Analysis of Air Shaker Principles to Remove Citrus Fruit

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THE forced-air, or air shaker concept of removing Florida citrus fruit has been under development since the early 1960's (Whitney and Patterson, 1972). It offers some significant advantages. Continuous, down-the-row fruit removal is possible with no physical attachment to the tree. A high percentage of fruit can be removed at a fast rate when the fruit-bonding strength has been uniformly reduced by an abscission chemical to about 25 N or less. High machine reliability is one of its inherent advantages. At present the air shaker's main disadvantages are high power requirement, large capital investment, and dependence on an abscission chemical for satisfactory performance.

The purposes of this paper are to (a) describe the general theory of shaking trees with air and (b) to describe the methods of manipulating ducted air flow from fans to achieve air shaking of citrus trees.

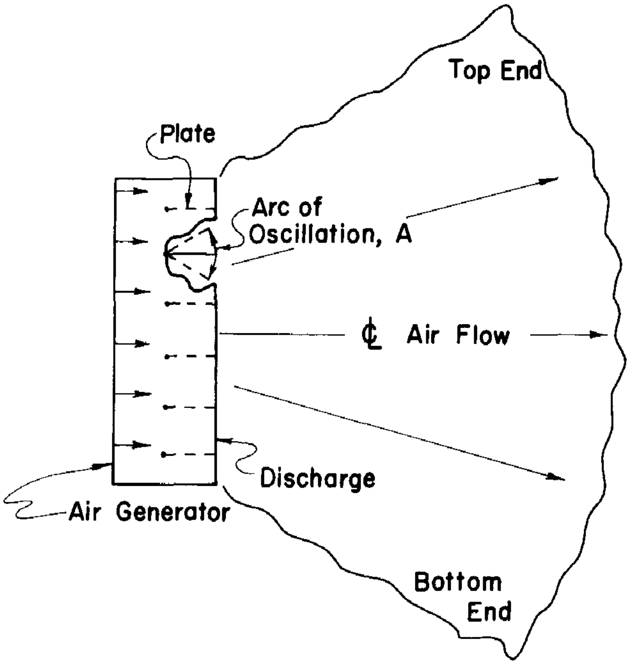

FIG. 1 Profile view of air shaker concept using oscillating, parallel plates.

GENERAL THEORY OF AIR SHAKING

Removal of fruit by air shaking utilizes pulses of air as a cyclic forcing function to shake the tree. The forcing function is essentially applied in one direction. Limb displacement in the general direction of the air velocity is achieved by air drag on the tree structure. The limb springs back after the magnitude of the air drag is significantly reduced. The forcing function of air is applied on a cyclic basis to set up a shaking motion of the fruit-limb-leaf system, thus removing the fruit by shaking. Generally, the frequency of the forcing function should be somewhat greater than the damped, natural frequency of the fruit-stem-limb system. In this way, the limb is repeatedly energized by the force of air drag prior to its maximum displacement or spring back, thus producing a snapping action to remove the fruit from its stem. Of course, the magnitude of the forcing function must be adequate at the selected frequency to cause sufficient limb movement. The optimum frequency and magnitude of the forcing function required can vary considerably depending on the fruit load, fruit bonding strength, and limb structures.

Other considerations are pertinent to the overall health and vigor of the citrus tree. Exposure time to high air shaking forces has an upper limit if the tree is to have a long, productive life. There is also a definite upper limit of shaking force per unit area from air drag which the limbs and leaves can tolerate independent of exposure time. To minimize localized tree damage, the area of application should be maximized while the exposure time and force or drag per unit area should be minimized. This is especially true on the larger and stiffer limbs, and also on heavily fruited limbs, because the relative velocity of the air and limb is greater due to less displacement of these limbs during shaking. Air drag of fruit on these limbs are sometimes sufficient to shake the fruit without depending on limb displacement for removal.

METHODS OF MANIPULATING AIR

The development of air shakers to date has involved the manipulation of air flow from a ducted fan. Initially, (Whitney and Patterson 1972), air from a rectangular discharge was directed with parallel oscillating plates (Fig. 1) at various parts of the tree at a cyclic rate of approximately 1 cps. Air from the discharge vertically swept the tree as the plates moved between their extremes of arc oscillation. Those portions of the tree at either end of the

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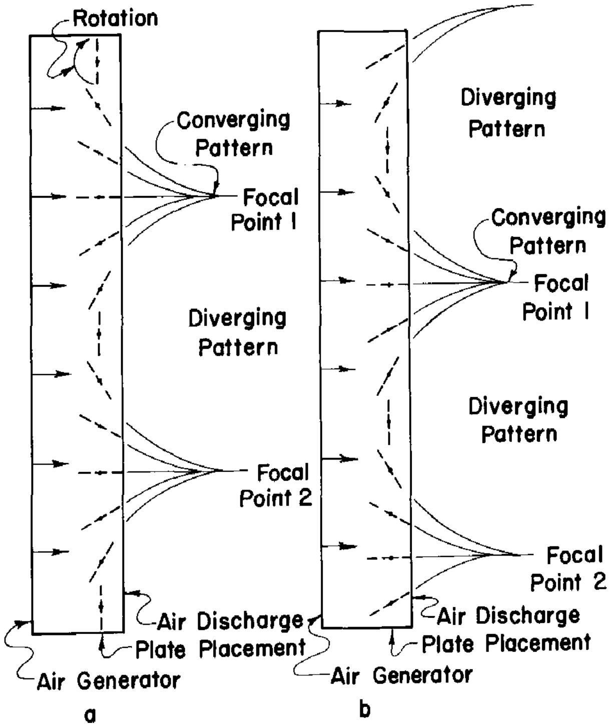

FIG. 2 Profile views of center pivot system. Phase angle between plates = $[\pi/6]$ radians. Plates have rotated $[\pi/3]$ radians between a and b to show movement of focal points.

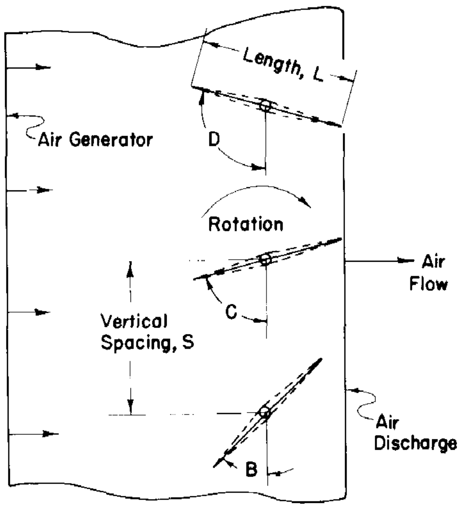

FIG. 3 Close up profile view of center pivot system. D-C = C-B = phase angle between plates = P = $[\pi/6]$ radians.

oscillation pattern received air pulses once each cycle of oscillation. At the center of oscillation, the tree received 2 air pulses per cycle of oscillation. For some distance either side of center, the tree received 2 air pulses per cycle of oscillation but at different time periods between pulses. This type of air manipulation usually removed fruit from the outside canopy of the tree, but did not penetrate well past the canopy to shake the inner portions of the tree because the air velocities diminished quickly in this area. Other systems of manipulating air were investigated in an attempt to overcome the shortcomings of the parallel plates.

Center Pivot System

Air from a vertical, rectangular discharge approximately the height of a tree was manipulated by a set of out-of-phase plates (MC GEE 1969) (Fig. 2). This was called the center pivot system and is shown as a close-up in Fig. 3. The plates were mounted on horizontal shafts and were driven in the same direction at the same rotative speed. The rotational phase angle between plates was constant and the angular offset between plates was in the same direction going up or down the discharge height. This type of out-of-phase plate arrangement caused the air to be converged from given heights of the discharge separated by heights of little or no air flow or what might be termed as diverging patterns. As the plates rotated, the converging and diverging patterns moved either up to down through the tree depending on the direction of rotation. Fig. 2a and 2b show how the patterns moved down the discharge with clockwise rotation of the plates. At any height on the discharge, a pattern repeated itself every π radians of plate rotation. Any portion of the tree alternately saw the converging and diverging patterns at a cyclic rate associated with the driven speed of the plates. The converging pattern had the capability of maintaining air velocities in excess of 50 m/s for up to 3 to 4 m from the discharge. The converging pattern (high velocity air) forced the limb away from the discharge while the diverging pattern (reduced velocity air) allowed the limb to spring back. When the two patterns were alternately applied to a tree at the proper cyclic rates and velocity magnitudes, oscillating limb motion or shaking resulted. Two other plate systems have been used to create similar converging and diverging air patterns and are described below.

Upstream Pivot System

This system consisted of vertically spaced air foils (or flat plates) mounted horizontally, spaced vertically, and pivoted upstream on shafts (Figs. 4 and 5). Each plate was oscillated through an arc by a crank system which was driven from a common drive. Each crank disk rotated at the same constant speed and could be adjusted to any phase relationship with adjacent disks. This resulted in approximately the same phase relationship between adjacent plates. The rotational phase angle between disks was constant and the angular offset between disks was in the same direction going up or down the discharge. The total arc of oscillation could be adjusted by varying the radius of the disk and/or the lever arm on the plate shaft. The neutral plane of each plate's arc of oscillation could be adjusted with respect to its lever arm by means of an adjustable quadrant section. A constant drive speed on the disks determined the speed of the plate oscillation movement. The upstream pivot system could develop adjacent converging and diverging patterns as shown in Fig. 4. At the center of the diverging portions of the pattern, air was discharged rather than being blocked as in the center pivot system. As the disks rotated, the converging and diverging patterns moved either up or down through the tree, depending on the direction of disk rotation. Figs. 4a and 4b show how the patterns moved down the discharge (or tree) with clockwise rotation. At any height on the discharge, a pattern repeated itself every 2 π radians of rotation of the disks. The principle of shaking was the same as described for the center pivot system.

Wobble Plate System

Elliptical plates were mounted on a

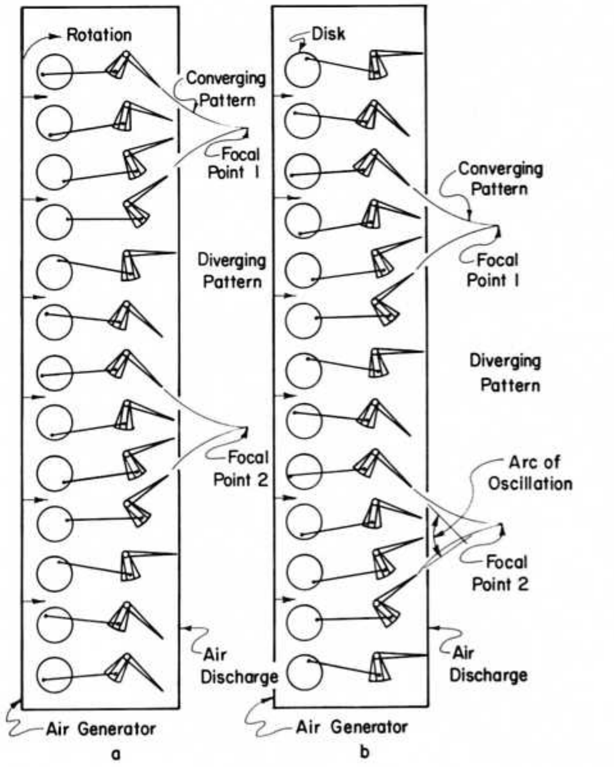

FIG. 4 Profile views of upstream pivot system. Phase angle between disks = [π/3] radians. Disks have rotated π radians between a and b to show movement of focal points.

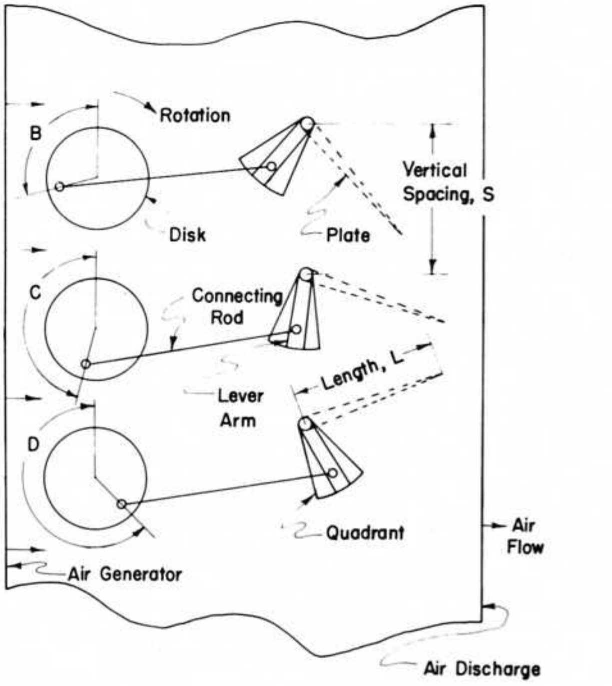

FIG. 5 Close up profile view of upstream pivot system. D-C = C-B = phase angle between disks = P = [π/3] radians.

common vertical drive shaft (Wininger 1967) (Figs. 6 and 7). The major axis of each elliptical plate was set at the same included angle with the drive shaft. The horizontal projection of the major axis was equal to the minor axis length so the the plates could rotate on the vertical drive shaft in a vertical rectangular discharge. Adjacent wobble plates were adjusted at the same phase angles about the shaft and the angular offset between plates was in the same direction going up or down the shaft. Rotative speed of the drive shaft and wobble plates was constant. As shown in Fig. 6, the converging and diverging patterns developed by the wobble plates were very similar to those of the upstream pivot system. Figs. 6a and 6b show how the pattern moved downward when the shaft rotation was clockwise (view shaft from top). Rotation of the shaft in the opposite direction would cause the patterns to move upward. At any given height of the discharge, a pattern repeated itself every 2π radians of shaft rotation. The principle of shaking was the same as the center pivot system.

GENERAL DISCUSSION

Figs. 3, 5, 6, and 7 show the impor-

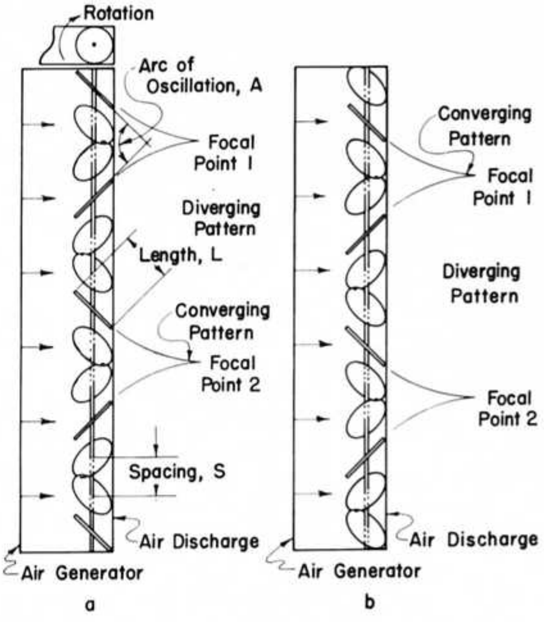

FIG. 6 Profile views of wobble plate system. Phase angle between plates = [π/3] radians. Plates have rotated [π/3] radians between a and b to show movement of focal points.

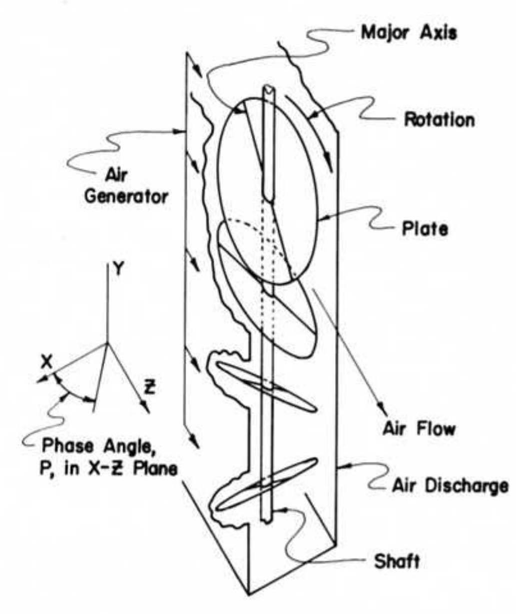

FIG. 7 Isometric view of wobble plate system. Phase angle = [π/3] radians.

TABLE 1. FACTORS WHICH DESCRIBE AIR MANIPULATION SYSTEMS.*

System	Converging & diverging profile function of	Focal point speed along discharge, m/s	Frequency of focal point occurrence height, cps
Upstream pivot or Wobble plate	S, P, A, L	$\frac{S \times 2\pi \times R}{P}$	R
Center pivot	S, P, L	$\frac{S \times 4\pi \times R}{P}$	2 R

* S = Vertical spacing of plates, meters
R = Speed of main drive, cps
P = Phase angle between adjacent plates, radians
A = Total angle of oscillation (upstream pivot); π radians minus twice the included angle between main axis and drive shaft (wobble plate)
L = Length of major axis on wobble plates; length of upstream or center pivot along direction of air movement, meters

tant dimensions which determined how the plate systems manipulated the ducted air flow. These dimensions were plate spacing (S), length (L), phase angle (P), and arc of oscillation (A). The rotational speed (R) of the systems determined the travel speed and frequency of the patterns.

For a given air generator source, the fruit removal effectiveness of the plate systems mainly depended on the profile of converging and diverging patterns, the speed at which the converging patterns (focal points) moved vertically along the discharge, and the frequency with which the converging patterns (focal points) occurred at any given height along the discharge. The factors which defined these attributes are given in Table 1.

The profiles of the air patterns were relatively important because they determined the rate of air velocity change along the discharge height and the volume flow rate of air in the converging and diverging segments of the patterns. The degree of convergence or divergence in the air profiles could be increased (focal point moved closer to the discharge) by increasing A in the wobble plate and upstream pivot systems and by increasing P and L/S (limited to 1 in center pivot system) in all systems. Such a change generally improved the shaking action by increasing the difference in air velocity magnitudes between the converging and diverging patterns. The center pivot system was unique in this respect in that the air discharge velocity could be reduced to near zero at the center of the diverging pattern, thus maximizing the difference in air velocities. One limitation, however, of this system was that except for L, an adjustment of convergence or divergence of the profiles also affected focal point speed (Table 1). In the other two systems, because of A, the converence and divergence could be changed without affecting the focal point speed. Increasing the degree of convergence in all 3 systems was beneficial only to a point; because for any given distance from the discharge, there was an optimum amount of convergence to achieve peak air velocities. The volume of air flow or height of discharge contained in the converging air pattern increased with increasing S and decreasing P. To some extent, the magnitude of the forcing function was determined by this volume flow rate. Increasing the degree of convergence in all systems increased the horizontal width of the converging air pattern because the air was forced together in a vertical direction. This increased the effective width of the shaking pattern.

The speed at which the focal point traveled along the discharge is defined in Table 1 as a function of S, R, and P. For example, if $S = 0.3$, $R = 0.5$, and $P = (\pi/6)$ radians, then the speed of the focal points of the center pivot system was 3.6 m/s. For best fruit removal efficiency, high focal point speeds (in excess of 6 m/s) were usually desirable to achieve the maximum time rate of change of limb velocity and thus maximum snap action on the fruit-stem system. The maximum focal point speed resulted in minimum exposure time of the forcing function (focal point) to the fruit-stem system, and its upper speed limit was determined by the capability of the focal point to achieve enough snap action of the fruit-stem system for fruit separation. Generally, higher focal point speeds can be used with greater forcing function magnitudes because of the increased capacity to move the fruit-stem system in less exposure time.

The frequency of focal point occurrence was strictly a function of R. In the example above, frequency of occurrence $= 2R = 2(0.5) = 1$ cps. Higher frequencies (1.4 to 1.6 cps) have been better suited for light fruit loads and small fruit bonding strengths whereas the lower and medium frequencies (1 to 1.3 cps) have achieved best results on high fruit bonding strengths and heavy loads where greater limb displacement was required.

From a design standpoint, other factors should be considered with the 3 air manipulating systems. The wobble plate system was the simplest to drive and maintain. However, this simplicity required that the width and depth (parallel to air flow) of the discharge containing the wobble plates be equal. This could be a problem if one wide discharge were desirable with one set of plates and the depth dimension had to be minimized because of limited working space in the grove. However, if more than one set of plates could be used, then two or more narrow discharges might be a compromise with the wobble plate system. In the other 2 systems, the plate width can be varied independent of the depth (plate length).

The lowest air volume flow rate was possible with the center pivot system because a portion of the air discharge is blocked at all times. This could potentially reduce the air power required if excessive static pressures can be avoided in generating the necessary air volume flow rates.

The upstream pivot and wobble plate systems offered somewhat greater flexibility than the center pivot system in developing a wide range of converging pattern profiles and focal point speeds. In addition, the air patterns developed by the upstream pivot system can be skewed at the bottom and top of the discharge to achieve a greater height of tree coverage and top of the discharge to achieve a greater height of tree coverage from a given discharge height by adjusting the neutral oscillation plane of adjacent plates in the desired direction of skewing.

SUMMARY

Air shakers offer some significant advantages in removing citrus fruit in that no physical attachment is made to the tree. Cyclic pulses of high velocity air are used as the forcing function to shake the tree. Three out-of-phase plate systems were utilized to develop these pulses, which moved vertically through the tree. Given an air generator source, the fruit removal effectiveness of the systems depended mainly on the profile of the pulses, their vertical speed along the dis-

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charge, and the frequency at which they occurred at any given height along the discharge.

CONCLUSIONS

1 To minimize localized tree damage due to air shaking, the exposure time and force or air drag per unit area should be minimized while the area of air drag application should be maximized.

2 Because of the adjustable arc of oscillation, the upstream pivot and wobble plate air manipulation systems provide greater flexibility in developing a wide range of converging pattern profiles, and focal point speeds than does the center pivot system.

3 The lowest potential air volumetric flow rate can be achieved with the center pivot system because a portion of the discharge can be blocked at all times.

4 The wobble plate system was the simplest to drive and maintain.

References

1 McGee, A. L. 1969. Apparatus for harvesting fruit growing on trees. U.S. Patent No. 3,448,567.

2 Whitney, J. D. and J. M. Patterson. 1972. Development of a citrus removal device using oscillating forces air. TRANSACTIONS of the ASAE 15(5):849-855, 860.

3 Wininger, L. W. 1967. Fruit harvesting machine. U.S. Patent No. 3,310,231.