</td>
<td>0.49</td>
<td>0.03</td>
<td>0.76</td>
</tr>
</tbody>
</table>

n = 90  r_0.05 = 0.22  r_0.01 = 0.28
Tables IX and X present simple correlations among fruit color index, fruit retention force, F/W, rigidity and force-deformation moduli for 144 random samples picked on the first day and on the fifteenth day of the 1968 harvest season. As can be seen from these tables, significant correlations exist among color index, fruit retention force, F/W and force-deformation moduli for both days of measurement. The simple linear regressions of fruit retention force and F/W on color index for the first day of the harvest season were

\[ F = 1335.6 + 17.7C, \quad r^2 = 0.29, \quad n = 144, \quad S_y = 133.1 \quad [26] \]

\[ F/W = -205.2 + 3.2C, \quad r^2 = 0.08, \quad n = 144, \quad S_y = 53.3 \quad [27] \]

for the range 84.5 ≤ C ≤ 109.0

where
- F = fruit retention force, grams
- F/W = fruit retention force/fruit weight
- C = fruit color index

Similarly, for the fifteenth day of the harvest season the regression equations were

\[ F = 1728.7 + 21.7C, \quad r^2 = 0.28, \quad n = 144, \quad S_y = 113.4 \quad [28] \]

\[ F/W = 488.0 + 6.2C, \quad r^2 = 0.26, \quad n = 144, \quad S_y = 34.1 \quad [29] \]

for the range 84.0 ≤ C ≤ 100.0

The simple linear regressions of individual force-deformation moduli on color index were also obtained. Comparison of similar regression equations, for the first and fifteenth day of the harvest season, using the analysis of covariance (33) revealed that similar regressions were homogeneous with respect to residual variance and did not have significantly different slopes. Levels for the two days of measurement were, however, significantly
different. For example, the simple linear regressions of tangent modulus on color index for the first and fifteenth day, respectively, were

\[ Y = -5.16 + 0.07C, \quad r^2 = 0.33, \quad n = 144, \quad S_y = 0.51 \quad [30] \]

for the range \(84.5 \leq C \leq 109.0\)

\[ Y = -4.54 + 0.06C, \quad r^2 = 0.17, \quad n = 144, \quad S_y = 0.47 \quad [31] \]

for the range \(84.0 \leq C \leq 100.0\)

where \(Y\) = tangent modulus

\(C\) = fruit color index

Although the slopes of the above equations are not significantly different, the levels are significantly different at \(P \leq 0.005\). This indicates that the tangent modulus for fruits of equal color decreases as the harvest season progresses. Since the tangent modulus is an indicator of how firmly the individual druplets are bound together, it also is measure of how firmly the fruit is attached to the core. This explains the reason for the previously reported significant negative correlation between fruit retention force and time of harvest.

Due to the significant correlations among fruit retention force, F/W, fruit color and tangent modulus, it may be concluded that both fruit retention force and F/W are indirect indicators of fruit quality. A machine which harvests selectivity on the basis of fruit retention force level or F/W level will also harvest on the basis of fruit quality.
TABLE IX  SIMPLE CORRELATIONS AMONG COLOR INDEX, FRUIT RETENTION FORCE, F/W, RIGIDITY AND FORCE-DEFORMATION MODULI FOR THE FIRST DAY OF THE 1968 HARVEST SEASON.

<table>
<thead>
<tr>
<th>Color Index</th>
<th>Fruit Retention Force</th>
<th>F/W</th>
<th>Rigid Modulus</th>
<th>Angle Modulus</th>
<th>Tangent Modulus</th>
<th>Linear Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color Index</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fruit Retention Force</td>
<td>0.54</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F/W</td>
<td>0.28</td>
<td>0.73</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rigidity</td>
<td>0.02</td>
<td>0.10</td>
<td>0.32</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle Modulus</td>
<td>0.53</td>
<td>0.63</td>
<td>0.43</td>
<td>0.26</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Tangent Modulus</td>
<td>0.57</td>
<td>0.69</td>
<td>0.52</td>
<td>0.24</td>
<td>0.93</td>
<td>1.00</td>
</tr>
<tr>
<td>Linear Limit</td>
<td>0.54</td>
<td>0.62</td>
<td>0.42</td>
<td>0.08</td>
<td>0.74</td>
<td>0.87</td>
</tr>
</tbody>
</table>

n = 144  \begin{align*} r_{0.05} &= 0.16 \\ r_{0.01} &= 0.21 \end{align*}

TABLE X  SIMPLE CORRELATIONS AMONG COLOR INDEX, FRUIT RETENTION FORCE, F/W, RIGIDITY AND FORCE-DEFORMATION MODULI FOR THE FIFTEENTH DAY OF THE 1968 HARVEST SEASON.

<table>
<thead>
<tr>
<th>Color Index</th>
<th>Fruit Retention Force</th>
<th>F/W</th>
<th>Rigid Modulus</th>
<th>Angle Modulus</th>
<th>Tangent Modulus</th>
<th>Linear Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color Index</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fruit Retention Force</td>
<td>0.53</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F/W</td>
<td>0.51</td>
<td>0.95</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rigidity</td>
<td>0.33</td>
<td>0.30</td>
<td>0.40</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle Modulus</td>
<td>0.35</td>
<td>0.68</td>
<td>0.68</td>
<td>0.39</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Tangent Modulus</td>
<td>0.41</td>
<td>0.73</td>
<td>0.72</td>
<td>0.36</td>
<td>0.95</td>
<td>1.00</td>
</tr>
<tr>
<td>Linear Limit</td>
<td>0.47</td>
<td>0.73</td>
<td>0.70</td>
<td>0.36</td>
<td>0.82</td>
<td>0.87</td>
</tr>
</tbody>
</table>

n = 144  \begin{align*} r_{0.05} &= 0.16 \\ r_{0.01} &= 0.21 \end{align*}

1 This heading applies to the columns in both Table IX and Table X.
Dynamic Response of Canes and Fruit Attachment System

The raspberry plant is a complex structure consisting of canes, shoots, intermediate limbs, fruit attachment members and foliage. As with most biological materials, mechanical properties of the canes and limbs may be time dependent when subjected to dynamic loading since both internal damping and external damping may be expected.

In addition, properties are influenced by existing environmental conditions, resulting in large variation even within one field of fruit. Since many approximations must be made in dynamic analysis of such a system, results may be used only as a rough guide for design. In analyzing the dynamic response of the raspberry plant, the following simplifying assumptions were made: The plant was considered as two separate systems, the fruit attachment system and the central plant cane which supports the fruit attachment system. The canes were assumed to have elastic properties. Internal and external damping were not considered.

The method of analyzing the vibratory characteristics of the raspberry fruit attachment system was similar to that used by Wang (37) for coffee fruit. Wang considered the coffee-cherry peduncle system as a cantilever beam with a concentrated end mass. Natural frequency was estimated by measuring the spring constant of the peduncle and analyzing as a simple spring-mass system. Since the spring constant of the stem (figure 30) attaching the raspberry to the secondary limb structure is negligible, the fruit-stem system was analyzed as a simple pendulum. On this basis, the estimated natural frequency of the fruit attachment
system was

\[ \omega_n = \left[ \frac{g}{(l + 0.5h)} \right]^{1/2} \]  

where \[ g \] = acceleration due to gravity
\[ h \] = fruit length
\[ l \] = fruit stem length

Based on the dimensions reported in Table III and a fruit weight of \( 3.52 \pm 0.97 \) gm, the estimated natural frequency of the fruit attachment system varied from 135 to 164 cycles per minute.

If base motion is applied to the cane and not to the fruit attachment system, investigation of the modes of vibration of the canes is important. Fridley and Adrian (13) suggest that optimum design frequency of a fruit harvesting system should be a natural frequency of the tree system. Adrian et al (1) showed amplitude magnification at resonant frequencies in controlled tests on olive limbs when base motion was applied at an antinode.

The method of influence coefficients (36) was used to estimate the modes and frequencies of two selected raspberry canes. Since there is a large variation in cane size, two canes of different

\[
\begin{align*}
\text{Fruit} & \quad \text{mg} \\
\hline
\text{Stem} & \quad l \times h/2
\end{align*}
\]

Figure 30 Fruit attachment system idealized as a simple pendulum.
physical appearance were selected, one representing the largest diameter of fruit bearing canes and the other representing the smallest diameter. The canes were removed from the field in the spring of 1969, just as leaf buds were beginning to emerge. An epoxy base was cast on the root end of each cane to facilitate holding while measurements were conducted. Each cane was divided into eight stations spaced at six inch intervals along its length. The canes were held vertically (figure 31) and stiffness influence coefficients were determined by measuring the deflection at all stations while a horizontal load of 200 grams was successively applied to each station.

The flexibility matrix resulting from one such test is shown in Table XI. The values presented in the table are the

![Figure 31 Measurement of the stiffness influence coefficients of a raspberry cane.](image)
deflections in inches resulting from the successive application of a load of 200 grams at 6 inch intervals up the cane. (Cij is the deflection at station j resulting from load application at station i.) As can be seen, the flexibility matrix is nearly symmetric indicating that for static loads of short duration, the material in the raspberry canes may be considered elastic.

After determination of the influence coefficients, a small deformation was observed in the cane upon load removal. The cane relaxed, returning to zero position after thirty minutes.

**TABLE XI FLEXIBILITY MATRIX, [C], FOR A RASPBERRY CANE LOADED AS A VERTICAL CANTILEVER BEAM.**

<table>
<thead>
<tr>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>0.04</td>
<td>0.08</td>
<td>0.11</td>
<td>0.16</td>
<td>0.19</td>
<td>0.21</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>0.15</td>
<td>0.22</td>
<td>0.30</td>
<td>0.40</td>
<td>0.51</td>
<td>0.60</td>
<td>0.65</td>
</tr>
<tr>
<td>3</td>
<td>0.08</td>
<td>0.22</td>
<td>0.40</td>
<td>0.60</td>
<td>0.84</td>
<td>1.05</td>
<td>1.26</td>
<td>1.40</td>
</tr>
<tr>
<td>4</td>
<td>0.11</td>
<td>0.32</td>
<td>0.61</td>
<td>0.92</td>
<td>1.38</td>
<td>1.76</td>
<td>2.17</td>
<td>2.50</td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td>0.40</td>
<td>0.84</td>
<td>1.37</td>
<td>2.02</td>
<td>2.62</td>
<td>3.29</td>
<td>3.90</td>
</tr>
<tr>
<td>6</td>
<td>0.19</td>
<td>0.51</td>
<td>1.06</td>
<td>1.74</td>
<td>2.66</td>
<td>3.65</td>
<td>4.50</td>
<td>5.45</td>
</tr>
<tr>
<td>7</td>
<td>0.20</td>
<td>0.62</td>
<td>1.28</td>
<td>2.18</td>
<td>3.29</td>
<td>4.55</td>
<td>6.08</td>
<td>7.60</td>
</tr>
<tr>
<td>8</td>
<td>0.24</td>
<td>0.69</td>
<td>1.44</td>
<td>2.45</td>
<td>3.90</td>
<td>5.50</td>
<td>7.62</td>
<td>9.70</td>
</tr>
</tbody>
</table>

After determination of the flexibility matrix, the cane was cut into pieces midway between each station and each piece was weighed. For estimation of modes and natural frequencies, the mass of the cane was considered to be lumped at each of the eight stations, reducing the infinite degree of freedom system
to a discrete system with eight degrees of freedom. Table XII presents the mass matrix for the same cane as described in Table XI. The values presented in Table XII are the weights, in grams, which were considered lumped at each station.

TABLE XII MASS MATRIX, [m], FOR A RASPBERRY CANE

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>10.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>9.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>6.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>8</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.5</td>
</tr>
</tbody>
</table>

In order to estimate the modes of vibration of the canes and the corresponding natural frequencies, a process of matrix iteration (36) was used. Using a consistent set of units, the mode of vibration is

\[
\{Z_1\} = \omega_1^2 \begin{bmatrix} C \\ \text{m} \end{bmatrix} \{Z_1\} = \omega_1^2 \begin{bmatrix} D \end{bmatrix} \{Z_1\} \tag{33}
\]

where

- \{Z_1\} = the column matrix for the first mode
- [C] = the flexibility matrix (Table XI)
- [m] = the diagonal mass matrix (Table XII)
- [D] = [C] [m] = the dynamic matrix
- \omega_1 = the fundamental (first) natural frequency of the cane

These data apply to the same cane for which the flexibility matrix was presented in Table XI.
Figure 32 Calculated modes of vibration and corresponding natural frequencies for two raspberry canes.
The last column of the dynamic matrix was normalized and used as an initial approximation for the mode shape. Application of the iterative procedure shown in equation [33] resulted in convergence to the first principle mode and yielded the fundamental frequency, $\omega_1$. For determination of the second mode and the second natural frequency, a sweeping matrix, devoid of the first mode, was used in the iterative procedure.

$$\{Z_2\} = \omega_2^2[D][S_1]\{Z_2\}$$  \[34\]

where

- $\{Z_2\}$ = the column matrix for the second mode
- $[S_1]$ = the sweeping matrix
- $\omega_2$ = the second natural frequency of the cane

The first two modes and corresponding resonant frequencies for the two raspberry canes are presented in figure 32. The calculated resonant frequencies of the two canes were 185 and 218 cycles per minute for the first mode and 786 and 1032 cycles per minute for the second mode. The inclusion of fruit and limb mass and damping would reduce these frequencies considerably. Due to the simplifying assumptions used in these determinations, the resulting values are not indicative of the actual dynamic response of the complete plant. The results are, however, useful in designing a harvesting machine. The large differences observed between the two canes indicate that attempting to design a harvesting machine which operates at a resonant frequency of the plant system is impractical. Furthermore, application of base motion to only one part of the canes (figure 10) is also impractical since the resulting inertial force developed in the fruiting portions will be variable, depending upon the properties
of the individual canes.

**Elastic Modulus of Raspberry Canes**

The elastic modulus of the two canes studied in the previous section was estimated by both an energy method and by a numerical solution of the Euler equation for large deflections of tapered beams. The energy solution was based on Rayleigh's method (36) for determination of the fundamental frequency of a continuous system. The fundamental frequency as obtained from the matrix iteration procedure was substituted into Rayleigh's formulation and the resulting equation was solved for the elastic modulus.

\[
E = (\omega_1)^2 \frac{\int_0^L m(x) Z^2 \, dx}{\int_0^L I(x) \left( \frac{d^2 Z}{dx^2} \right)^2 \, dx}
\]

where
- \( I(x) \) = moment of inertia of the cane cross section per unit of length
- \( L \) = total length of the cane
- \( Z \) = mode shape
- \( m(x) \) = mass of the cane per unit of length
- \( \omega_1 \) = fundamental frequency of the cane

The canes were considered as tapered cantilever beams of circular cross section. \( I(x) \) and \( m(x) \) were determined by plotting the values of cane diameter and cane mass for each of the eight stations used in determining the flexibility matrix and fitting straight lines. A parabolic mode shape, \( Z = C_1 x^2 \), satisfying the boundary conditions for a cantilever beam, was chosen. The resulting estimates of elastic modulus for the two canes shown in figure 32 were 295,000 lb/in\(^2\) for cane 1 and 469,000 lb/in\(^2\) for cane 2.
A second estimate of the elastic modulus was obtained by use of numerical solutions of the Euler equation for large deflections of truncated cones with concentrated end loads, as presented by Diener et al. The tabulated solutions, which were used by these authors in studying the deflection of apple limbs, are of the form

\[ \frac{y}{L} = \frac{P_a L^2}{EI_o} \cdot f(q,c) \]  

[36]

where

- \( E \) = elastic modulus
- \( I_o \) = moment of inertia of cross section at root of limb
- \( L \) = limb length
- \( P_a \) = concentrated load applied at limb tip
- \( q = \frac{P_a L^2}{EI_o} \)
- \( c = \) taper of limb = tip radius/root radius
- \( y = \) deflection of limb tip

Substituting appropriate values of \( I_o, P_a, L, y \) and \( c \) for the two raspberry canes, into the tabulated solutions resulted in estimates of elastic modulus of 255,000 lbs/in\(^2\) and 463,000 lbs/in\(^2\) for canes 1 and 2 respectively.

Control of Physical Properties - Growth Regulators

The following discussion does not directly pertain to design of a mechanical harvester but is included since it may significantly affect the performance of mechanical harvesting systems for raspberries. Since the high ratio of fruit retention force to fruit stem strength may seriously limit the picking efficiency of a mechanical harvester, an attempt was
made to reduce fruit retention force through the use of chemical growth regulators. Unrath and Kenworthy (23) successfully used growth regulators to reduce the fruit retention force of cherries. A similar technique was applied to raspberries in an attempt to improve the suitability of the plants to mechanical harvesting. Since no published results on the use of growth regulators on raspberries could be obtained, growth regulators were selected on the basis of their effect on other fruit.

A randomized block consisting of fourteen plots (figure 33) each having ten plants, was used for the growth regulator trials. The selected growth regulators were succinic acid 2,2-dimethylhydrazide (Alar) and a mixture of equal parts of 2,4,5-trichlorophenoxypropionic acid (2,4,5-TP) and naphthaleneacetic acid (NAA). Three concentrations of each of the growth regulators were applied to individual plots at two different application dates as shown in Table XIII.

Growth regulators were applied using a semi-circular spray boom (figure 34) with four No. 650067 T-Jet spray nozzles spaced to apply relatively uniform coverage on the fruit bearing portion of the plants. Two such booms were used to avoid possible mixing of growth regulators. The spray solution was placed in the liquid tank on the boom end (figure 34) and air at 40 psig was applied to the tank with a portable air compressor. The resulting rate of discharge of each spray boom was 1000 cc/min. The concentration of Alar placed in the spray tank was 1000 ppm while the concentration of 2,4,5-TP+NAA was 20 ppm. In order to obtain the low concentrations
Figure 33  Randomized plots for growth regulator trials

Figure 34  Spray boom for applying growth regulators
(Table XIII) 250 cc of the solution was applied to the selected 10 plant plot, while to obtain the medium concentrations, 500 cc was applied and for the high concentrations, 1000 cc was applied. This was accomplished by making one fifteen second pass of the spray boom over a plot for low concentrations, two passes (30 seconds) for intermediate concentrations, and four passes (one minute) for high concentrations.

### TABLE XIII GROWTH REGULATOR TREATMENTS

<table>
<thead>
<tr>
<th>Treatment Number</th>
<th>Plot Number (see Fig.33)</th>
<th>Growth Regulator</th>
<th>Concentration (p.p.m.)</th>
<th>Application Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>check</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>Alar</td>
<td>1000</td>
<td>June 17</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>Alar</td>
<td>2000</td>
<td>June 17</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>Alar</td>
<td>4000</td>
<td>June 17</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>2,4,5-TP+NAA</td>
<td>20</td>
<td>June 17</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>2,4,5-TP+NAA</td>
<td>40</td>
<td>June 17</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>2,4,5-TP+NAA</td>
<td>80</td>
<td>June 17</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>check</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>11</td>
<td>Alar</td>
<td>1000</td>
<td>June 28</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>Alar</td>
<td>2000</td>
<td>June 28</td>
</tr>
<tr>
<td>11</td>
<td>13</td>
<td>Alar</td>
<td>4000</td>
<td>June 28</td>
</tr>
<tr>
<td>12</td>
<td>9</td>
<td>2,4,5-TP+NAA</td>
<td>20</td>
<td>June 28</td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td>2,4,5-TP+NAA</td>
<td>40</td>
<td>June 28</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
<td>2,4,5-TP+NAA</td>
<td>80</td>
<td>June 28</td>
</tr>
</tbody>
</table>

Three plants in each plot were selected for comparative purposes. On each of five days during the harvest season, three
fruit were picked at random from each selected plant in each plot. Fruit retention force, fruit weight, fruit color, rigidity and force-deformation characteristics were determined for each fruit. Analysis of variance tests were conducted, comparing the measured variables of the growth regulator treatments. Results of the tests indicated that both types of growth regulators significantly affected fruit retention force, fruit color and fruit weight. The type of growth regulator, its concentration and its time of application all affected fruit retention force. Furthermore, the effect was dependent upon time of harvest.

Since fruit retention force, fruit weight and F/W all influence harvester design, the effect of growth regulators on these parameters was investigated more fully. The simple regressions of fruit retention force on harvest time were determined (Table XIV) for each treatment. The analysis of covariance (33) was used to compare the regression for each growth regulator treatment to the pooled regression for treatments 1 and 8. This analysis compared homogeneity of residual variance, slope and level of the two regression lines in order to find significant differences. Similar comparisons were made for fruit weight (Table XV) and F/W (Table XVI).

Tables XIV, XV, XVI are based on 90 observations for the check and 45 observations for each growth regulator treatment. The first column in each table represents the treatment as shown in Table XIII. The fourth column is the intercept and the fifth column is the slope of the regression equation, \( Y = a + bT \), where \( Y \) is the dependent variable named in the title of the table.
The regression equations apply for the interval, $1 \leq T \leq 15$, where $T$ is time in days and $(T = 1)$ is the first day of harvest. The ninth, tenth and eleventh columns in each table indicate results of the covariance analysis. In cases where the homogeneity of residual variance show a significant difference, the tests for slope and level are not valid.

The results of the covariance analysis indicate that the use of growth regulators could significantly affect the performance of a mechanical harvester. For example, treatments 3 and 14 significantly reduced fruit retention force while treatments 5, 11 and 14 significantly reduced F/W, for the early part of the harvest season. Since the highest ratio of fruit retention force to stem strength occurs early in the harvest season, these treatments could possibly increase the picking efficiency of a mechanical harvester during the first part of the harvest. Further trials are necessary before any firm conclusions may be drawn.
TABLE XIV VARIATION OF FRUIT RETENTION FORCE WITH TIME AS AFFECTED BY GROWTH REGULATOR TREATMENTS

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean (gm)</th>
<th>Standard Deviation</th>
<th>Significance of Covariance Analysis</th>
<th>Significance of Homogeneity of Variance</th>
<th>Slope</th>
<th>Analysis Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check (pooled)</td>
<td>254.0</td>
<td>146.5</td>
<td>347.7 -13.4 -.43 P≤ 0.01 132.9</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>282.6</td>
<td>150.8</td>
<td>382.6 -14.3 -.45 P≤ 0.01 136.3</td>
<td>NS</td>
<td>NS</td>
<td>P≤ 0.25</td>
</tr>
<tr>
<td>3</td>
<td>280.3</td>
<td>126.7</td>
<td>287.3 -1.0 -.04 NS¹ 128.1</td>
<td>NS</td>
<td>P≤ 0.025</td>
<td>NS</td>
</tr>
<tr>
<td>4</td>
<td>389.7</td>
<td>181.1</td>
<td>452.7 -9.0 -.23 NS 178.1</td>
<td>NS</td>
<td>NS</td>
<td>P≤ 0.005</td>
</tr>
<tr>
<td>5</td>
<td>289.2</td>
<td>132.8</td>
<td>316.8 -4.0 -.14 NS 133.0</td>
<td>NS</td>
<td>P≤ 0.10</td>
<td>P≤ 0.25</td>
</tr>
<tr>
<td>6</td>
<td>315.1</td>
<td>126.3</td>
<td>392.3 -11.0 -.41 P≤ 0.01 116.3 P≤ 0.25</td>
<td>NS</td>
<td>NS</td>
<td>P≤ 0.01</td>
</tr>
<tr>
<td>7</td>
<td>280.6</td>
<td>122.1</td>
<td>350.6 -10.0 -.39 P≤ 0.01 113.8 P≤ 0.25</td>
<td>NS</td>
<td>NS</td>
<td>P≤ 0.25</td>
</tr>
<tr>
<td>9</td>
<td>287.7</td>
<td>180.1</td>
<td>386.6 -14.1 -.37 P≤ 0.01 169.1</td>
<td>NS</td>
<td>NS</td>
<td>P≤ 0.25</td>
</tr>
<tr>
<td>10</td>
<td>266.1</td>
<td>148.1</td>
<td>310.0 -6.3 -.20 NS 146.7</td>
<td>NS</td>
<td>P≤ 0.25</td>
<td>NS</td>
</tr>
<tr>
<td>11</td>
<td>288.2</td>
<td>162.2</td>
<td>344.4 -8.0 -.23 NS 159.5</td>
<td>NS</td>
<td>NS</td>
<td>P≤ 0.25</td>
</tr>
<tr>
<td>12</td>
<td>264.9</td>
<td>143.1</td>
<td>375.8 -15.8 -.52 P≤ 0.01 123.2</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>13</td>
<td>339.0</td>
<td>185.9</td>
<td>445.2 -15.2 -.39 P≤ 0.01 173.4</td>
<td>NS</td>
<td>NS</td>
<td>P≤ 0.005</td>
</tr>
<tr>
<td>14</td>
<td>292.1</td>
<td>143.1</td>
<td>273.6 2.6 .09 NS 144.2</td>
<td>NS</td>
<td>P≤ 0.25</td>
<td>P≤ 0.005</td>
</tr>
</tbody>
</table>

¹ NS indicates no significant difference between the pooled check and the growth regulator treatment at P ≤ 0.25
TABLE XV. VARIATION OF FRUIT WEIGHT WITH TIME AS AFFECTED BY GROWTH REGULATOR TREATMENTS

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean (gm)</th>
<th>Standard Deviation</th>
<th>Significance of $a$</th>
<th>Significance of $b$</th>
<th>Significance of $r$</th>
<th>Significance of Covariance Analysis of Variance</th>
<th>Slope</th>
<th>Analysis Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check (pooled)</td>
<td>3.52 0.97</td>
<td>3.01 0.07 .35 $P \leq 0.01$ 0.92</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>3.92 1.46</td>
<td>4.10 -0.03-.09</td>
<td>NS 1.48</td>
<td>NS</td>
<td>$P \leq 0.05$</td>
<td>P $\leq 0.10$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.76 1.21</td>
<td>1.80 0.14 .54 $P \leq 0.01$ 1.03</td>
<td>NS</td>
<td>NS</td>
<td>$P \leq 0.10$</td>
<td>P $\leq 0.005$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4.14 0.83</td>
<td>4.15 -0.00-.01</td>
<td>NS 0.84</td>
<td>NS</td>
<td>$P \leq 0.05$</td>
<td>P $\leq 0.005$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3.33 1.16</td>
<td>3.43 -0.01-.06</td>
<td>NS 1.18</td>
<td>NS</td>
<td>$P \leq 0.05$</td>
<td>NS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4.08 0.76</td>
<td>4.14 -0.01-.05</td>
<td>NS 0.77 $P \leq 0.25$</td>
<td>P $\leq 0.025$</td>
<td>P $\leq 0.005$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>3.94 0.95</td>
<td>4.57 -0.09-.45 $P \leq 0.01$ 0.86</td>
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<td>NS</td>
<td>$P \leq 0.005$</td>
<td>P $\leq 0.025$</td>
<td></td>
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</tr>
<tr>
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<td>4.64 0.82</td>
<td>4.95 -0.04-.26</td>
<td>NS 0.80</td>
<td>NS</td>
<td>$P \leq 0.005$</td>
<td>P $\leq 0.005$</td>
<td></td>
<td></td>
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<tr>
<td>10</td>
<td>3.98 0.94</td>
<td>4.16 -0.02-.12</td>
<td>NS 0.94</td>
<td>NS</td>
<td>$P \leq 0.01$</td>
<td>P $\leq 0.10$</td>
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<tr>
<td>11</td>
<td>3.85 0.96</td>
<td>3.83 0.00 .01</td>
<td>NS 0.97</td>
<td>NS</td>
<td>$P \leq 0.10$</td>
<td>P $\leq 0.10$</td>
<td></td>
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</tr>
<tr>
<td>12</td>
<td>4.29 0.89</td>
<td>4.33 -0.00-.03</td>
<td>NS 0.90</td>
<td>NS</td>
<td>$P \leq 0.05$</td>
<td>P $\leq 0.005$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>4.32 1.14</td>
<td>4.40 -0.01-.04</td>
<td>NS 1.15</td>
<td>NS</td>
<td>$P \leq 0.05$</td>
<td>P $\leq 0.005$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>3.51 1.41</td>
<td>3.85 -0.05-.16</td>
<td>NS 1.41</td>
<td>NS</td>
<td>$P \leq 0.01$</td>
<td>NS</td>
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</table>
### TABLE XVI  F/W VARIATION WITH TIME AS AFFECTED BY GROWTH REGULATOR TREATMENTS

<table>
<thead>
<tr>
<th>Treatment (pooled)</th>
<th>Mean (gm)</th>
<th>Standard Deviation</th>
<th>Significance of Covariance Analysis Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Check</td>
<td>82.8</td>
<td>65.1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>93.5</td>
<td>105.1</td>
<td></td>
</tr>
<tr>
<td>3</td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>98.0</td>
<td>50.8</td>
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</tr>
<tr>
<td>5</td>
<td>101.4</td>
<td>75.1</td>
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</tr>
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<td>80.8</td>
<td>36.3</td>
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<td>74.8</td>
<td>37.5</td>
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<td>45.8</td>
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<td>65.8</td>
<td>39.9</td>
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<td>82.7</td>
<td>47.4</td>
<td></td>
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<td>14</td>
<td>103.1</td>
<td>78.2</td>
<td></td>
</tr>
</tbody>
</table>

Significance of Covariance Analysis Level

- P ≤ 0.01
- P ≤ 0.05
- P ≤ 0.10
- NS

Significance of Covariance Analysis Level

- P ≤ 0.005
- P ≤ 0.025
- P ≤ 0.10
- NS
MATHEMATICAL MODELS FOR THE TOOLS

Completion of the Tool Analyses

In this chapter, the elementary tool analyses and the analysis of the product characteristics are combined in order to obtain mathematical models representing the performance of each tool in the process. The resulting equations determine the design specifications of the individual tools.

Tool for Feeding and Cane Orientation

Figure 11 indicates that the total fruit bearing portion of the raspberry plant is located in a 5 foot height interval. Selecting a value of $45^\circ$ for $\theta$ (figure 8) the maximum necessary feed roll length is

$$5/\sin (45^\circ) = 7.1 \text{ ft.}$$

Selecting an external feed roll diameter of 4 inches with $\theta = 45^\circ$, from equation [3] the necessary relationship between feed roll rotation and forward speed is

$$n_r = 118.8S \quad [35]$$

where $n_r =$ feed roll speed, revolutions per minute

$S =$ forward speed of harvesting machine, miles per hour

Letting $x = L$, in equation [5] and solving for $P_a$, the resulting estimate of the horizontal reaction force between a single cane and a feed roll is

$$P_a = \frac{[3yEI_o c(1-c)^3]}{[(1-3c+3c^2-c^3) L^3]} \quad [36]$$

where $L =$ the distance above the soil surface at which the feed roll contacts a cane,

$y =$ the horizontal cane deflection at the load point,

and $E$, $I_o$ and $c$ are as previously defined. Due to the
inclination of the feed rolls, \( L, y \) and \( c \) depend upon the position on the feed rolls at which contact with each individual cane occurs.

The total reaction force between the canes and feed rolls depends upon the total number of canes in contact at any instant. Assuming a maximum number of ten canes and ten shoots per plant and considering a feed roll length of 7.1 feet and a plant spacing of 2.5 feet, a maximum of 40 canes and shoots will be in contact with the feed rolls. Assuming that the flexural properties of the shoots are similar to those of the canes and noting that one feed roll compresses only half of the plant, the total reaction force on one feed roll will result from contact with 20 canes. Assuming that the 20 canes are equally spaced at 3 inches down the row, the height (inches) above ground at which a feed roll contacts a cane (figure 35) is

\[
L = 6 + z \tag{37}
\]

where \( z = \) the horizontal distance (inches) behind the front of the feed roll at which cane contact occurs.

Based on a plant width of 10 inches at ground level and 60 inches at the 5.5 foot height, assuming all canes are so oriented and further assuming that it is desired to compress all plants to an 8 inch width at the 0.5 foot level and a 4 inch width at the 5.5 foot level, it can be shown by geometrical interpretation (figure 36) that the horizontal cane deflection (inches) is

\[
y = 3.8 + 0.504z \tag{38}
\]

where \( z \) is as previously defined.
Figure 35 Estimating the point of contact between the canes and the feed rolls.

Figure 36 Estimating the deflection of the canes by the feed rolls.
Cane taper, as defined in equation [5], is also a function of the distance above ground at which loading occurs. Figure 37 shows a raspberry cane represented as a tapered circular cantilever beam. The dimensions used in this figure are those of the same cane as described in Tables XI and XII and represent the largest expected size of raspberry canes. By geometrical interpretation of figure 37, cane taper may be defined as

\[ c = 0.95 - 0.0088z \]  

[39]

where \( z \) is as previously defined.

Substituting values for \( L, y \) and \( c \) as given in equations [37], [38], and [39] respectively, into equation [36], \( P_a \) now becomes the load on the feed roll at any distance \( z \) measured.

Figure 37 Determining cane taper as a function of the point of load application
rearward from the front end of the feed roll. The total load imposed by twenty canes evenly spaced at 3 inches along the 5 foot horizontal length of the feed roll is

\[ P_{\text{total}} = \sum_{z=0,3,-}^{57,60} (P_a) \]  

Evaluating equation [40] based on \( I_o = 0.0052 \text{ in}^4 \) and \( E = 455,000 \text{ lb/in}^2 \) (data for the same cane as described in figure 37), the total horizontal reaction force between one feed roll and the canes it compresses was estimated at 249 lbs. The reaction force varied from 118 lbs. at the front of the feed roll to 0.35 lbs. at the rear of the feed roll. Even though equation [36] underestimates the load for large deflections, due to simple beam theory, the above calculated value for total reaction force can be expected to be high since it was assumed that all canes and shoots were of maximum rigidity, were subjected to maximum possible deflection and were rigidly attached to the soil surface.

**Tool for Selective Harvesting**

Analysis of cane properties indicated large variations in size, rigidity and modes of vibration of individual canes. If base motion is applied to a fixed point on each cane, resultant displacements at equal distances from the point of application will differ according to the properties of the individual canes. Since maximum acceleration developed at any point in a cane depends upon both frequency and displacement, the inertial force developed in the fruit will depend upon cane properties. Inertial force must, however, be controlled within the limits set by equation [6]. This can be accomplished only by applying both known displacement and known frequency to all fruit bearing
portions of the plant, indicating that base motion should be applied to all the plant. One method of obtaining this desired result is by applying the base motion to the feed rolls (figure 38). All fruit bearing portions will then be subjected to the same maximum displacement at the same frequency as the rolls pass the plants.

Both inertia shakers and fixed displacement shakers are commonly used for base motion application in tree fruit harvesting. Since the displacement produced by an inertia shaker is a function of the resisting load, the maximum acceleration produced by an inertia shaker depends upon physical properties of the plant. A fixed displacement shaker appears to be preferable for selective harvesting of raspberries since it will produce constant maximum base motion displacement, independent of the plant characteristics.

Both the fruit retention force and the F/W ratio, for fruit of similar quality, decrease during the harvest season as is shown by equations [23] and [24]. The force required for fruit removal therefore depends upon the specific date of harvest, indicating that the applied base motion must be adjusted to suit the time of harvest. The expected variation of fruit retention force and F/W ratio is summarized in Table XVII.

### TABLE XVII MEANS AND STANDARD DEVIATIONS OF FRUIT RETENTION FORCE AND F/W RATIO BASED ON DATA COLLECTED IN 1968

<table>
<thead>
<tr>
<th></th>
<th>First Day of Harvest Season</th>
<th>Fifteenth Day of Harvest Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fruit Retention</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force (gm)</td>
<td>291 ± 102</td>
<td>162 ± 142</td>
</tr>
<tr>
<td>F/W Ratio</td>
<td>96 ± 45</td>
<td>46 ± 43</td>
</tr>
</tbody>
</table>
Sixty eight percent of the measures defining a normal distribution fall within the range of the mean + one standard deviation, while 95 percent fall within the range of the mean + two standard deviations. Hence, 84 percent of the measures have values less than the sum of the mean plus one standard deviation, and 97.5 percent have values less than the mean plus two standard deviations. The estimated required base motion accelerations for 50, 84 and 97.5 percent fruit removal, based on the F/W distributions and equation [8], are given in Table XVIII. The necessary accelerations for other levels of fruit removal may be estimated by applying equation [8] to the corresponding values of F/W taken from the cumulative distribution curves in figure 19.
The collected data on fruit stem strength are not directly applicable to design of the picking tool since the loading used in determination of stem strength is not necessarily the same as actual stem loading during mechanical harvesting. Figure 22 shows the cumulative distribution of minimum stem strength \( \alpha = 0^\circ \) and hence does not give a reliable estimate of \( F_d \) in equation [6]. The trials on hand picking by direct tensile force indicated that if all the mature fruit is removed, 30 percent of the fruit may have stem damage. It is therefore apparent that to prevent stem damage, fruit removal efficiency for one pass of the harvester must be less than 70 percent. Overall fruit removal efficiency, considering the whole season, may be greater but only with a decrease in overall quality of the harvested fruit. Since fruit retention force decreases with fruit maturity, the fruit remaining after one pass of the harvester may be picked at a later date but the quality of the resulting fruit will be reduced. Since color index is an indicator of fruit quality, the acceleration required to remove fruit of reduced quality may be estimated. For example, using

<table>
<thead>
<tr>
<th>Fruit Removal (percent)</th>
<th>First Day of Harvest</th>
<th>Fifteenth Day of Harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper Limit of F/W</td>
<td>Motion Acceleration (ft/sec²)</td>
</tr>
<tr>
<td>50</td>
<td>96</td>
<td>3090</td>
</tr>
<tr>
<td>84</td>
<td>141</td>
<td>4540</td>
</tr>
<tr>
<td>97.5</td>
<td>186</td>
<td>5980</td>
</tr>
</tbody>
</table>
equations [26] and [28] with a fruit color index of 85, fruit retention force is estimated as 164 grams on the first day of harvest and 110 grams on the last day of harvest. Similarly, using equations [27] and [29] with a color index of 85, F/W is estimated as 67 on the first day of harvest and 38 on the last day of harvest. Corresponding required accelerations for fruit removal are only 2160 and 1220 ft/sec², respectively.

A simple device for applying fixed displacement base motion to the feed rolls is a slider crank mechanism. The maximum acceleration developed by a slider crank mechanism is

\[
\ddot{s}_{\text{max}} = (\omega_b)^2 r_s (1 - k)
\]

where

- \( k \) = crank length/connecting rod length
- \( r_s \) = crank length
- \( \omega_b \) = angular velocity of crank

The necessary amplitude and frequency for fruit removal may be determined by combining equations [8] and [41]. Figure 39 shows the maximum acceleration developed by a slider crank mechanism, with a connecting rod length of one foot, for several fixed amplitudes and a range of frequencies. F/W has also been plotted on the ordinate by relating maximum acceleration and F/W through equation [8]. This figure may be used for determining the base motion characteristics which will develop the required accelerations listed in Table XVIII.

**Tool for Fruit Collection and Conveying**

From the results of drop tests determining the bruising characteristics of raspberry fruit, it was found that if the free fall distance of the fruit is greater than 4.5 cm, the impact
Maximum acceleration developed by a slider crank mechanism, with one foot connecting rod length, for several amplitudes and a range of frequencies. The corresponding upper limit of F/W ratio for fruit removal is also plotted on the ordinate.
velocity must be limited to less than 94 cm/sec (187 ft/min). Since base motion is applied to feed rolls, the collection tool may be no higher than the feed rolls if it is to intercept all the harvested fruit. Although most fruit removal should occur in the region of maximum acceleration directly above the feed rolls, it is apparent that fruit with low retention force may be removed while the feed rolls are still at a considerable distance. A cushioning system, to limit the impact velocity of fruit striking the collection tool, therefore appears to be mandatory. Substituting the values for terminal velocity and allowable impact velocity into equation [17], the necessary upward air velocity supplied by a cushioning air stream is

$$(3960 - 187) \approx 3800 \text{ ft/min}.$$
Tool for Fruit Storage

The permissible depth of raspberries in a container may be estimated by applying equation [18], noting that from the force-deformation data, K has a value of 20γ. The mean and standard deviation of tangent modulus from Table VIII are 1.32 and 0.54 respectively. Since soft fruit may be on the bottom layer in a container, a good estimate of γ for determining the allowable compressive load on the bottom fruit layer is

\[(1.32 - 0.54) = 0.78\]

Since bruising of one drupelet (Table V) represents a bruise depth of approximately 1 mm, an overall deformation of 1 mm on the lower layer of fruit in a container will not result in bruising as this represents total deformation throughout the diameter of the fruit. On this basis, the allowable compressive load on a single fruit is

\[(1) (20) (0.78) = 15.6 \text{ gm}\]

Using a mean fruit weight of 3.52 gm and neglecting bridging or interaction between individual fruit, this represents 4 layers of fruit in the container. Since average fruit diameter is 2 cm, container filling depth must not exceed 8 cm.

The necessary storage tool capacity may be estimated from Table IV. A harvesting rate of 35 lb/min represents 4500 individual fruit per minute. Based on a mean fruit diameter of 2 cm and a filling depth of 4 layers of fruit, a container with surface area of 4500 cm² (700 in²) will be filled every minute. This estimate is based on a fruit removal efficiency of 100 percent for a forward speed of 1 mile per hour at the peak of the
harvest season.

The effect of in-transit vibrations on raspberry fruit stored in containers was not evaluated. O'Brien et al (26,27), in studies on transport damage to cling peaches and tomatoes, found that limiting vertical accelerations to less than 0.2g reduced transport damage to acceptable levels. As soil surface conditions in raspberry fields are very uniform and harvester design speed is one mile/hour, expected vertical accelerations are less than 0.2g. The only probable in-transit vibration damage is in transport of fruit from the field to the processing plant.
DESIGN AND FABRICATION OF TOOLS

Introductory Remarks

This chapter summarizes the design and fabrication of the tools selected to mechanize the process. Tool design was based on the specifications given in the previous chapter while the materials and methods used were those which would allow fabrication in a small machine shop. No attempt was made to create optimum tool designs. The purpose of prototype tools was to test the basic design principles and to check the validity of the assumptions made during the tool analyses.

Tool for Feeding and Cane Orientation

The selected feed roll inclination was 45° while the selected length was 6 feet. The front end of the feed rolls was designed to operate 1 foot above the soil surface. Although figure 11 indicates that the vertical fruit distribution begins at 0.5 feet above the soil surface, the lower portion of the distribution is caused by canes which have grown outward, away from the center of the row. Gathering and compressing these canes between the feed rolls will effectively raise the lower end of vertical fruit distribution curves above the one foot level.

Each feed roll was fabricated by welding four, 1/8 inch x 2 inch x 72 inch long, cold rolled steel flats in the configuration shown in figure 40. One inch diameter, cold rolled steel stub shafts were inserted into each end of the fabricated section and welded in place. The outer surfaces of each feed roll were covered with one-half inch foam rubber attached with contact cement. The total weight of each feed roll was approximately
Figure 40
Feed roll fabrication

Figure 41
Feed roll mounting and drive train
25 pounds.

The feed rolls were each attached to upper and lower sway-bars (figure 41) by means of self-aligning ball bearings in flange cartridges. The radial load rating of the selected bearings was 1680 lb at 100 rpm. This corresponds to the inertial loading developed in the bearings for a maximum base motion acceleration at $4300 \text{ ft/sec}^2$. The feed rolls were timed $90^\circ$ out of phase and driven through a roller-chain-and-gear drive train (figure 41) forcing them to rotate in opposite directions. Front and rear feed roll clearance could be adjusted independently by rotation of the swaybars about their upper pivot points.

**Tool for Selective Harvesting**

Oscillatory motion was applied to the feed rolls with four synchronized crank and connecting rod mechanisms, one at each end of each feed roll (figure 42). The connecting rods, which had a length of 1 foot between pivot points were fabricated by attaching self-aligning, double row, ball bearing, rod ends to each end of 8 inch lengths of one-inch steel pipe. The selected rod ends had a radial load limit of 7090 lb. The connecting rods were attached to the feed roll swaybars 1 foot below their upper pivot points. The crank end of each connecting rod was attached to a steel disk centered on a shaft (figure 43). Tapped holes spaced at 0.25, 0.50, 0.75, 1.00 and 1.25 inches from the center of rotation of the disk were used for attaching the connecting rods. This created a possible range of strokes from 0.5 to 2.5 inches in 0.5 inch increments. Although this base motion deviates
Figure 42  Method of applying base motion to the feed rolls

Figure 43  Method of varying the base motion amplitude
slightly from slider crank motion, the deviation for the range of strokes used is insignificant and the curves presented in figure 39 are applicable.

The four cranks were driven and synchronized by means of a roller-chain drive train (figure 44). The cranks were timed so that the lateral oscillation of both feed rolls was in phase.

Fruit Collection, Conveying and Storage

The primary purpose of the prototype harvester was to test the tools for feeding, cane orientation and selective harvesting. No attempt was made to design collection, conveying and storage tools based on their proposed mathematical models. Fabrication of these tools may be logically undertaken after testing and evaluation of the feeding and selective harvesting tools. This

Figure 44 Drive train for applying the base motion
avoids unnecessary cost in the initial design stages and simplifies testing of individual tools by eliminating possible interaction.

A simple collection and conveying device (figure 45) consisting of nylon screens, passing from the feed roll sway-bars to the machine frame, was used as a tool for collection and conveying during evaluation of the feeding and selective harvesting tools. Fruit which was intercepted by the oscillating screens was conveyed to stationary storage containers placed at the front end of the screens.

Figure 45  Nylon screens used as temporary collection and conveying tools during testing of the tools for feeding and selective harvesting.
SYNTHESIS AND CONSTRUCTION OF THE MACHINE

Purpose of the Prototype Machine

As was previously stated, only the feeding, cane orientation and selective harvesting tools were designed and fabricated on the basis of the proposed mathematical models. The purpose of the prototype harvesting machine was to evaluate the performance of these tools. The completed machine consisted of a frame to suitably position the tools in relation to the plants, powering systems for both forward movement and base motion application, control systems to permit adjustment of the design parameters, drive trains and supportive members. Temporary collection, conveying and storage tools, as previously described, were also incorporated in the machine. The machine frame was designed to accommodate the proposed tools for fruit collection, conveying and storage. Incorporation of these tools into the machine is a logical final step after evaluation of the feeding and harvesting tools.

Powering Systems

A harvesting machine may be either self-propelled or trail-type. In the latter case, power is supplied by a tractor towing the machine, while in the former case, motive power is supplied by a power unit placed on the harvester. Since the prototype machine served only as a carrying frame for evaluation of the feeding and harvesting tools, a trail-type construction was selected due to lower cost and design simplicity. The machine was towed with a Massey Ferguson model 65 tractor with the feed rolls being driven from the tractor power take-off.
Figure 46  Plan view of the harvester
Figure 47  Front view of completed machine

Figure 48  Rear view of completed machine
This tractor was selected as it had a power take-off driven from the transmission, permitting automatic synchronization of feed roll speed with speed of forward travel. The tractor power take-off completed one revolution for each 21 inches of forward travel, necessitating a drive train ratio of 2.38/1 to satisfy equation [35].

A small power unit, mounted on the harvester, acted as a powering system for the base motion. The reason for using a separate power unit for base motion application was in order to readily obtain a large range of frequencies during test runs. If a suitable base motion frequency could be established, base motion could also be powered by the tractor.

Frame and Supporting Members

The machine was supported on two pneumatic wheels and a pinned connection at the tractor drawbar. Welded rectangular hollow steel sections (2 inch x 2 inch x 3/16 inch thick) were used for the frame members supporting the tools. No assessment of the structural strength of the frame was undertaken. A plan view of the harvester is shown in figure 46, while two views of the completed machine are shown in figures 47 and 48.

Trellising Modification

The trellising system currently used was not suitable for the harvester since the size of posts used to support the trellis wires is often more than six inches in diameter. This could cause possible interference between the feed rolls and the posts. The trellising system used in the harvesting test plot was modified by using 2 inch x 2 inch x 36 inch high bean poles in
place of the existing posts, to allow the feed rolls to pass. A view of this trellising system is shown in figure 49.

Figure 49 View of machine entering a row. The modified trellising system is shown.
MACHINE EVALUATION

Scope of Test

The complete assessment of machine performance necessitates both functional tests and durability tests. Since loads imposed on a harvesting machine are nearly impossible to duplicate in a laboratory, a durability test must usually be conducted by operating the machine for a suitable period of time in actual field conditions. Similarly, complete functional evaluation must be the result of many hours of operation in diverse field conditions, in order to assess performance in a large variety of field and crop conditions. Only one 200-foot-long row of raspberries was available for field trials during 1969. No durability evaluation could, therefore, be undertaken and only a cursory assessment of functional performance could be completed. Similarly, no assessment of the effect of fruit variety could be undertaken since only the Willamette variety was available for test purposes. The results presented in the following discussion were obtained from single runs for each machine setting. Since replicate runs are usually required for reliable assessment, the results must be treated accordingly.

Evaluation of the Feeding and Cane Orientation Tool

Possible interaction between tools was eliminated by not powering the selective harvesting tool during assessment of the feeding and cane orientation tool. On the basis of limited tests, performance of the tool for feeding and cane orientation was satisfactory. The feed rolls effectively concentrated the plants at the point of base motion application and held the canes in a
vertical position independent of the speed of forward travel. Synchronization of feed roll rotation with forward speed was achieved. No visible plant damage occurred for a range of forward speeds up to three miles per hour. A lower spacing of eight inches between external roll surfaces and an upper spacing of four inches resulted in sufficient contact with the plants and allowed the rolls to pass the modified trellising system with no interference. Figures 50, 51 and 52 illustrate the action of the feed rolls during operation.

**Evaluation of the Selective Harvesting Tool**

The method of application of base motion was satisfactory. Fruit bearing portions of the canes appeared to receive equivalent displacements as the harvester passed down the row, indicating that the maximum acceleration produced in the fruiting zone could be quite closely controlled.

The prediction of possible fruit stem damage, as indicated by the measurements of physical properties, was verified during field testing of the selective harvesting tool. From the mathematical model for this tool (figure 39) it can be seen that various combinations of stroke and frequency may be used to produce the same maximum acceleration. Wang (37) in studies on mechanical coffee harvesting concluded that combinations of high frequencies and low amplitudes were preferable to low frequencies and high amplitudes since plant deflection is smaller and shaking time is reduced. Both of these factors may significantly influence plant damage. Due to the small plot size only limited assessment of the above variables could be completed. Results
and conclusions based on limited testing of the selective harvesting tool may be summarized as follows:

(i) Only fifty percent of the mature fruit could be removed with no damage to the fruit stems in the early part of the harvest season. This was accomplished with a maximum base motion acceleration of 2600 ft/sec\(^2\), resulting from a 1 inch stroke at a frequency of 2700 cycles per minute. The remaining mature fruit could be removed on subsequent passes at later dates but only with reduction in fruit quality. In similar trials toward the end of the harvest season, approximately sixty five percent of the mature fruit could be removed with no appreciable fruit stem damage.

(ii) Increasing the acceleration above 2600 ft/sec\(^2\) in the early part of the harvest season increased fruit removal but also initiated failure of the fruit stems. For example, a maximum acceleration of 4100 ft/sec\(^2\), resulting from a stroke of two inches at a frequency of 2200 cycles per minute, removed approximately 85 percent of the mature fruit but the resulting fruit sample contained 10 percent fruit with stems attached, some leaves and some immature fruit. The required accelerations and resulting fruit removal agree quite closely with the predicted values presented in Table XVIII.

(iii) The full extent of the damage caused by applying excessive base motion acceleration is not immediately apparent. Although fruit with stems attached may be observed in the collected fruit, some of the fruit may suffer stem damage but remain attached to the canes. This fruit subsequently dies and
is not available at later harvest dates. Figure 53 illustrates such damage.

(iv) High frequencies and low amplitudes appeared to be preferable to low frequencies and high amplitudes when plant damage was considered. It was not possible to conduct sufficient tests on the available plot to determine suitable limits of frequency and amplitude. Similarly, results on the optimum length of time of base motion application were inconclusive. Since forward speeds during test runs were one mile per hour, the selective harvesting tool can be expected to meet the necessary capacity requirements of one acre per hour, as previously determined.

Figure 53 Fruit stem damage due to excessive base motion acceleration
Although it is possible to remove all the mature fruit on a plant for each pass of the harvester by applying sufficient base motion acceleration, this is not feasible for two reasons. Hand sorting of the fruit is required before the processor will accept it. Secondly, the fruit removed during sorting and the damaged green fruit remaining on the plants will reduce the total yield for the season. A more logical solution appears to be removal of from 50 to 65 percent of the mature fruit at each pass of the harvester, the remaining fruit being allowed to mature before removal. This will result in a high overall fruit removal efficiency for the whole season but with reduced fruit quality.

**Evaluation of Machine Construction**

The primary reasons for using trail-type construction for the harvesting machine were reduced cost and design simplicity, when compared to a self-propelled machine. Although the purpose of the machine was to serve as a carrier frame during tool evaluation, its performance indicated that such a design could possibly be used for a commercial raspberry harvesting machine. A self-propelled machine has advantages where maneuverability is important and when tools require a high level of supervision. Since raspberry rows are straight, a pull-type machine is sufficiently maneuverable, if headlands are of sufficient width to allow unobstructed turning. Furthermore, the feeding and selective harvesting tools require little supervision, once they have been adjusted to suit crop conditions. The final choice between a trail-type or self-propelled machine must be based on the level of supervision required for the fruit storage.
tool once it has been incorporated in the machine. If an operator is required to supervise and control the fruit storage tool, a self propelled machine would be a logical choice.

**Concluding Remarks**

Although performance of the prototype harvester met design expectations and the use of such a machine in Willamette raspberries would be economically beneficial, other raspberry varieties may be better suited to mechanical harvesting. The retention force, color and firmness of mature raspberry fruit are strongly dependent upon fruit variety (10). Visual observation of the fruit attachment systems of several different raspberry varieties indicated that two varieties, Chief and Red Radabout, have fruit cores which are much shallower than the cores in the Willamette variety (figure 54). Limited comparison indicated that due to the core configuration the fruit retention force, for fruit of similar color and firmness, was appreciably lower for these varieties than for the Willamette variety. The recently developed Matsqui variety is also reported to have lower fruit retention force than the Willamette variety (7). The next logical step in development of a raspberry harvesting system therefore should be investigation of physical properties of other suitable varieties of raspberries to find a variety with a lower ratio of fruit retention force to fruit stem strength. A breeding program aimed at developing a raspberry variety more suitable for mechanical harvesting should also be undertaken.

Further work on the use of growth regulators with the aim
of reducing fruit retention force is also indicated. Initial trials indicated that suitable growth regulator treatments could significantly alter fruit retention force and its variation over the harvest season. Although no machine trials were conducted on the plots receiving growth regulator treatments, measurement of physical properties indicated that growth regulator treatments could be beneficial. Treatment 14 (Table XIV) for example, could possibly increase fruit removal at the beginning of the harvest season, since it significantly reduced fruit retention force early in the harvest season.

![Diagram showing the influence of fruit core shape on fruit retention force]

**Figure 54** The influence of fruit core shape on fruit retention force
OBSERVATIONS AND CONCLUSIONS

The following is a summary of the nature and scope of the completed study, the results of the experimental investigations and the subsequent conclusions. The study applies specifically to raspberry production in the British Columbia lower mainland. Conclusions are based on results obtained from investigation of the Willamette variety of raspberries. Other raspberry varieties may be expected to produce quite different results.

1. A systematic design procedure, oriented toward design and testing of a biological-machine-system was used to develop a mechanical raspberry harvesting system. The selected design was based on the physical and mechanical properties of the raspberry plant and the existing economic conditions in the raspberry industry.

2. An economic study, comparing present hand harvesting methods in the lower mainland to a theoretical mechanical harvesting system indicated that:

(a) A machine with gross seasonal fruit removal efficiency of 40 to 60 percent will satisfactorily compete with the present cost of hand harvesting.

(b) Machine capacity should be at least one acre per hour. This represents a minimum design speed of one mile per hour.

(c) For the range of yields expected in the lower mainland, the break-even point is not strongly dependent upon machine purchase price, for prices under $11,500, provided that machine capacity is at least one acre
per hour.

(d) A machine which harvests fruit suitable only for processing will serve over 95 percent of the industry.

3. Measurement of the physical and mechanical properties of the raspberry plant and its fruit was undertaken in order to determine pertinent design parameters. Results may be summarized as follows:

(a) The results of this investigation will provide useful information for the design of both field and processing equipment for cane fruits.

(b) Correlations among fruit properties and the force-deformation moduli obtained from flat plate loading of the raspberry fruit, indicated that tangent modulus and fruit color are direct indicators of fruit quality.

(c) Significant correlations among fruit retention force, F/W ratio, fruit color and force-deformation moduli showed that both fruit retention force and F/W ratio are indirect indicators of fruit quality. Design of a selective harvesting tool could be based on either of these parameters.

(d) Since fruit retention force and F/W ratio were negatively correlated with harvest time, a selective harvesting device employing either of these parameters must be adjusted to suit the desired selection level for the particular harvest day.

(e) Fruit retention force and F/W ratio appear to be dependent upon environmental conditions and may vary.
significantly from season to season.

(f) The Willamette variety of raspberries was found to have a high ratio of fruit retention force to fruit stem strength. On the basis of these measurements, it was shown that the fruit removal efficiency during a single pass of a mechanical harvester must be less than 70 percent, if damage to the fruit attachment system is to be within acceptable limits. High overall efficiency may be obtained but only by harvesting fruit of reduced quality.

(g) Due to low fruit stem strength and high fruit retention force, the force applied to the fruit by a mechanical raspberry harvesting system must be closely controlled to prevent fruit stem damage and to obtain maximum allowable efficiency of fruit removal. This indicates that if vibratory harvesting methods are used, base motion must be applied to the complete fruiting zone of the plant. The wide variation in flexural strength and size of the raspberry canes indicates that application of base motion to a fixed point on the canes is not feasible.

4. Mathematical models for the various tools required in a mechanical raspberry harvesting system were constructed, based on the physio-mechanical properties of the plant and its fruit. The tools considered were a tool for feeding and cane orientation, a tool for selective harvesting, a tool for fruit collection and conveying and a tool for
fruit storage.

5. Full scale models of the feeding and cane orientation tool and the selective harvesting tool were fabricated and incorporated into a prototype harvester. Limited field testing indicated that tool performance met design expectation as predicted by measurement of physical properties of the raspberry plant. Test results indicated the following limitations on mechanical harvesting of Willamette raspberries:

(a) Due to a combination of high fruit retention force and low fruit stem strength, only 50 percent of the mature fruit could be removed in one pass of the harvester at the beginning of the harvest season without fruit stem damage. Late in the harvest season approximately 65 percent of the mature fruit could be removed in one pass of the harvester without fruit stem damage. The fruit remaining on the plants after one pass of the harvester could be satisfactorily removed on subsequent passes at later dates, as fruit retention force decreases with increased maturity.

(b) Overall fruit removal efficiency may approach 100 percent for the whole harvest season even though maximum allowable fruit removal efficiency is much lower for a specific harvest date.

(c) The quality of fruit obtained by a mechanical harvesting will be lower than the quality obtained by hand picking. This is due to the fact that the fruit
must, on the whole, be more mature for removal by mechanical methods. The fruit obtained by mechanical harvesting will, therefore, be suitable only for processing; it will not be suitable for the fresh fruit market.

(d) In spite of low fruit removal efficiency and reduced fruit quality, use of this mechanical harvesting system could be economically beneficial when compared with the cost of hand harvesting.

6. Initial trials on the use of two chemical growth regulators indicated that growth regulator application could significantly influence the fruit retention force and F/W ratio. The effect of the growth regulator was found to be dependent upon the type of regulator, its date of application and its concentration. The proper use of growth regulators could possibly improve the performance of a mechanical harvester in Willamette raspberries.

7. Although mechanical harvesting of Willamette raspberries was shown to be economically beneficial, and the proposed harvester design could be used for harvest mechanization, the Willamette variety is not especially suitable for mechanical harvesting. Cursory examination of the fruit attachment systems of other raspberry varieties indicated that several varieties may be much more suitable for mechanical harvesting.
SUGGESTIONS FOR FURTHER STUDY

Although it has been shown that mechanical harvesting of the Willamette variety of raspberries is feasible, the high ratio of fruit retention force to fruit stem strength limits fruit removal efficiency and reduces the overall quality of machine harvested fruit. The following investigations are therefore proposed for future study:

1. Measurement of the physical and mechanical properties of other suitable varieties of raspberries should be undertaken in an attempt to find a variety having a lower ratio of fruit retention force to fruit stem strength.

2. Further investigation should be conducted concerning the possibility of lowering fruit retention force through the use of growth regulators.

3. A raspberry breeding program should be initiated with the aim of developing a variety suitable for mechanical harvesting. An ideal variety would have a low ratio of fruit retention force to fruit stem strength, would have fruit that matured uniformly and would have sufficient cane strength to eliminate the need for a trellising system.
LITERATURE CITED


