Optimum Shaking Action for Citrus Fruit Harvesting

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THE results of research on tree-shaker harvesting of citrus in Florida have indicated that shaking is a practical method of removing the fruit (1, 2)*. Basic information on the effect of limb displacement, shaking frequency, and shaking action on fruit removal was needed in order to design more efficient tree shakers. Although two investigators (3, 4) have studied the effect of frequency and limb displacement on the removal of other fruit crops, the results could not be applied to citrus because the shaking frequencies investigated were much higher than the frequencies found suitable for removing citrus. Individual limbs were studied in 1963 and 1964 to determine the effect of limb displacement, shaking frequency, and limb size on fruit removal.

Procedure

A prototype tree shaker furnished by the FMC Corporation† was used to shake all of the "Valencia" orange limbs and some of the "Pineapple" orange limbs. The shaker employed a rapidly, recycling hydraulic cylinder supported on rollers inside a stationary tube making it an inertia-type tree shaker which the operator could hold on to. The stroke of the recycling cylinder could be adjusted to oscillate from 1 to 6 in. and the frequency could be set from 100 to 500 cpm. The FMC shaker had an impact-type motion characteristic of other shakers that have been tested.

A crank-type inertia shaker was modified to obtain relatively smooth shaking motion by adding a flywheel to the crank drive. The stroke of this flywheel shaker could be changed from 4 to 6 in. by changing the crank throw. The flywheel shaker was used to shake some of the Pineapple orange limbs.

The acceleration of each limb was measured with a strain-gage accelerometer mounted on the shaker boom. The acceleration signal was electronically integrated twice to obtain the limb displacement. Limb acceleration and displacement were recorded on a two-channel strip chart recorder.

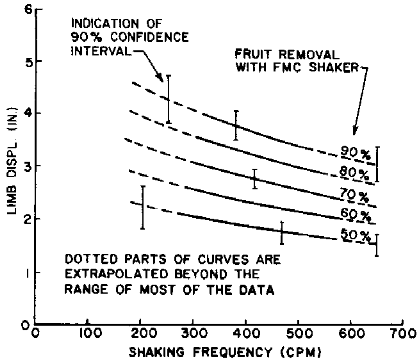

FIG. 1 Curves for constant fruit removal of Valencia oranges. Each curve is a solution to equation [2], for 4-in.-diameter limbs. For other size limbs, the curves would be shifted slightly but would have the same shape.

Three to five limbs on each tree were selected for shaking, and the remainder of the tree picked by hand. The diameter of each limb at the point of shaker attachment and the length of each limb were measured. Limb length was defined as the distance from the base of the limb out to a limb diameter of one-half inch.

The point of tree-shaker attachment was determined by asking an experienced tree-shaker operator to indicate where he would attach the shaker on each of several limbs. The locations the shaker operator specified were approximately one-fourth the length of the limb from the trunk on Pineapple oranges and three-tenths the length of the limb on Valencia oranges. The reason for the apparent difference in point of attachment is that the Pineapple limbs were taller (189 in. average length) than the Valencia limbs (145 in. average length) but the point of shaker attachment remains at approximately the same height above ground level. Each limb was shaken approximately 5 sec.

Ninety-nine limbs of both the Pineapple and Valencia varieties were selected and divided into 11 groups of nine limbs each. Each group was selected in such a way that it contained a complete range of limb sizes and the average limb size of each group was approximately equal.

Each group of nine Valencia limbs was shaken with a different combination of shaker stroke and frequency using the FMC tree shaker. Seven of the eleven groups of Pineapple limbs were shaken with the FMC shaker and the remaining four groups with the flywheel shaker.

Discussion of Results

A computer was utilized to fit a regression equation of the following form to the data for fruit removal:

$$R = C_0 + C_1(D) + C_2(f) + C_3(S) + C_4(f)(S) \quad \ldots \quad [1]$$

where

R is the fruit removed with the shaker, referred to as fruit removal (percent)

C_0, C_1, C_2, C_3, and C_4 are coefficients determined by the computer to effect the best fit of the equation to the data.

D is the limb diameter at the point of shaker attachment, in.

f is the shaking frequency, cpm

S is the peak-to-peak displacement amplitude of the limb at the point of shaker attachment, referred to as limb displacement, in.

In addition to the first-order terms, the second order term $C_4(f)(S)$ was included in the equation because a preliminary analysis of the data indicated the removal of Pineapple oranges was accurately predicted by this term. Markwardt (4) found the product of frequency and limb displacement significant in predicting fruit removal of cherries.

The computer analysis of the data resulted in the following equations for fruit removal:

Valencia oranges – FMC shaker

$$R = -15.3 + 6.13D + 13.94S + 0.0197fS \quad \ldots \quad [2]$$

Pineapple oranges – flywheel shaker

$$R = 7.12 + 5.92S + 0.0395fS \quad . \quad [3]$$

Pineapple oranges – FMC shaker

$$R = 7.46 - 2.78D + 0.0488fS \quad . \quad [4]$$

The limits of stroke and frequency for which the equations are valid and the accuracy of the equations are discussed later in this report.

The independent variables were added to the regression equation in a stepwise manner; the variable which produced the greatest reduction in the total variation was added first. The procedure was terminated any time the reduction in the variation was not sig-

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* Numbers in parentheses refer to the appended references.

† Trade names are used in this publication solely for the purpose of providing specific information. Mention of a trade name does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or an endorsement by the Department over other products not mentioned.

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nificant at the 50 percent level. Therefore, each of the terms in the final regression equation reduced the variation of the dependent variable (R) at the 50 percent confidence level.

Limb Displacement and Shaking Frequency

Fruit removal depended primarily on limb displacement and shaking frequency and is plotted as a function of these variables in Figs. 1 and 2. Fruit removal of both Valencia and Pineapple oranges was directly proportional to limb displacement for the complete range of limb displacements investigated. This was true for both shakers and both varieties of fruit.

Fruit removal of Pineapple oranges increased much more rapidly with increasing frequency (Fig. 1) than did the removal of Valencia oranges (Fig. 2). The different effects of shaking frequency on removal of Valencia and Pineapple oranges can be explained by the fact that the Pineapple oranges were smaller than the Valencia oranges. According to Wong (5), the smaller the fruit, the higher the optimum frequency is for removing it. If the optimum shaking frequency of Valencia oranges is in the region of 200 to 300 cpm, increasing the frequency above this range would not increase fruit removal very much as shown in Fig. 1. If the optimum shaking frequency for Pineapple orange removal was in the range of 400 to 500 cpm, increasing the shaking frequency from 200 to 300 cpm to 400 to 500 cpm would increase fruit removal as shown in Fig. 2. The effect of fruit size may also explain the difference between the shaking frequencies found suitable for shaking citrus and for shaking other smaller fruit such as prunes and cherries.

Limb Diameter

Limb diameter had relatively little effect on fruit removal compared to the effects of frequency and limb displacement. Approximately 13 percent more fruit was shaken off the large (4.4-in. diameter) Valencia limbs than off the small (2.4-in. diameter) limbs. These results were reversed in Pineapple oranges where 11 percent less fruit was shaken off the large (6.4-in. diameter) limbs than off the small (2.2-in. diameter) limbs when shaken with the FMC shaker. Limb diameter was not included in the regression equation for Pineapple oranges (equation [3]) shaken with the flywheel shaker.

Shaker Action

A comparison of fruit removal obtained with the flywheel shaker and the FMC shaker is shown in Fig. 2. Typical tracings of the acceleration and displacement curves (Fig. 3) show the relatively smooth action of the flywheel shaker compared to the FMC shaker. The action of the FMC shaker is similar to that of other shakers previously tested. The flywheel shaker removed a substantially greater percentage of the fruit than the FMC shaker (Fig. 2) though the difference between the two shakers appears to be less at higher frequencies. At a frequency of 400 cpm, the difference in fruit removal was approximately 18 percent while at 600 cpm the difference was about 12 percent.

Prediction of Fruit Removal for a Complete Shaker Harvest System

Fruit removal predicted from the curves in Fig. 2 (or equation [4]) for the FMC shaker was less than the removal obtained when harvesting whole trees with a complete shaker harvest system. Possible reasons for this are that an experienced shaker operator attaches the shaker at the most advantageous point on each limb and shakes the limbs as long as necessary to remove most of the fruit. The removal shown in Fig. 2 for individual limbs multiplied by 1.5 agrees closely with the removal in four different tests using a complete harvest system in which the shaking frequency and limb displacement were recorded. Predicted fruit removal from Fig. 1 or equation [2] for Valencias is very close to the removal obtained using a complete system.

The confidence intervals shown in Fig. 1 indicate the accuracy of the curves for fruit removal of Valencia oranges. Fruit removal can be predicted with a maximum accuracy of ± 6 percent in the very center of the plot; the accuracy decreases to ± 12 percent at the corners of the plot. Confidence intervals were not calculated for fruit removal of Pineapple oranges (Fig. 3); however, they would be similar to the confidence intervals shown for Valencia oranges. Equations [2], [3], and [4] are valid only for the range of strokes and frequencies plotted in Figs. 1 and 2.

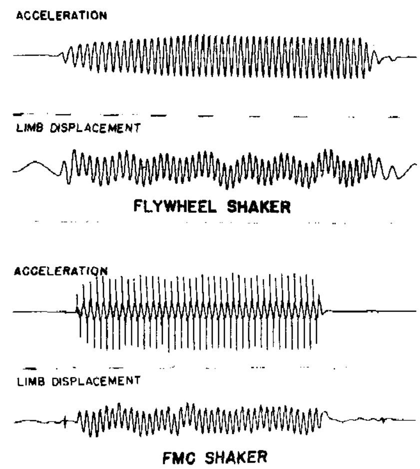

FIG. 3 Typical charts showing the relatively smooth shaking action of the flywheel shaker (top) compared to the FMC shaker (bottom). The calibration factors on both charts are 10 g per cm for the acceleration trace and 2.5 in. per cm for the limb displacement. The chart speed was 20 mm per sec.

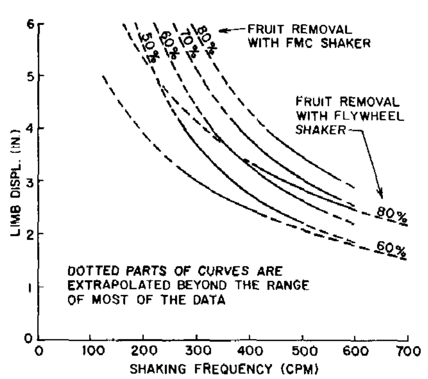

FIG. 2 Curves for constant fruit removal of Pineapples oranges. Each curve for the flywheel shaker is a solution to equation [3], and each curve for the FMC shaker is a solution of equation [4], for 4-in. diameter limbs. For other size limbs, the curves would be shifted slightly but still have the same shape.

Results of Test on Whole Trees

The FMC variable-stroke shaker was used to shake all of the limbs on nine Pineapple orange trees. Three trees were shaken with a 2-in. cylinder stroke, three trees with a 4-in. cylinder stroke, and three trees with a 6-in. cylinder stroke. The operator was free to shake the tree at any frequency within the capabilities of the shaker and to shake the limbs as long as he felt was desirable. The limb displacement and shaking frequency were recorded for each limb and averaged to obtain an average limb displacement and frequency for each whole tree.

The average fruit removal for each group of trees shaken with the same cylinder stroke was compared with the fruit removal from individual limbs

TABLE 1. COMPARISON OF FRUIT REMOVAL OF WHOLE TREES WITH THAT OF INDIVIDUAL LIMBS

No. of replications*	Average frequency, cpm	Average limb displacement, inches	Fruit shaken off of trees, percent	1.50 × Fruit removal from Figure 2 for limbs percent
3	477	1.89	63.5	60.4
3	341	3.76	90.7	88.3
3	326	4.53	91.8	102.5

* Each replication of this test was one tree.

shown in Fig. 2 for Pineapple oranges shaken with the FMC shaker. The adjusted removal from Fig. 2 agrees closely with the removal for the 2 and 4-in. cylinder strokes (Table 1). Obviously, fruit removal with the 5-in. cylinder stroke would have to be less than 102 percent adjusted removal from Fig. 2. These results indicated that the relative effects of limb displacement and frequency on fruit removal are the same for the relatively uncontrolled conditions of this test on whole trees and the more controlled conditions when shaking single limbs.

Fruit Removed with Stems

The regression equation for the percent of fruit removed with stems was determined for each of the tests by a procedure similar to that used for fruit removal. Based on a preliminary analysis of the data, percent stems for both tests on Pineapple oranges were fitted to the following equation:

$$T = C_0 + C_1R + C_2D + C_3f + C_4\,Df \qquad [5]$$

in which T is the fruit removed with stems as a percent of the total fruit shaken off and R, D, and f are the same as previously defined. All first and second-order terms of the above independent variables were used in the case of Valencia oranges. The only independent variable which had a consistent effect in all three tests was shaking frequency. Percent stems decreased from approximately 25 percent at 300 cpm to 8 percent at 600 cpm (Fig. 4).

Summary

Fruit removal with a tree shaker and the fruit removed with attached stems were investigated for a range of limb sizes, shaking frequencies, limb strokes, and smoothness of shaking action in Pineapple and Valencia orange varieties.

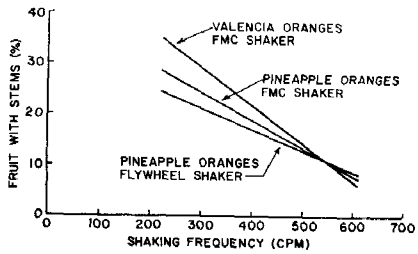

FIG. 4 Percent of fruit removed with stems. Frequency was the only independent variable which significantly affected the percent of fruit removed with stems.

Limb size had relatively little effect on fruit removal of either Pineapple or Valencia oranges compared to the effects of frequency and limb displacement. Removal of Pineapple oranges increased more rapidly with increased shaking frequency than did the removal of Valencia oranges. Fruit removal of both Pineapple and Valencia oranges was directly proportional to the limb displacement. A smooth shaking action removed substantially more fruit in Pineapple oranges than did an impact-type shaking action. Smoothness of shaking action was not evaluated in Valencia oranges.

The percent of fruit removed with stems was not materially affected by limb diameter, limb stroke, or smoothness of shaking action. However, higher shaking frequencies removed substantially less fruit with stems than did lower frequencies.

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