11-1990

Elliptical Combing Motion for Harvesting Bell Peppers

J. H. Wilhoit
Auburn University

George A. Duncan
University of Kentucky, gduncan@uky.edu

Larry G. Wells
University of Kentucky, larry.wells@uky.edu

Elliptical Combing Motion for Harvesting Bell Peppers

J. H. Wilhoit, G. A. Duncan, L. G. Wells
Assoc. Member ASAE, Member ASAE, Member ASAE

Abstract

A new concept for mechanically harvesting bell peppers, intended specifically for multiple-pass harvesting, utilized spaced horizontal fingers combing vertically upward through plant foliage in an elliptical path alternating from both sides of the row. An apparatus based on this concept was designed and built, and harvest tests were conducted to determine the effect of two main machine operating parameters, vertical picking speed and disk angle. Harvesting performance was evaluated in terms of harvest efficiency, fruit damage, and plant damage as it related to multiple-pass harvesting. Fruit removal, both harvestable size and immature, increased significantly as vertical picking speed increased. Branch breakage also tended to increase as vertical picking speed increased, partially accounting for the increased fruit removal. Fruit damage increased significantly as the disk angle increased. Overall, the average harvest efficiency for the tests was 81% and the average fruit damage was 5.9%.

Introduction

Many different kinds of peppers (*Capsicum annuum* L.), ranging from the large, blocky bells to the tiny, hot tabasco, are produced in the United States. Bell peppers account for the largest portion of all pepper production with nearly 65% of the total acreage (Marshall, 1976; Nonnecke, 1989). All of the pepper types have traditionally required hand harvesting. Because the fruit do not set uniformly, multiple harvests are needed to maximize yields. These multiple hand harvests contribute to very high harvest labor requirements.

In the early 1980s, there was substantial production of bell peppers for processing in Kentucky. In response to high harvest labor requirements which were a constraint to the potential for expanding production, a project was initiated in the Agricultural Engineering Department at the University of Kentucky to evaluate a new concept for mechanically harvesting peppers. The concept was directed specifically at harvesting bell peppers and was intended for multiple pass harvesting over the entire harvest season (Wilhoit, 1983).

This article describes the concept and the apparatus built for testing it and reports the results of experiments conducted to evaluate the performance of the apparatus.

Review of Literature

High costs and potential labor scarcities have prompted a great deal of research on pepper harvest mechanization over the years. Fullilove and Futral (1972) investigated several different concepts for once-over harvesting of the medium-to-large size pimento pepper. A stripping action produced by spaced fingers raking completely through the plant was tried in two different directions; horizontally at right angles to the row, and vertically upward. Peppers were successfully removed using this principle, but pepper damage was high and various machine problems were encountered. They also constructed and tried a machine that used counter-rotating picking cylinders made from double open-helix bars. The bars pulled the plants into the machine by screw action and removed the fruit by a combination of bending, shaking, and snapping. This concept showed a lot of promise.

Shaw (1973) investigated the principle of a stripping action produced by spaced fingers raking through the plant for multiple-pass harvesting of bell peppers. He used an offset double-crank mechanism (or hay-rake type assembly) to produce the desired motion of fingers raking across the plants at right angles to the row in synchronization with the forward velocity of the machine. The long fingers [76 cm (30 in.)] were designed to rake across the entire plant in a single sweep, and they were inclined so that detached peppers could roll free for collection. Mature fruit removal of up to 70% was reported for field tests with the machine, but plant damage was sometimes severe. The effect of this damage on subsequent yields from the same plant was not determined.

In a study of different harvesting principles from all over the world, Marshall (1979) found the double open helix element developed by Fullilove and Futral (1972) to be the best element for harvesting a wide range of pepper types. He constructed a full prototype harvester utilizing this element and did extensive testing on machine operating parameters and on collection and cleaning equipment (Marshall et al., 1986; Marshall and Esch, 1986). Good harvest efficiency results with bell peppers were reported with this prototype, but fruit and plant damage tended to be higher than for other pepper types. The effect of the use of this open-helix harvester on multiple harvest yields has not been reported. Another open-helix harvester, tested extensively on jalapeno peppers in Texas, has shown suitability for multiple harvests with yield recovery comparable to multiple hand

Article was submitted for publication in October 1989; reviewed and approved for publication by the Power and Machinery Div. of ASAE in April 1990.

The authors are **J. H. Wilhoit**, Assistant Professor, Agricultural Engineering Dept., Auburn University, Auburn, AL; **G. A. Duncan**, Professor, and **L. G. Wells**, Professor, Agricultural Engineering Dept., University of Kentucky, Lexington.

  0883-8542 / 90 / 0606-0673

harvesting (Posselius and Valco, 1985). Collection and cleaning equipment developed for the Texas harvester worked well with several types of peppers but was not suitable for bells because of extensive damage caused by the conveyor system.

Analysis and Design

Harvesting Principle

The apparatus developed in this study for harvesting bell peppers utilized spaced horizontal fingers combing upward through the plant canopy to dislodge the larger peppers while allowing the small peppers and foliage to pass through. The desired motion was produced by mounting the fingers on parallel bars connecting parallel and inclined rotating disks. Two disk-and-bar assemblies were used, one on each side of the row, and the fingers from each side penetrated only to the center of the plant row. The assemblies were counter-rotating, and finger penetration from each side of the row was made out-of-phase (alternating) to reduce the potential for plant uprooting. Figure 1 illustrates the disk-and-bar assemblies operating on a row of pepper plants. The disks were at an angle from the vertical so that the path of the fingers could be made approximately vertical relative to the plant by synchronizing the forward speed of the machine and the disk rotation. The inclined disks also made the transverse path of the fingers elliptical rather than circular. The elliptical path made it possible for the fingers to reach peppers near the center of the plant while combing through a minimal section of plant foliage. The bars connecting the disks were inclined, sloping upward from front to rear, so that the plant canopy was engaged in a series of upsweeps by successively higher fingers as the disk-and-bar assemblies moved past the plants. Figure 2 shows the elliptical path of the fingers and illustrates the coverage of the plant canopy by successively higher finger paths.

Other investigations have used the same principle of selectivity for multiple-pass harvesting but have covered the entire plant with a single motion of the fingers (Shaw, 1973; Siow et al., 1979). Such a motion can cause the plant branches to bend through large angles, resulting in excessive branch breakage that can reduce subsequent yields. This concept was specifically intended to provide full plant coverage with several smaller finger strokes instead of a single large one. Smaller strokes are accomplished by having the raking come from both sides of the row so that finger penetration is only through one half of the plant, by having shorter finger paths due to the elliptical path shape, and by having plant engagement by successively higher finger paths. It was also hoped that the reduced engagement between fingers and foliage would allow the use of a more aggressive motion to facilitate fruit detachment.

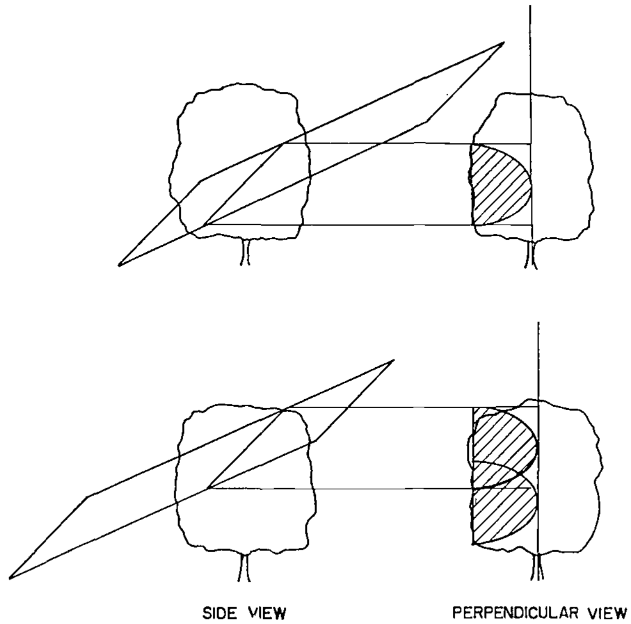

Figure 2–Coverage of the plant canopy by successively higher elliptical paths as the harvesting mechanism moves past.

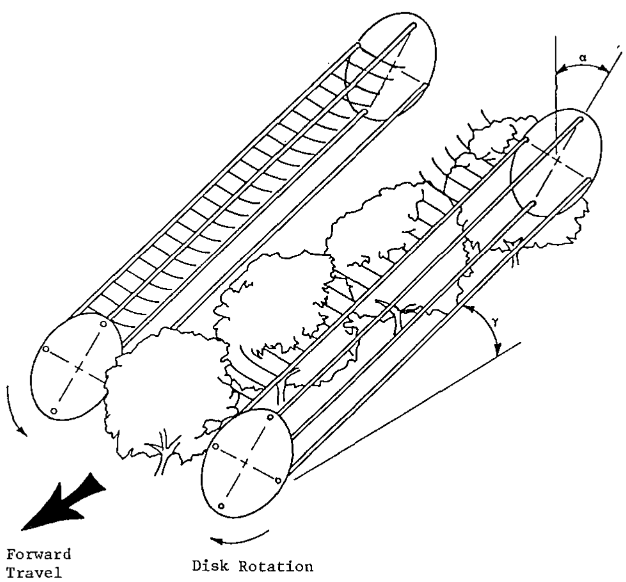

Figure 1–Disk-and-bar assemblies operating on a row of pepper plants, illustrating the mechanical harvesting concept.

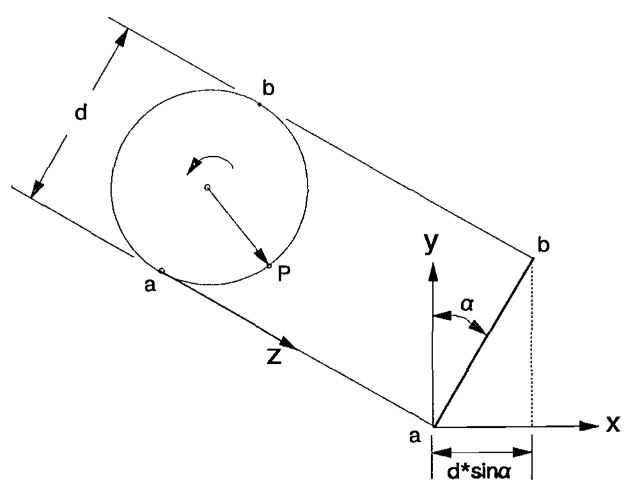

Figure 3–Front and side views of an inclined disk set in the x, y, z coordinate system.

Machine Parameters

Figuie 3 shows a schematic of a disk inclined at an angle α from the vertical with the x, y, z coordinate system defined so that the disk is in the x-z plane. The projection normal to the surface of the disk is also shown with the diameter, d, and rotational speed, ω, identified. Picking fingers mounted on the connecting bars, represented by point P on the periphery of the disk, should have a motion as near vertical as possible relative to the pepper plant to reduce the drag through the foliage. This vertical motion can be accomplished by synchronizing the forward movement of the apparatus with the rearward movement of the fingers.

The ground speed required to achieve this synchronization has been determined previously by Suggs and Splinter (1967), who used the same type of mechanism for a tobacco defoliator on a harvester for flue-cured tobacco. In accordance with their analysis, the relationship for the ground speed V_g is:

$$V_g = \frac{\omega d}{\pi} \sin \alpha \qquad (1)$$

This velocity is the horizontal component of the average velocity in the x direction of point P as the disk rotates one-half revolution. During that time, the point P moves from position a to position b while the disk-and-bar assembly moves forward a distance d sin α.

The vertical component of the average peripheral velocity, which will be referred to as the vertical picking speed V_v, gives some measure of the intensity of the dynamic interaction between the picking fingers and the plant. This parameter should affect both fruit removal and plant damage. The vertical picking speed is given by:

$$V_v = \frac{\omega d}{\pi} \cos \alpha \qquad (2)$$

Combining equations 1 and 2:

$$\frac{V_g}{V_v} = \tan \alpha \qquad (3)$$

Another factor that should affect both fruit removal and plant damage is the frequency that sections of plant foliage are engaged by the combing fingers as the disk-and-bar assemblies move past. As illustrated in figure 2, this frequency is dictated by the overlap between successively higher finger paths, which depends on both the height of the elliptical path and the vertical spacing S between the paths. The height of the elliptical path is given by d cos α. The vertical spacing S is given by:

$$S = V_g \frac{2\pi}{\omega n} \tan \tau \qquad (4)$$

where $2\pi/\omega n$ is the time between successive finger/plant engagements if n is the number of equally spaced connecting bars that have fingers and τ is the inclination angle of the connecting bars (see figure 1). Substituting equation 1 into equation 4:

$$S = \frac{2d}{n} \sin \alpha \tan \tau \qquad (5)$$

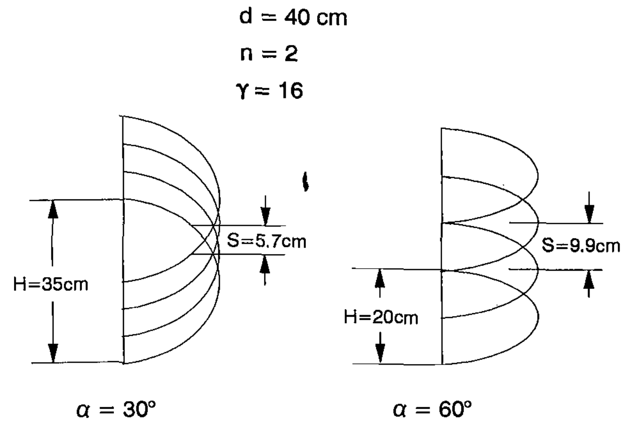

Figure 4–Overlap of finger paths as spacing S and path height I angles, ∝ = 30 and ∝ = 60.

As α increases, the height of the elliptical path decreases and the spacing increases, so there will be less overlap between paths. This concept is demonstrated in figure 4, which shows the overlap of finger paths for the mechanism operated at two different disk angles (α = 30°, α = 60°) with the bar angle, τ, and the vertical picking speed held constant. The larger angle, with the flatter elliptical path and greater spacing, S, gives nearly the same plant coverage as the smaller angle but with a lower frequency of foliage engagement because of less overlap.

Experimental Apparatus

An experimental apparatus was constructed based on the preceding concept and analysis. The single-row apparatus was tractor-drawn, attached to the three point hitch via a toolbar, and supported on two caster wheels in back. The reels (disk-and-bar assemblies) were powered by a hydraulic motor. The frame was constructed from square structural tubing. The apparatus was constructed without any equipment for collecting or cleaning the peppers, because this was an initial evaluation concerned mainly with the fruit detachment and the operation of the picking mechanism.

The two reels are shown in figure 5. The disks, 40 cm (15.75 in.) in diameter, were connected by four bars 180 cm (71 in.) long. The disks were mounted on pivoting

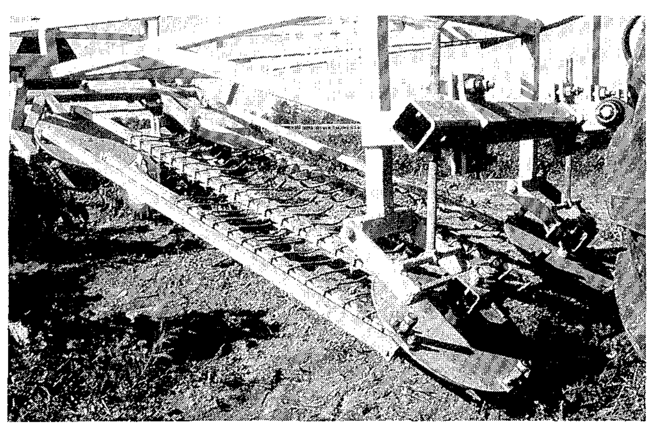

Figure 5–Disk-and-bar assemblies of the bell pepper harvesting mechanism.

brackets so that the disk angle was adjustable from approximately 15° to 65° from vertical. The frame was constructed with the bar angle at 18°, but it could be adjusted somewhat by raising or lowering the tractor hitch or the caster wheels. The disks of both reels were driven by a single roller chain powered by a hydraulic motor. A single chain was used so that the sequence of alternating finger penetrations would be synchronized and constant.

Fingers were mounted on two of the four connecting bars of each reel. They were made from 8 mm (5/16 in.) round bar and were 20 cm (7.875 in.) long with an upward curvature over the last 6 or 7 cm (2.5 in.). Rubber tubing was placed over the ends of the fingers, extending 1 to 2 cm beyond tips, as suggested by Gentry et al. (1977) to divert peppers and reduce spearing. A bracket secured by a bolt was used to mount individual fingers on the connecting bars. Fingers could be added, repositioned, or removed as needed. In this study, 18 fingers were used on each of the two bars of each reel.

Experimental Procedure

Field experiments harvesting bell peppers with the apparatus described above were conducted to determine the effects of two main machine operational parameters, disk angle (α) and vertical picking speed (V_v), on harvesting performance. Special emphasis was given to evaluating performance based on plant damage as it related to multiple-pass harvesting.

Peppers of the variety 'Keystone Resistant Giant' were grown at the University of Kentucky South Farm in rows with 20 to 25 plants. Original plans called for several harvests over the entire harvest season and hand picked plots to be used as controls for comparing yields between mechanical and hand harvesting. Severe damage from corn borer infestation destroyed a portion of the crop and delayed formalized testing in the remaining portion until late September, when the plants had recovered sufficiently, so plans had to be altered. Hand picked plots had to be eliminated, and the apparatus could be used for only one harvest. For that harvest, tests were conducted at three levels of each of the two machine operation parameters, disk angle (α) and vertical picking speed (V_v). The three disk angles were 42, 50, and 58.5° and the three vertical picking speeds were 0.23, 0.38, and 0.53 m/s (0.75, 1.25, 1.75 ft/s). For the tests, the finger spacing was set at 6.3 cm (2.5 in.), which is generally considered the minimum diameter for harvestable or mature peppers. There were two replications at each of the nine treatment combinations of operating conditions. Disk angle and vertical picking speed levels were chosen to give as wide a range as possible of reasonable operating conditions for ground speed (V_g) and reel rotational speed (ω). Operating conditions, which ranged from V_g = 0.21 m/s (0.675 ft/s) and ω = 23 rpm to V_g = 0.87 m/s (2.86 ft/sec) and ω = 77 rpm, were determined for each treatment combination of and V_v using equations 1 through 3.

Prior to each test, unhealthy or barren plants were eliminated from the row to be harvested to minimize the effect of the earlier corn borer infestation. Rotted fruit were also removed from the remaining plants. After each test with the harvesting apparatus, the total number of mature size peppers [harvestable size, diameter greater than 6.3 cm (2.5 in.)], both removed and not removed from the plants in the row, was counted to determine harvest efficiency. These peppers were also categorized by removal conditions, i.e., damaged or not damaged and harvested cleanly or with foliage attached. Since there was not enough time left in the harvest season for determining subsequent yield, two other measurements of plant damage relating to multiple harvests were made. The total number of smaller peppers [diameter less than 6.3 cm (2.5 in.)], both removed and not removed from the plants, was counted to determine a ratio of immature fruit removed, and a subjective rating of damage ranging from 1 for slight to 3.5 for severe was made on each individual pepper plant.

Results and Discussion

Because of the damage to the pepper plants from corn borer infestation, harvest tests had to be postponed until the near end of the harvest season, and rows for mechanical harvesting had to be carefully chosen to have enough healthy plants. This difficulty resulted in insufficient randomization of the treatment combinations in regards to disk angle, so the results for this factor (except for fruit damage) were not analyzed statistically. The vertical picking speed was varied over all three disk angles, so the results for this factor could be analyzed statistically considering the disk angle as a block effect.

Vertical Picking Speed

The vertical picking speed results for the five measured performance indices (harvest efficiency, immature fruit removal, cleanliness rating, fruit damage, and plant damage rating) are shown in Table 1. Fruit removal, both mature and immature, increased significantly as vertical picking speed increased. These results are shown in figure 6. Harvest efficiency went from 76% at V_v = 0.23 m/s (0.75 ft/s) to 84% at V_v = 0.53 m/s (1.75 ft/s), and the increasing trend held for each of the disk angles except α = 42°, as seen in figure 6a. The trend toward more fruit removal at higher vertical picking speeds reflects the dynamic action involved with the detachment of fruit and branches from the plant during mechanical harvesting.

The cleanliness rating, which is the percentage of harvestable size peppers that were removed from the plant

TABLE 1. Effect of vertical picking speed on the mechanical harvesting of bell peppers, Kentucky 1982

	Performance Indices				
Vertical Picking Speed (m/s)	Harvest Efficiency (%)	Immature Fruit Removal (%)	Cleanli-ness* Rating (%)	Fruit Damage (%)	Plant Damage† Rating
0.23 (0.75 ft/s)	76 a‡	46 a	64 a	4.7 a	1.76 a
0.38 (1.25 ft/s)	83 b	56 b	65 a	7.7 a	1.87 a
0.53 (1.75 ft/s)	84 b	61 b	58 a	5.7 a	1.85 a

* The percentage of mature peppers removed that were free of attached branches or foliage

† Subjective ratings of 1, 2, 3, or 3.5 given to individual plants for minor, medium, major, and severe damage due to mechanical harvesting.

‡ Values followed by the same letter in a column are not significantly different (α = 0.05) by Duncan's Multiple Range test.

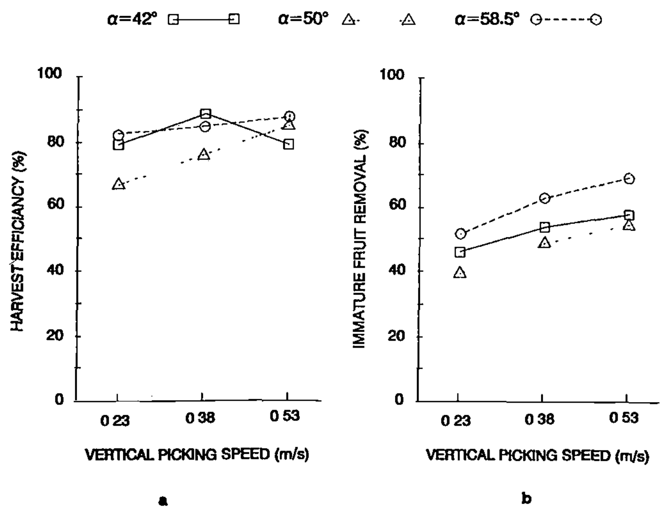

Figure 6–Harvest efficiency and immature fruit removal as affected by vertical picking speed for three different disk angles. (1 m/s = 3.3 ft/s).

free of attached branches or foliage, was not significantly affected by the vertical picking speed. The rating was lower, however, at the highest vertical picking speed, indicating that more branches were being broken off the plants. Fruit damage was also not significantly affected by the vertical picking speed. The plant damage rating, while not significantly affected by the vertical picking speed, was lowest at the lowest speed, giving further indication of increased branch breakage at higher vertical picking speeds. This branch breakage may have partially accounted for the increased fruit removal at higher vertical picking speeds, since many of the peppers that were removed (both harvestable-size and immature) were attached to branches broken off the plants.

Disk Angle

The disk angle results are shown in Table 2. Fruit removal, both mature and immature, was substantially lower at $\alpha = 50°$ than at the other two angles, while the cleanliness rating was much higher. The plant damage rating was also much lower for $\alpha = 50°$. The consistency of these results indicate that the condition of the plants used for the test at $\alpha = 50°$ may have been different. The plants apparently were much less brittle, contributing to fewer broken branches, less plant damage overall, and decreased fruit removal.

TABLE 2. Effect of disk angle on the mechanical harvesting of bell peppers, Kentucky 1982

	Performance Indices				
Disk Angle (degrees)	Harvest Efficiency (%)	Immature Fruit Removal (%)	Cleanli-ness* Rating (%)	Fruit Damage (%)	Plant Damage† Rating
42	82 NS‡	53 NS	53 NS	3.3 a§	1.86 NS
50	76	48	73	3.0 a	1.67
58.5	85	62	58	11.3 b	1.95

* The percentage of mature peppers removed that were free of attached branches or foliage

† Subjective ratings of 1, 2, 3, or 3.5 given to individual plants for minor, medium, major, and severe damage due to mechanical harvesting.

‡ No statistical analyses (NS) were done on these results because of the effect of differences in plant conditions.

§ Values followed by the same letter in a column are not significantly different ($\alpha = 0.05$) by Duncan's Multiple Range test.

Fruit damage should not have been affected by plant conditions, so these results were analyzed statistically. Fruit damage was affected by the disk angle, with the damage at $\alpha = 58.5°$ (11.3%) significantly higher than at the lower two angles (3.0 and 3.3%). The higher the disk angle, the flatter (more horizontal) the disk, and the shorter the elliptical path. For a shorter ellipse, there is more of a straight portion of the path as the fingers move toward the center of the plant. The fact that fruit damage was not significantly affected by the vertical picking speed indicates that more peppers were being damaged by spearing or shattering from the horizontal movement of the fingers into the plant than by the vertical impact of the fingers striking the peppers.

Performance Evaluation

The harvest efficiency averaged 81% overall and ranged from 67 to 89% for the nine operating conditions of vertical picking speed and disks angle. Fruit damage increased as the disks angle increased, but the overall average was still only 5.9%. Considering these results by themselves, the feasibility of mechanically harvesting bell peppers with this concept looks good. The suitability of the mechanism for multiple-pass harvesting, however, is still in question because of the problems of immature fruit removal and branch breakage. Over 50% of the immature fruit were removed in all but three of the nine tests, with an excessive 70% for $V_v = 0.53$ m/s (1.75 ft/sec) and $\alpha = 58.5°$. The removal of such a large portion of the immature fruit is bound to have an effect on subsequent yield, but harvest tests earlier in the season and the measurement of subsequent yield will have to be done to determine the extent of the effect.

Branch breakage was a problem in all of the tests. It was observed that a substantial portion of the immature fruit that were removed were attached to branches broken off the plants. The extensive branch breakage, however, was partially due to the corn borer damage, as many of the larger branches had hollow centers. Branch breakage may be less severe earlier in the season when plants are less brittle. The plants used for the tests at $\alpha = 50°$ seemed to be less brittle, and they suffered substantially less plant damage and immature fruit removal, although harvest efficiency was also lower.

Although many large branches were broken, the plants did not sustain severe leaf-stripping, an important consideration because of the photosynthetic capacity of the plants and the shading that the leaves provide for the peppers. Furthermore, less than 4% (10 out of 269) of the total number of plants harvested during the tests were excessively damaged as indicated by a plant damage rating greater than 3.

Finger penetration from each side of the row was made out-of-phase to reduce the potential for plant uprooting. This feature was successful, as none of the plants were uprooted during the tests. Uprooting may be more of a problem earlier in the season when the soil is less compacted.

In this study, no attempt was made to collect harvested peppers. Collection of mechanically harvested peppers has been reported as a major problem by several investigators (Fullilove and Futral, 1972; Shaw, 1973; Posselius and Valco, 1985), and it may be especially difficult with this concept because the fingers remain horizontal and they comb so close to the ground at the lower end of the reels (see figure 5). Cleaning is another difficulty with mechanically harvested peppers due to the large number of peppers removed attached to branches. Esch and Marshall (1987) developed effective trash removal equipment for their open helix harvester, but the required system of cleaning beds could add substantially to the cost of a harvester based on this concept.

Summary and Conclusions

A study was conducted to evaluate a new concept for multiple-pass mechanical harvesting of bell peppers alternating from both sides of the row. The concept utilized spaced horizontal fingers combing upward through plant foliage in an elliptical path. An apparatus based on this concept was designed and built, and field tests were conducted to determine the effect of two main machine operating parameters, vertical picking speed and disk angle, on harvesting performance. The following conclusions were drawn from the study:

1. Fruit removal, both mature and immature, increased significantly as vertical picking speed increased.
2. Branch breakage tended to increase as the vertical picking speed increased, contributing to increased fruit removal.
3. Fruit damage increased significantly as the disk angle increased from 50° to 58.5°.
4. For all harvest tests combined, the average harvest efficiency was 81% and the average fruit damage was 5.9%.
5. No plants were uprooted during the harvest tests.
6. Collecting and cleaning the peppers may be difficult with this concept because of the motion and the large number of branches attached to the peppers.

Acknowledgments. The authors wish to acknowledge the valuable counsel and cooperation of Dr. Dean Knavel, Professor, Department of Horticulture, in conducting this study and the assistance of Mr. George Day and Mr. Tim Smith, Engineers, Agricultural Engineering Department, in fabricating and testing the experimental apparatus.

References

Esch, T.A. and D.E. Marshall. 1987. Trash removal from mechanically harvested peppers. *Transactions of the ASAE* 30(4): 893-898.

Fullilove, H.M. and J.G. Futral. 1972. A mechanical harvester for pimento peppers. University of Georgia Research Report 142.

Gentry, J.P., J.A. Miles and W.W. Hinz. 1977. Development of a chili pepper harvester. ASAE Paper No. 77-1026. St. Joseph, MI: ASAE.

Marshall, D.E. 1976. Estimates of harvested acreage, production, and grower value for peppers grown in the United States. Report available from Pickle Packers International, Inc., St. Charles, IL 60174.

———. 1979. Performance of a mechanical pepper harvester. ASAE Paper No. 79-1062. St. Joseph, MI: ASAE.

Marshall, D.E. and T.A. Esch. 1986. Recovery and damage of mechanically harvested peppers. *Transactions of the ASAE* 29(2): 398-401.

Marshall, D.E., T.A. Esch and S.R. Dragt. 1986. Influence of certain open helix variables on pepper damage. *Transactions of the ASAE* 29(3): 714-717.

Nonnecke, I.L. 1989. *Vegetable Production.* New York: Van Nostrand Reinhold.

Posselius, J.H., Jr. and T.D. Valco. 1985. Pepper harvester research in Texas. ASAE Paper No. 85-1064. St. Joseph, MI: ASAE.

Shaw, L.N. 1973. The application of an offset double crank mechanism in a selective bell pepper harvester. *Transactions of the ASAE* 18(4): 606-609.

Siow, E.H., C.H. Thomas and S.H. Rollason. 1979. Design of a stripper harvester for some pepper varieties. ASAE Paper No. 79-1562. St. Joseph, MI: ASAE.

Suggs, C.W. and W.E. Splinter. 1967. Factors affecting the design of the finger bar and knife tobacco defoliators. *Transactions of the ASAE* 10(2): 264-269.

Wilhoit, J.H. 1983. An elliptical combing motion used for harvesting bell peppers. Unpublished M.S. thesis, University of Kentucky, Lexington.