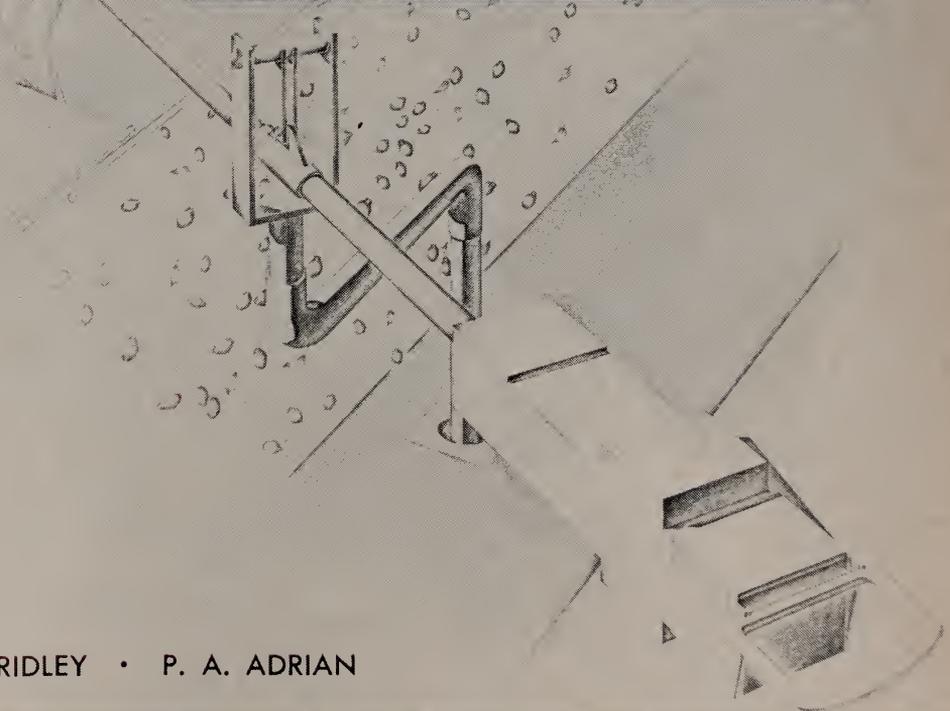
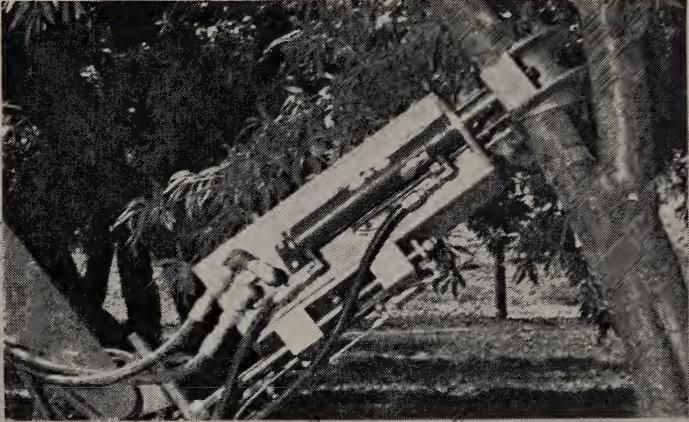




MECHANICAL HARVESTING EQUIPMENT FOR DECIDUOUS TREE FRUITS



R. B. FRIDLEY • P. A. ADRIAN

This publication reports on basic studies of tree-shaking and the development of new types of shakers. Injury to tree bark resulting from shaker use was also investigated and led to the design of improved methods of attaching to trees described herein. Details on pickup machinery developed to collect fruit which can be shaken to the ground, and an improved fruit catching-frame for collection of other fruits, are given. Methods of catching fruit with minimum injury to the fruit are also described.

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MECHANICAL HARVESTING EQUIPMENT FOR DECIDUOUS TREE FRUITS¹

INTRODUCTION

Since 1942, intensive study of mechanical harvesting has been carried on in California (Fairbank, 1946; Lamouria and Hartmann, 1955; Lamouria *et al.*, 1961; McKillop *et al.*, 1955).² Today, the state's almond and walnut harvest is completely mechanized and much progress has been made in similar harvesting of other deciduous tree fruits. In Michigan and New York considerable progress has been made on the harvesting of tart cherries (Levin *et al.*, 1960; Markwardt, 1962). Even prior to 1956 progress had been made which stimulated an interest in mechanical harvesting, and this resulted in the organization of an extensive cooperative project on prune harvest mechanization carried on by the University of California Agricultural Experiment Station and the Agricultural Engineering Research Division of the United States Department of Agriculture. The work was expanded in 1958 to include other deciduous tree fruits and olives.

In 1956, a thorough survey was made of methods used to harvest prunes (Fridley and Parks, 1957). The equipment studied included machines to shake trees to remove fruit, frames to catch fruit as it was shaken from the tree, and machines to pick up fruit from the ground.

Tree-shaking methods. Four methods of tree shaking were studied:

- pole-shaking by hand; secondary limbs were shaken with an oak or aluminum pole having a hook

- shaking of secondary limbs with a hand-carried pneumatic power shaker, with reciprocating action supplied by a double-acting air piston
- cable-shaking
- boom-shaking.

Table 1 compares the four shaking methods. Pole-shaking often caused excessive removal of small branches because a vigorous shake was required to remove all fruit, and because some crew members beat the trees rather than using the hook. Damage from hand-carried shakers was most pronounced when shakers were not held perpendicular to the limb, thus causing the hook to slide along it, skinning the bark and breaking small branches. Careless cable-shaking caused excessive breakage of primary limbs and damage to tree bark was observed with all shakers (see page 22).

In cable-shaking, a cable connected a tractor-mounted eccentric to a hook placed over the limb. One man in the tree placed the hook, and the tractor driver tightened the cable by means of a take-up mechanism, or by moving the tractor. Initial tension on the cable was determined by the operator and this, plus the fact that all the displacement of the limb induced by the eccentric was in the same direction from a neutral position of the limb, frequently resulted in limb breakage. Because the cable could not support a compression force the effective shaking frequency was limited.

Boom-shaking was similar to cable-shaking except that the cable was re-

¹ Submitted for publication May 20, 1965.

² See "Literature Cited" for publications referred to in the text by author and date.

TABLE 1
COMPARISON OF SHAKING METHODS, 1956

Method	Frequency	Stroke	Approximate fruit removed	Labor requirement
	<i>cpm</i>	<i>inches</i>	<i>per cent</i>	<i>Man-hours per acre*</i>
Pole.....	.....	.....	95-100	19-25
Pneumatic.....	1800-1900	.....	90-95	9-12
Cable.....	400-600	1¾-3	90-95	4-8
Boom.....	400-1000	1¼-2	90-95	1-4

* For harvesting all fruit in one operation.

TABLE 2
FRUIT COLLECTION METHODS, 1956, COMPARED FOR EFFECTIVENESS AND FRUIT QUALITY

Method	Fresh fruit having visible damage	Dried fruit having major mechanical damage	Trash (foreign materials)	Fruit missed
	<i>per cent of total fruit (by weight)</i>			
Hand from ground.....	10-27	3-10	1	negligible
Hand from tree.....	5	1	negligible	...
Frames*.....	1-14	1-3	0.2-2	5-11
Pickup machines†.....	10-29	5-10	4-13	2-6

* The hand operation of picking up windfalls ahead of this operation is not included.

† Includes damage during pickup and boxing operations and damage caused by falling.

TABLE 3
FRUIT COLLECTING METHODS, 1956, COMPARED FOR HARVESTING RATE AND LABOR EFFICIENCY

Method	Crew size	Harvest rate	
		<i>Bozes per man-hour</i>	<i>Trees per hour</i>
Hand from ground.....	Family	4-5	...
Portable frames:			
Pole shaking.....	3†	3-8	4-12
Pneumatic shaking*.....	8†	7	15-20
Boom shaking*.....	9†	17-20	30-35
Tractor mounted frames:			
Cable shaking.....	5†	7-10	12-16
Pickup.....	2-3†	15-22	...

* Two sets of frames used to keep shaking crew busy.

† Includes shaking crew.

‡ Includes crew to rake fruit out from tree row.

placed by a rigid member supported by a tractor-mounted or self-propelled boom. Some shakers were firmly attached to the tree by means of a clamp; a few were not attached to the tree but applied a pushing action only. The latter type usually devel-

oped an impact or impulse rather than an oscillating motion for vibration excitation.

Fruit-collecting methods. Prunes were collected by hand picking from the



Fig. 1. Pole-shaking and hand harvest of prunes from the ground.

tree, hand pickup from the ground, catching on frames, or machine pickup from ground. Picking by hand from the tree was common only for easily bruised varieties. Few French prunes (which represent most of California's acreage) were harvested in this manner. Picking by

hand from the ground was best done by families, with the men shaking and the women and children picking up (fig. 1).

In catching-frame harvesting, fruit removed by one of the four shaking methods was caught on a frame and delivered to boxes. Catching-frames were hand-



Fig. 2. Portable frame to collect prunes used with hand-carried, powered shakers.



Fig. 3. Pickup machine with reel-type pickup mechanism and metal water-filled bin behind tractor.

carried or hand-pulled, self-propelled, or tractor-mounted. Hand-moved frames generally consisted of a thin-wall tubing framework with a canvas catching-surface (fig. 2).

Self-propelled or tractor-mounted frames need not be light, and their construction varied from light framework with a canvas catching-surface, to wood framework with plywood surface, to metal framework with a sheet metal surface.

Machine pickup from the ground (fig. 3) was used primarily for French prunes, as other varieties damage quite easily. Proper land preparation was found to be essential for this pickup method. The standard land preparation was to disk twice, landplane twice, and roll twice. Best results were obtained when the second operation with each piece of equipment was in the direction of harvest. Observation indicated that the most important factor was to work the ground at proper moisture content, which varies with different types of soils.

The pickup machines studied during the 1956 survey were all basically reel-type devices—that is, fruit was picked up by a reel rotating against the direc-

tion of travel. Tractor-mounted and self-propelled devices having rubber or metal fingers in the reel were used.

Table 2 gives data on fruit quality and effectiveness. Per cent of fruit damaged during hand pickup and machine pickup was affected by soil preparation and fruit maturity; figure 4 shows the effect of both of these variables. Excluding damage to fruit caused by falling, pickup machines damaged 1 to 11 per cent of the fruit (Miller, 1963).

The main factors contributing to fruit damage with catching-frames were catching-surface materials and the methods of transferring fruit from frame to box. Hard surfaces cause splitting of some turgid fruit.

The amount of foreign material with prunes caught on frames was largely dependent on the method of shaking. Branches and leaves removed by pole shaking were collected with the fruit. Pickup machines collected more foreign material from poorly prepared land than from well-prepared land.

Fruit loss onto the ground was frequently a problem with catching-frames and sometimes with pickup machines. Most fruit missed by frames fell to the

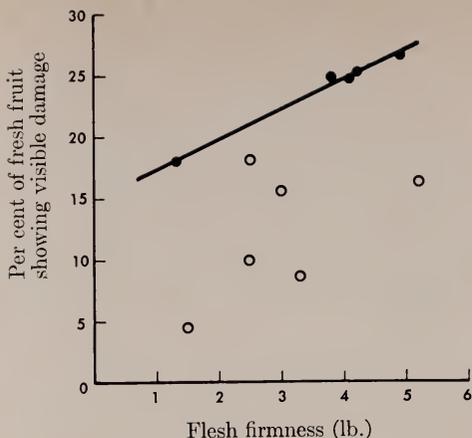


Fig. 4. Effect of fruit maturity (flesh firmness) and land preparation on visible damage caused by fruit falling to ground. The circles are data points: black circles show data for carefully picked fruit on land prepared for hand picking; white circles show data for fruit on land prepared for mechanical harvesting. Variation in data for mechanically harvested fruit is thought to be caused by variation in quality of land preparation. (The system of representing data points by circles, squares or triangles is used throughout various figures which follow.)

ground around the trunk of the tree because of ineffective seals. Missing of fruit by pickup machines was primarily caused by failure to properly level the land.

Table 3 shows labor requirements and

harvest rates of the various methods of harvest. The number of trees harvested per hour varied from orchard to orchard and was largely dependent on yield and on past pruning practices—that is, on the number of limbs, the amount of low bushy wood which interfered with shaker hookups, and tree-crotch height.

Although many types of equipment existed in 1956, almost none of the French prune crop was mechanically harvested, thus indicating the need for more efficient equipment as well as for better harvesting methods. To meet such needs, the following projects were undertaken between 1957 and 1964:

- a study of basic principles of tree-shaking
- development of design criteria for an inertia-type shaker
- studies of the relationship of shaker design to tree injury
- development of an impact-type shaker
- studies of inertia tree-shakers and the effect of pulsating air on selective harvest of coastal valley prunes
- development of a new principle of mechanical fruit pickup
- development of efficient fruit-collection equipment.

BASIC STUDIES OF TREE SHAKING

The studies of tree shaking determined the effect of (1) frequency and stroke on the tree at the point of attachment, and (2) the effect of clamp position on fruit removal, tree damage, power required, and forces developed (Fridley and Adrian, 1960). Extensive tests were conducted on French prune trees in five counties with a boom-type shaker designed for use on limbs (fig. 5), and limited tests were conducted on peaches, prunes, and olives with inertia-type shak-

ers designed for use on tree trunks or on limbs.

BOOM-SHAKER TESTS

These tests were conducted on 53 French prune trees, shaking each tree with a particular stroke and frequency. Fruit removed, fruit not removed, average force axial to the stem required to remove prunes from the tree, average weight of the prunes, and average maturity were



Fig. 5. Fixed-displacement shaker with force- and power-recording equipment.

recorded. Evaluation of limb breakage, bark skinning and possible root damage was made by visual observations. The frequency range was 400 to 1000 cpm (cycles per minute), the stroke range at the limb was $\frac{1}{2}$ inch to 2 inches, the clamp position was from one-sixth to one-half of the way out the limb.

To measure force exerted on limbs, strain gauges were bonded to the shaker member near the clamp and a Textronix Oscilloscope with an oscilloscope camera was used to make permanent records. To minimize effects of clamp inertia, a lightweight clamp of special design was used, and its inertia forces were measured and subtracted from force readings.

Power requirements were calculated from the product of instantaneous force and clamp velocity, where the later was assumed sinusoidal. This made it necessary to know the shaker member position in relation to the force signal, and therefore the position was determined by a switch which was closed once each cycle to produce a break on the force trace on the oscilloscope screen.

Figure 6 shows typical curves of the force exerted on tree limbs, and the instantaneous power required. Direct readings from these curves gave maximum force and maximum power required, and average horsepower was determined with a planimeter.

Fruit removal results. Removal has been found to be affected primarily by frequency, stroke, F/W (ratio of average removal force of the fruit to the average weight of the fruit), and tree structure—that is, the number of fruit-bearing hangers.

Table 4 and figure 7 give results of the tests on French prunes as well as fruit-removal information calculated from the following:

$$\text{Per cent removed} = 100 - 100e^{-ks^p N^\mu}$$

where S = peak to peak stroke in inches, N = frequency in cycles per minute, k = constant for a particular tree, and p and μ = constants for prunes.

The form of this equation was determined by graphical analysis from test results and the validity determined by determining p , μ , and k from a multiple regression analysis (Appendix A). The exponent p had an average value of 1.6, and μ had an average value of 1.1.

Exponents $p = 3/2$ and $\mu = 1$ gave adequate results for the ranges of frequency and stroke tested. Using these constants, the following values for k were deter-

TABLE 4
ACTUAL AND CALCULATED
PRUNE REMOVAL OBTAINED
BY MECHANICALLY SHAKING
PRIMARY LIMBS

Frequency	Stroke	Fruit removal	
		Actual	Calculated
<i>cpm</i>	<i>inches</i>	<i>per cent</i>	
445.....	1½	60	60
743.....	1½	79	78
878.....	1½	90	84
450.....	½	7	16
738.....	½	25	26
970.....	½	36	32
462.....	1	70	71
752.....	1	85	87
975.....	1	94	93
920.....	1½	96	97
740.....	1½	94	94
450.....	1½	83	84
990.....	1	87	87
790.....	1	81	80
450.....	2	95	92

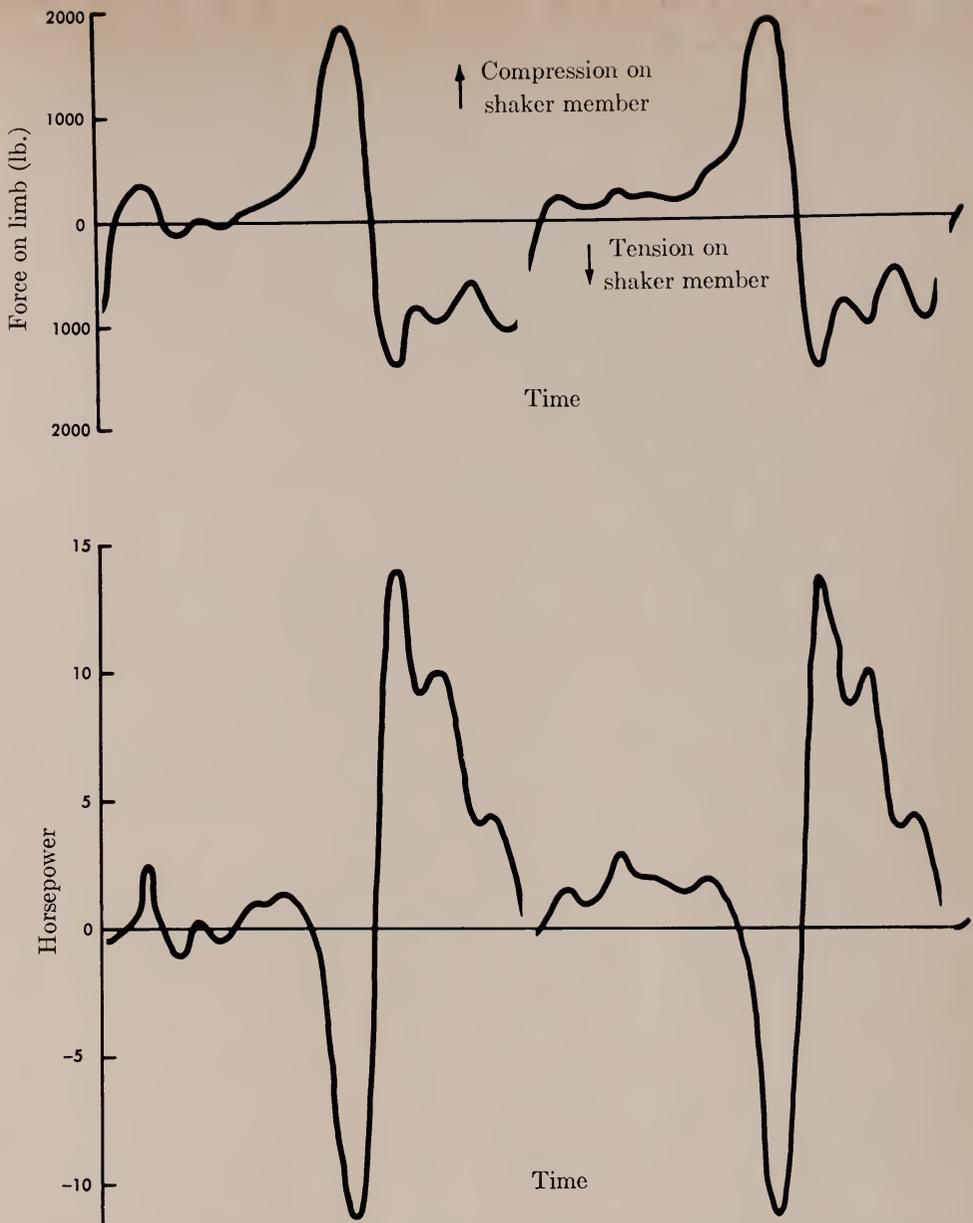


Fig. 6. Typical instantaneous force and instantaneous power requirements for shaking prune tree limbs. Curves show the fluctuation during the time required for two revolutions of the eccentric. Breaks in curves occur when the shaker member attached to tree is at extreme rear position. Area on the negative side of horsepower curve represents work done on the shaker by the limb itself.

mined for the average of several orchards tested in 1957 and for two different orchards tested in 1958:

- $k = 0.000205$ 1957 data
- $k = 0.00113$ 1958 grower orchard
- $k = 0.00270$ 1958 University orchard

These results were found to be significant at the 1 per cent level (Appendix A).

The values of p and μ are probably affected by the position of the clamp on the limb. This relationship was not evalu-

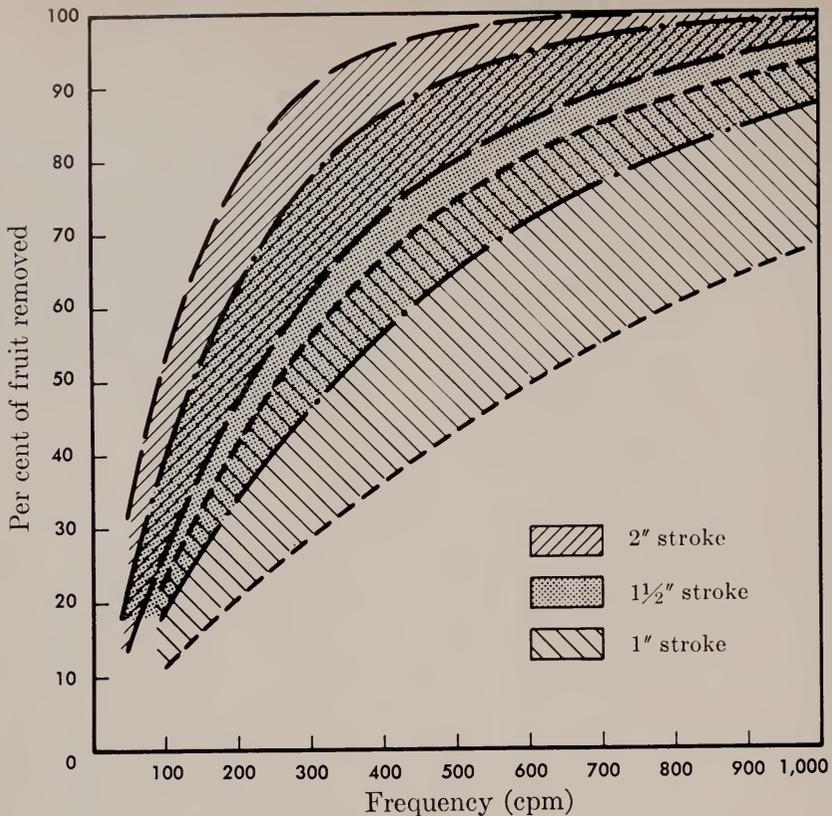


Fig. 7. Effect of frequency and stroke on the removal of French prunes. The range in per cent removed for each stroke given was caused by the variation in bonding force between fruit and tree, and by tree structure. Ranges of removal for the different strokes overlap, causing the apparent variation in shading. High per cent removal of fruit was the result of low bonding force, a stiff tree with few long hangers, and few fruit in the lower-center portion of tree.

ated; however, it was noted that the removal was not appreciably affected by clamp positions of one-fourth to one-half of the way from the main crotch to tree extremities. The values of p and μ given here are for this range of clamp positions.

Results of limited tests on olives suggested that a similar relationship could be developed. The greater difficulty in removing olives signifies a lower value for k with olives than with prunes. The values of p and μ are also likely to be different for olives than for prunes.

Force and power requirements.

Study of the force and power required to shake prune tree limbs with fixed-amplitude shakers indicated that both

factors varied with the frequency and stroke of the shaker, position of attachment on the limb, size of limbs, and the angle between the shaker and the limbs (figs. 8, 9). The power required was approximately proportional to the square of the stroke. The force was directly proportional to stroke. Power required depends on the damping, stroke, and frequency of every part of the limb, and complete analysis of the power would be extremely complicated, particularly as the stroke at points other than the point of attachment vary with frequency.

When fruit-removal curves (fig. 7) are compared with the power curves (fig. 9) it is found that less power is usually

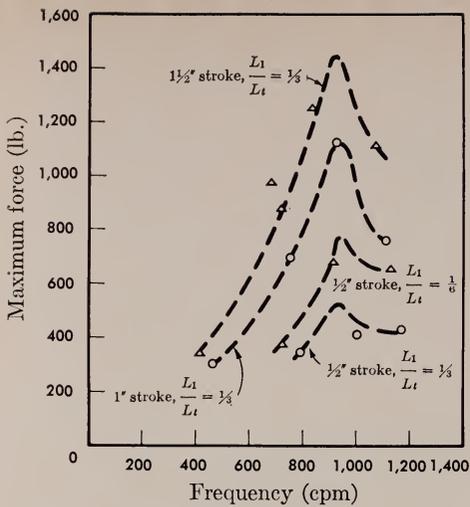


Fig. 8. Relationship of force, frequency, stroke, and position of attachment for shaking 5"-diameter prune tree limbs. The ratio of L_1 (distance from crotch to shaker clamp) to L_t (distance from crotch to end of limb) gives the position of attachment. Decrease in power as frequency was increased above 900 cpm was apparently the result of approaching a natural frequency of the limb.

needed to obtain a given per cent removal with long strokes and low frequencies. For example, to get 90 per cent removal of prunes the frequency, stroke, and power are as follows:

- 400 cpm, 2 inches and 1 horsepower
- 600 cpm, 1 1/2 inches and 1 3/4 horsepower
- 1100 cpm, 1 inch and 3 horsepower

Possible damage to trees must also be considered. Observations indicated that limb breakage increased more rapidly with an increase in stroke than with a comparable increase in frequency, whereas injury to the bark is associated with large shaking forces, and therefore is most likely at high frequencies.

Lowering the clamp position from a position one-third of the way out the limb to a position one-sixth of the way out the limb increased the power by about 35 per cent and the maximum force by about 75 per cent.

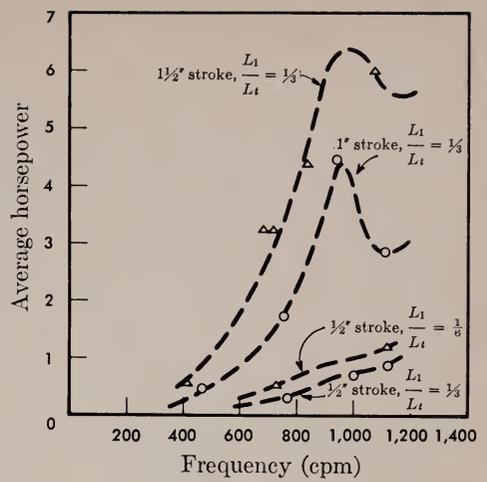


Fig. 9. Relationship of power, frequency, stroke, and position of attachment for shaking 5"-diameter prune tree limbs. The ratio of L_1 (distance from crotch to shaker clamp) to L_t (distance from crotch to end of limb) gives the position of attachment. Decrease in power as frequency was increased above 900 cpm was apparently the result of shaking near a natural frequency of the limb.

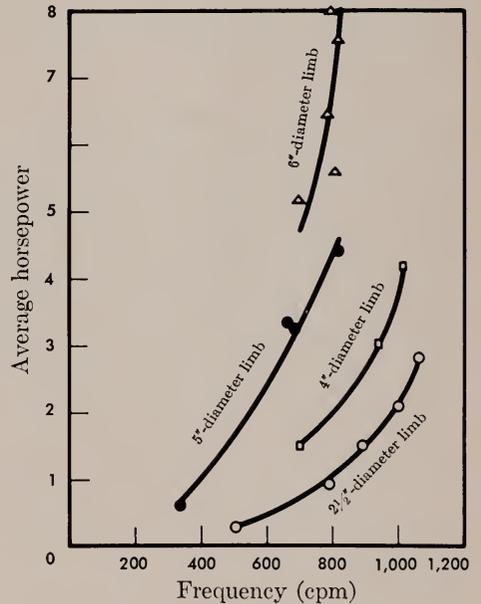


Fig. 10. Effect of limb diameter on power requirement for shaking prune tree limbs at various frequencies with a 1 1/2" stroke. Frequencies were not high enough to produce the effect of natural frequencies shown in figure 9.

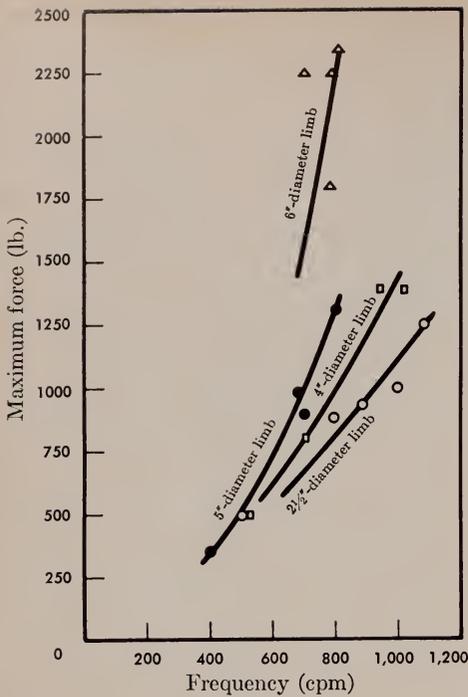


Fig. 11. Effect of limb size on force exerted to shake tree limbs at various frequencies with a 1½" stroke. Frequencies were not high enough to produce the effect of natural frequencies shown in figure 8.

Figures 10 and 11 show the effect of limb size on power and force requirements. The force and power increased approximately with the first and second power of the limb diameter, respectively.

Figures 12 and 13 show the effect of having the boom of the shaker at various angles to the limb. The important point here is that of these angles in relation to damage done to the tree by the clamp. Force and power are both increased as the included angle between the boom and the limb is decreased, and the force has a component longitudinal with the limb. This component of force is a cause of bark damage (see page 22.)

TRUNK-SHAKER TESTS

A study was made to determine the advantage of shaking trees at the trunk in more than one direction. Tests were con-

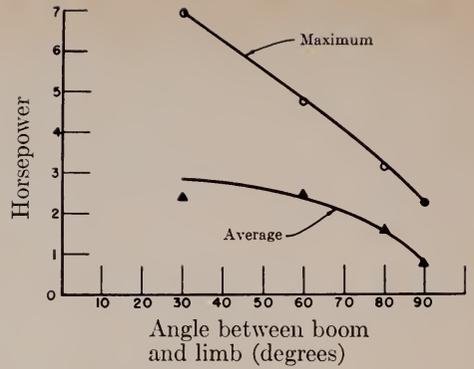


Fig. 12. Effect of angle of attachment on maximum and average power requirements for shaking a 3"-diameter limb with a 1½" stroke at 750 cpm. As the boom departs from perpendicular to limb the power requirement increases (see also fig. 13).

ducted in two prune orchards to evaluate the effects of variation in tree structure. One orchard was approximately 10 years old and had the normal condition of low, flexible hanger wood. The other orchard was about 40 years old and was representative of many older orchards whose trees have shorter hangers on secondary limbs. Four tree replications of each treatment were used in each orchard.

Trees were first shaken in one direction for 5 seconds and then a second shake of 5 seconds was applied in the same direction or at 30°, 45°, 60°, or 90° with respect to the original direction. For comparison purposes, two addi-

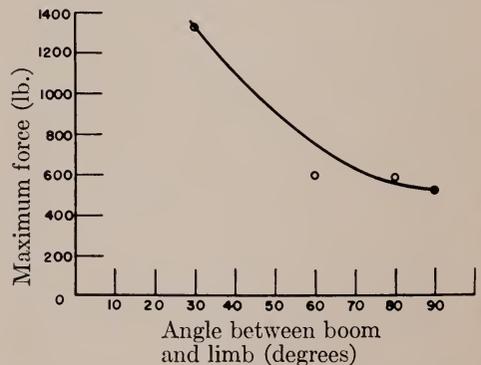


Fig. 13. Effect of angle attachment on maximum force required to shake a 3"-diameter limb with a 1½" stroke at 750 cpm.

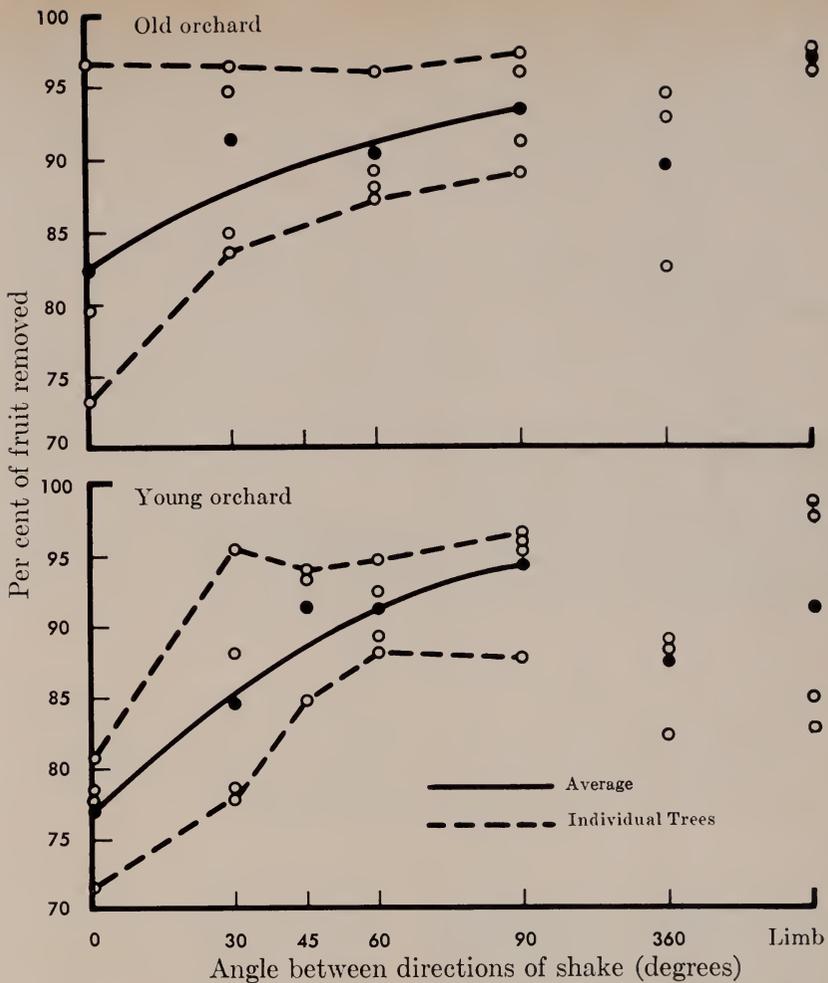


Fig. 14. Fruit removal resulting from shaking tree trunks in two directions (0° to 90° apart), compared with fruit removal by shaking with circular translation (360°), and by shaking limbs. White circles show the results obtained on individual trees, and dashed lines indicate the range of results from shaking in two directions. The solid line represents removal calculated from data for 0° to 90° , assuming increase in removal from 0° to 90° to be sinusoidal. Black points (averages of individual trees) show that the data correlate closely with this assumption.

tional treatments were shaking at the trunk with circular translation, and shaking the limbs. The total duration of shake for each test was 10 seconds.

Measurements were made on trees in each treatment to determine if any large difference in bonding force existed. The trees were first shaken, then gleaned with hand poles to determine the percentage removal. Figure 14 compares removals

from a young and an old orchard after shaking at the different angles.

In young trees a direction change of 0° to 90° resulted in a 17 per cent increase in removal. Removal for the 360° shake was 87 per cent, approximately equal to that for 30° to 45° . Although the removal of prunes by the trunk-shaker when using angles of 60° to 90° was slightly more than with the limb-shaker

used as a control, the number of primary limbs in the tree which were actually shaken by the limb-shaker must be considered. In the young orchard it was difficult to attach onto all primary limbs because of interference. Each tree had five to seven primary limbs and it was impossible to reach all limbs with one shaker. There was a large variation in removal between trees: two trees had a high removal of 97.5 and 98.5 per cent; two others had only 82.5 and 84.5 per cent. All limbs were shaken in the two trees having high removal.

Table 5 shows that removal in the older orchard was comparable to the younger orchard for the larger changes of position. However, removal for small angular changes was about 5 to 6 per cent better on older trees than on young trees. This apparently results from having fewer large hangers, which are most sensitive to direction of shake. Limb-shaking resulted

in a much better average removal and little removal variation between trees, because of being able to attach to all primary limbs with greater ease so that energy was transmitted to more tree area.

TABLE 5
PRUNE REMOVAL OBTAINED
BY MECHANICALLY SHAKING
TREES IN MORE THAN ONE
DIRECTION

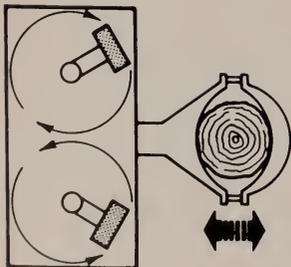
Shaking treatment	Fruit removal	
	10-year-old trees	Mature trees
	<i>per cent</i>	
Trunk with 0° change.....	77	83
Trunk with 30° change.....	85	91
Trunk with 45° change.....	91	..
Trunk with 60° change.....	91	90
Trunk with 90° change.....	94	94
Circular translation (360°)	87	90
Limb.....	91	97

INERTIA-TYPE TREE SHAKER DEVELOPMENT

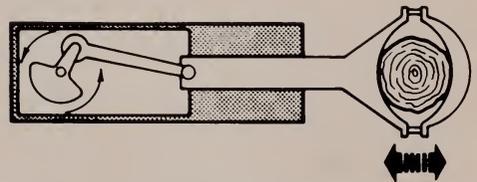
Research from 1957 to 1959 indicated the feasibility of, and need for, a shaker which could be mounted on catching-frames or other lightweight carrying vehicles. Therefore, a development program was initiated in 1958 on an inertia-type tree shaker (Adrian and Fridley, 1965; Adrian and Fridley, 1961).

The basic principle of the inertia shaker is the transmission to the tree of reactive forces developed by an oscillat-

ing mass attached to the tree. Two common sources of this type of force development are the slider-crank and the counter-rotating unbalanced weight assemblies (fig. 15). Both impress the same form of force on the system, and both methods were tested. In the slider-crank mechanism, the slider was attached to the tree so that the reciprocation of the housing supplied the exciting force. In the counter-rotating weight assembly, the housing was



Rotating weight



Slider-crank

Fig. 15. Schematic of rotating weight and slider-crank mechanisms.

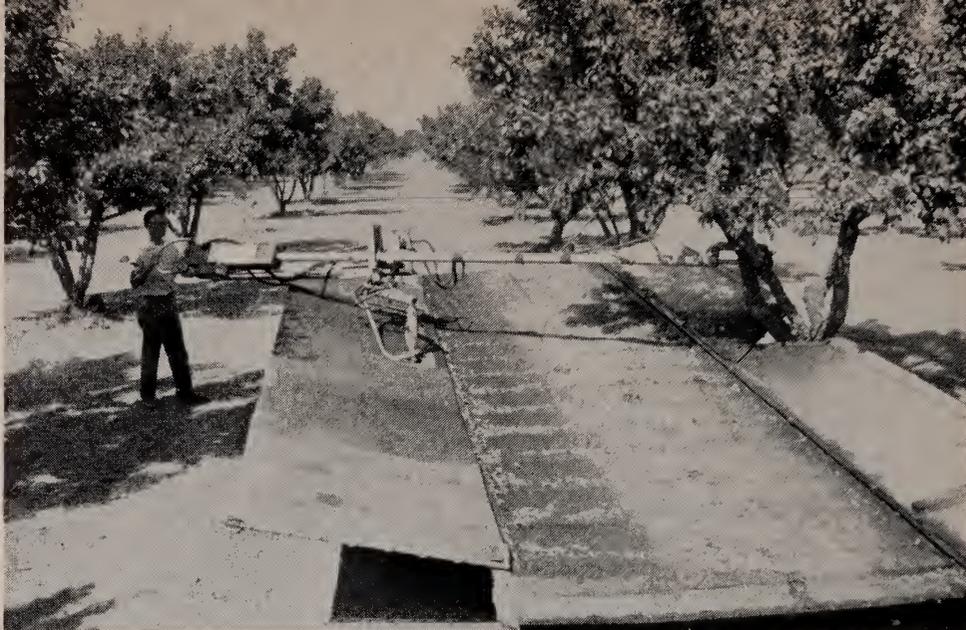


Fig. 16. Inertia shaker designed for use on limbs and mounting on self-propelled catching frame.

attached to the tree and the exciting force was developed by eccentric weights.

The first experimental unit constructed for limbs was a counter-rotating weight type. However, its large size led to the use of the slider-crank on catching-frames where positioning was a problem (fig. 16). The rotating-weight principle was used in a unit developed for shaking trees at the trunk, where space and size were not critical. This experimental unit was designed so that the two unbalanced weights were located on opposite sides of the tree (fig. 17). A reciprocating action was developed by rotating the weights in opposite directions at the same speed; circular translation action was developed by rotating the weights in the same direction at the same speed.

SHAKER MOUNTING

The limb-shaker was flexibly mounted at its center of gravity to permit maneuverability, to isolate vibration from the frame, and to reduce bark damage. Maneuverability for positioning the clamp was achieved with an arm having four pivots (fig. 18). The arm was free to

rotate 360° about pivot **E** in a horizontal plane, which permitted movement toward or away from the tree. Rotation about pivot **B** allowed elevation control, and rotation about pivots **C** and **D** allowed alignment control.



Fig. 17. Inertia shaker on trunk.

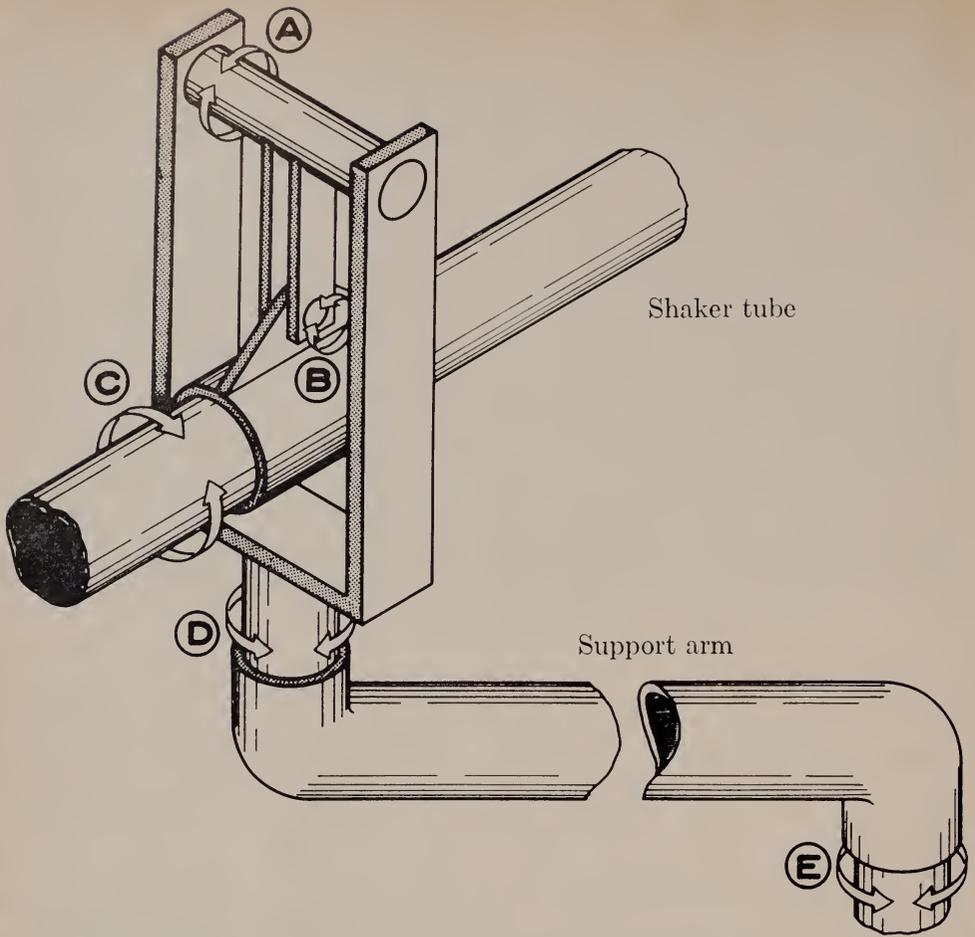


Fig. 18. Pivotal mounting for inertia shaker. A, B, C, D, and E show motions of the shaker made possible by this mount.

The vibration produced by the shaker was isolated from the carrying unit by each of two pairs of pivots, **A** and **B** and pivots **D** and **E**. The more nearly horizontal the shaker, the more effective the isolation.

Forces on the bark were reduced by Pivots **B** and **D** which allow freedom of motion of the shaker since the direction of its axis is not confined by the mounting.

The trunk-shaker was suspended from three sets of two small universal joints. The two universal joints were joined by a short shaft that permitted the shaker to swing freely in any direction necessary for the circular translation motion.

DESIGN CRITERION FOR INERTIA TREE SHAKERS

Proper relationship between weight and eccentricity is required to develop a desired stroke at the tree. Figure 19 shows the effect of eccentricity and mass ratio on the stroke delivered by experimental shaker units, and the ranges in strokes due to variation in limb size. To predict operating characteristics of the inertia principle for shaking trees it is necessary to develop a mathematical relationship for the system. Because the many interactions of side limbs and branches are

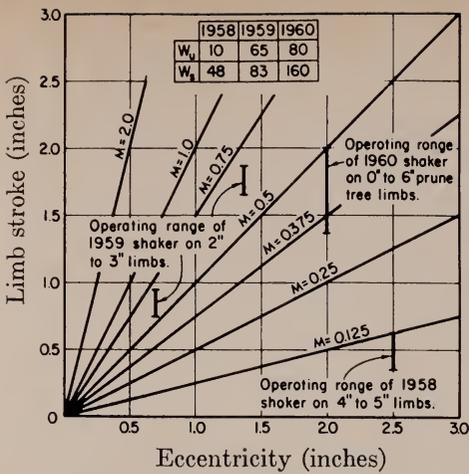


Fig. 19. Design chart for inertia-type shakers, showing effect of shaker eccentricity and mass on stroke delivered to tree limbs. Eccentricity is one-half the stroke of the unbalanced mass which develops the shaking force; M is the ratio of mass of unbalance to combined mass of shaker and limb. The four heavy vertical lines show operating range of different experimental shakers. The eccentricity of each shaker can be determined from the horizontal axes. The weights of the unbalanced masses (W_u) and the total shaker (W_s) are indicated in the figure in pounds.

difficult to describe mathematically, field tests were conducted to measure the relationships of stroke, frequency, power, force, and torque, and these were compared with results derived from known vibration theory (Appendix B).

FIELD EQUIPMENT, INSTRUMENTATION AND TEST PROCEDURE

To calculate power and reactive loads, the stroke developed at the limb and the phase shift between the impressed force and limb displacement must be known. To determine this, olive, prune, and apricot limbs were shaken at three points of attachment and at various frequencies, using the shaker shown in figure 16. Limb displacement was obtained with a linear potentiometer attached on the shaker tube. The phase angle, α , was

obtained from a position indicator making contact once per revolution. Resultant signals were fed into an optical oscillograph.

As a check, actual power input was also measured. The hydraulic system was instrumented with a tachometer, pressure gage, and a variable flow control to vary shaker speed. Power input to the shaker was determined from the hydraulic motor performance curves; this measurement included power necessary to overcome shaker friction, which was determined by measurements taken while running the shaker under no-load.

RESULTS

Stroke. During field tests the equation $S = 2mr/M_t$ (Appendix B) was found to define approximately the peak-to-peak stroke of a limb at point of attachment when shaken by an inertia shaker within the most common frequency range ($11 < \omega/\omega_n < 40$ where ω_n = fundamental frequency of limb). In this equation, mass M_t includes the effective mass of the limb as well as the total shaker mass, or

$$S = 2mr / (M_{\text{shaker}} + M_{\text{limb}}).$$

Effective weight of individual limbs averages between 20 and 60 pounds for 2 inch- to 6 inch-diameter limbs; tests with the trunk shaker indicated an effective weight of 800 to 1000 pounds for 5 inch- to 11 inch-diameter trunks.

The equation shows the importance of using proper relationships of unbalanced mass, total shaker mass, and eccentricity to obtain a desired stroke. Stroke is directly proportional to eccentricity, r , but not to the mass of unbalance, m , as the total shaker mass (which appears in the denominator) also includes the mass of unbalance.

Frequency and position of attachment, although not included as variables, do affect the stroke. Tests indicate that with the frequency range commonly used for harvesting, the stroke on any limb could vary as much as ± 35 per cent from the

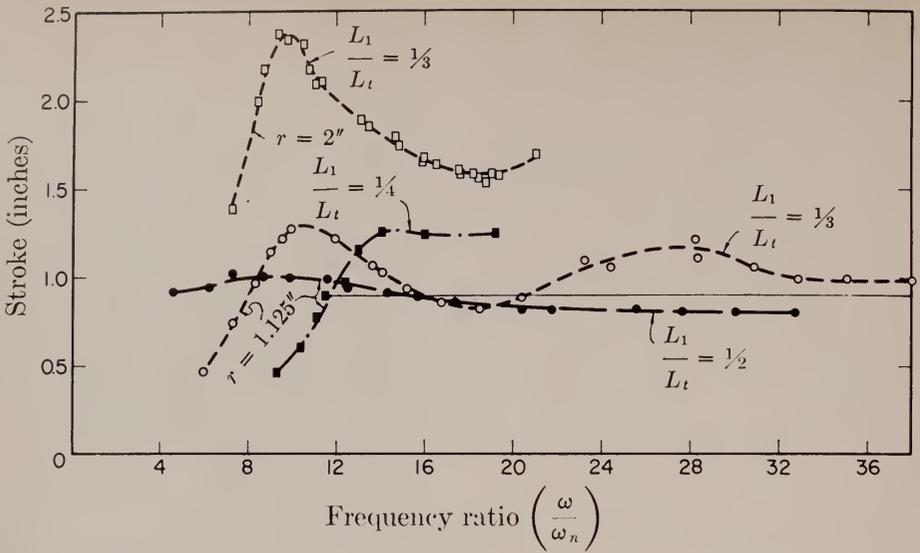
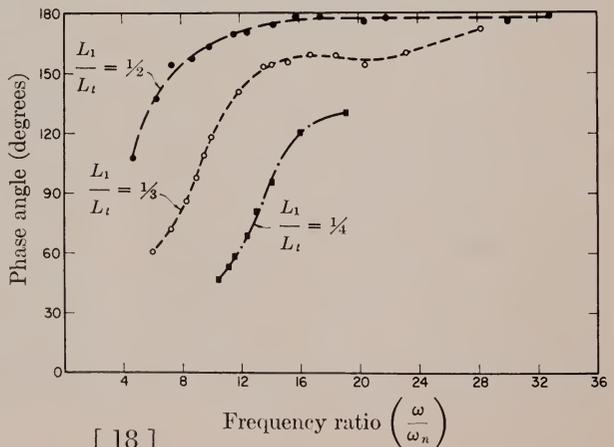


Fig. 20. Effect of frequency, eccentricity (r), and position of attachment $\left(\frac{L_1}{L_t}\right)$ on stroke delivered to a representative limb $5\frac{3}{4}''$ diameter at the base by an inertia shaker. $L_1 =$ distance from crotch to shaker clamp and $L_t =$ distance from crotch to end of limb. The straight horizontal line represents a typical calculated stroke for $r = 1.125''$, and helps to compare calculated stroke to actual stroke within the range of frequencies used in practice.

calculated value (fig. 20). Thus, the calculated stroke is an indicator of the average stroke produced in shaking many limbs. Amplification of stroke results from shaking at normal-mode frequencies. Several prune, olive and apricot limbs of 3 inch to 7 inch diameters were tested; all showed essentially the same type behavior. The fundamental mode of vibration for prune-tree limbs was approximately 60 cpm, and 30 to 36 for olives and apricots.

Power. Figure 21 shows the phase angle, α , for a typical olive limb, and it is representative of a number of limbs tested. From the phase angles and the strokes shown, power *vs.* frequency curves (fig. 22) were calculated using the equation $P_a = m\omega^3 S (\sin \alpha) / 4$ (Appendix B). Figure 22 also shows the calculated total power curve determined by adding power to overcome friction (from fig. 23) point by point to the calculated curve for the limb. The actual total power input curve

Fig. 21. Effect of frequency and position of attachment $\left(\frac{L_1}{L_t}\right)$ on phase angle between exciting force and limb displacement for the tests shown in figure 20.



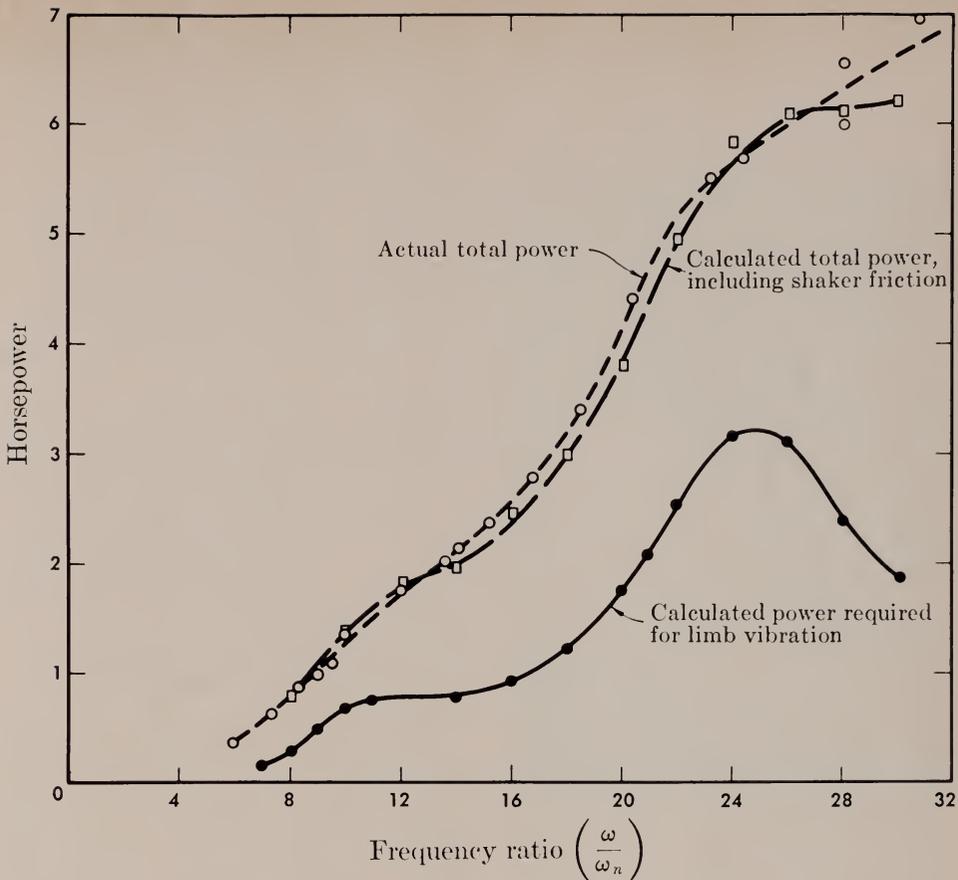


Fig. 22. Power needed for limb vibration with inertia shaker, and total power needed including shaker friction. Data is for same test as figures 20 and 21, with 1½" eccentricity and $\left(\frac{L_1}{L_t}\right) = \frac{1}{3}$

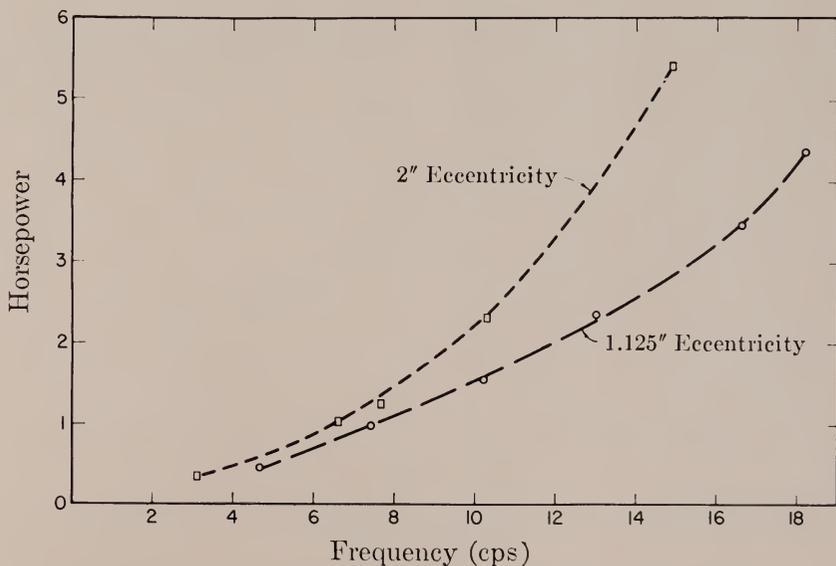


Fig. 23. Power required to overcome friction of slider-crank shaker tested.

was determined in the field from the average pressure and flow rate in the hydraulic power system.

Analysis of the curves shows that a high percentage of total power required at higher frequencies was used in overcoming shaker friction. A static test on this unit indicated that an average torque of about 60 inch-pounds was required to overcome static friction in the bearings. Additional losses occur during operation as a result of dynamic forces, and there is a reduction of hydraulic-motor efficiency because of pulsating loads.

Torque. Maximum torque is equal to $mr\omega^2 S (\pm 1 - \sin \alpha) / 4$. This equation (Appendix B) does not account for torque required to overcome shaker friction, or peak torques caused by the crankshaft assembly not developing purely sinusoidal motion. These are canceling effects. Because of this, and because $\sin \alpha$ has a maximum and minimum of ± 1 , it is reasonable to design for a maximum torque of $mr\omega^2 S/2$.

When maximum torque is high at the higher frequencies due to the ω^2 factor, $\sin \alpha$ is small; consequently, the quantity $\pm 1 - \sin \alpha$ is approximately 1. Thus a safety factor of approximately 2 (which is self-compensating for internal shaker friction) is achieved. This calculated maximum torque is reliable for use in the design of shafting, but as this is the peak torque encountered the power source

need not be selected to match. Because inertia of rotating parts helps overcome peak torque, torque requirements of the power source should be selected from average power consumption.

Force. The design force is $mr\omega^2 [(S/2r)^2 + 1 + (S/r) \cos \alpha]^{1/2}$ (Appendix B). It has been found that the ratio $S/2r$ appearing in this equation will usually be between 0.1 and 0.75 (depending on relative masses). Figure 24 gives the relationship $[(S/2r)^2 + 1 + (S/r) \cos \alpha]^{1/2}$ as a function of the phase angle α and the $S/2r$ ratio, and also shows that the value of the radical is less than 1 for the large phase angles found at high frequencies (fig. 21), where the maximum force is large due to the ω^2 factor. Therefore, experience indicates that it is practical to design for a maximum force $mr\omega^2$.

DESIGN PROCEDURE

First, estimate total shaker mass. For limb-shakers this mass should be as much, or more, than the effective mass of the larger limbs to maintain a fairly uniform stroke over various limb sizes. The lighter the unit, the smaller will be the reactive loads and the easier the unit will be to maneuver. Therefore, compromises in the actual design are necessary to determine what combination of shaker mass and eccentricity is most desirable.

Next, by adding the estimated shaker mass to the effective mass of the larger

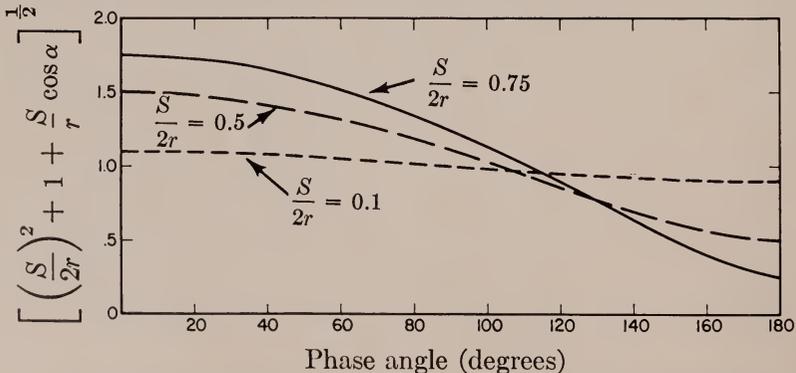


Fig. 24. Guide for determination of design force for inertia tree shakers. For details see page 55.

limbs, the value of mr required to obtain a desired stroke can be calculated from equation (7), page 55. The design force, $mr\omega^2$, can now be calculated, and the clamp and the tube connecting the clamp to the vibrator can be designed. The difference between the mass of the assembly attached directly to the limb and the estimated total shaker mass is the mass of unbalance, m . The eccentricity can now be determined, using the calculated value of mr .

If these values of mass and eccentricity are not reasonable, another estimate of total shaker mass must be made and the above procedure repeated.

COMMERCIAL DEVELOPMENT

The commercial development of inertia-shakers has included limb-and trunk-type units and both have seen widespread use. Most limb shakers are basically similar to the development discussed. Commercial trunk shakers use various designs for developing force, but most provide a force which is not solely in one direction.

Trunk shakers have the advantage of speed, particularly in orchards having many primary limbs, while limb shakers usually achieve better removal of fruit particularly on limber trees.



Fig. 25. Impact-type tree shaker use on peaches.

IMPACT-TYPE SHAKER DEVELOPMENT

Development of an impact-type shaker which could be mounted on a catching frame or other lightweight carrier was undertaken in 1960. The shaker was primarily designed for selective removal of mature peaches and apricots from the tops of trees. It had been observed that although a sustained shake gave best results on trees having a limber structure (including scaffold limbs, fruiting branches, and fruit stems), an impact gave satisfactory results on trees having a rigid structure. Apricot and almond trees are rigid, and if impact forces on limbs are directed toward the center of the tree so that they are transmitted longitudinally along fruit bearing hangers, peach trees generally respond like rigid structures.

The unit developed consisted of a tube 12-feet long and $1\frac{1}{2}$ -inch inside diameter, with a 5-pound free-floating piston inside (fig. 25). On one end of the tube a padded head was pushed against the limb. The piston was accelerated up the tube to the head by compressed air. The head was free to move relative to the tube within certain limits, and a heavy coil spring was mounted on the end struck by the piston. The spring reduced the magnitude of the impact forces by increasing the time over which the forces were applied (this also gave a greater stroke at the limb).

The unit was initially designed for automatic cycling so that if the operating valve was held open, the piston was accelerated up the tube automatically after it

was returned by low-pressure air to the operator end. During tests on peaches it was found that most of the fruit was removed by one impact. Thus, the automatic feature was unnecessary.

The shaker was supported by gimbals mounted on the end of a 4-foot-long arm which was free to pivot in a horizontal plane. This arrangement is satisfactory for shaking one-quarter of the tree; to shake more than one-quarter, the pivot for the arm must be moved around the tree to permit directing the force toward the tree center.

Field tests on clingstone peaches showed that the impact device did not require clamping on limbs and this resulted in a faster operation than with an inertia shaker. This was offset by the fact that use of the impact shaker required working on secondary branches to attain comparable removal. Fruit removal with the impact-type shaker when used on secondary limbs in properly trained peach trees was about 95 per cent. There was about 98 per cent removal with an

inertia-shaker on primary limbs and about 85 to 95 per cent removal with a trunk-shaker using circular translation motion. For these tests the limb shaker was operated at 500 to 700 cpm and the trunk shaker at 750 to 950 cpm. Strokes delivered were 1½ inch to 1¾ inch for limb shakers and about ½ inch for trunk shakers.

With the impact shaker, fruit fell almost straight down and not into the center of the tree, thus minimizing the possibility of fruit injury; additionally, some selectivity was achieved. On peaches it was found that selectivity could be accomplished only by shaking those secondary limbs having mostly mature fruit. Impact force had to be directed perpendicular to the limbs to prevent bark skinning. Limited tests on pears demonstrated that breakage of limbs is a major problem when an impact shaker is used on trees having brittle limbs.

The impact shaker found most commercial acceptance on almond trees, which have very rigid structure.

SHAKER DESIGN AND TREE INJURY

Limb breakage was affected by tree age as well as by stroke and frequency. On older trees, high frequencies with a short stroke appeared to remove the most fruit with a minimum of limb breakage. Low frequencies developed large amplitudes in the tops of old brittle trees, with resultant limb breakage. Trees hollowed by internal decay were particularly susceptible.

Frequency and stroke combinations in the order of increasing limb breakage are as follows: 1-inch stroke at 790 cpm (very little damage); 1-inch stroke at 990 cpm; 1½-inch stroke at 740 cpm; 1½-inch stroke at 920 cpm; 1-inch stroke at 450 cpm; 1½-inch stroke at 450 cpm (severe damage to very old trees).

No serious tree-root damage as a result of using shakers has been found.

Injury to the bark by the shaker clamp

was observed in the 1956 survey. This injury led to the problem of infection of *Ceratocystis* canker, first discovered on almonds in 1959 and later found on other stone fruits (DeVay *et al.*, 1960; DeVay *et al.*, 1962). Research directed towards reducing bark injury was initiated in 1962. Observations prior to 1962 indicated that injury to tree bark occurred while shaking and while clamping onto the limb. In some instances injury was caused by tangential stresses arising from either the design of the clamp or a poor clamping operation; in other instances it was caused by excessive radial stresses from clamping too firmly. Longitudinal stresses which arose when the shaking force was not directed perpendicular to the limb also caused injury. Use of the inertia shaker with a C-type clamp (fig.



Fig. 26. C-type clamp engaged on limb.

26) reduced or eliminated some of the problems; but sometimes excessive stresses still existed.

The maximum stresses that could be applied to the limb before injury or infection occurred were determined, and a study was then made of possible methods of attaching and shaking the limb without

exceeding these stresses (Adrian and Fridley, 1964).

STUDIES OF BARK STRENGTH

Figure 27 shows a testing device designed to apply either radial (compression) or

Fig. 27. Bark tester in use on compression tests.



tangential (shear) forces on the bark. Compression pads are shown in contact with the tree, and force is applied by the hydraulic cylinder in the background. The compression pad on the cylinder was 1 inch in diameter and the other was 0.71 inch in diameter. Shear pads did not contact the tree during compression tests. For shear tests, the arm in the foreground was replaced by a hydraulic cylinder to hold shear pads against the tree. Shear pads were 1 inch in diameter and knurled to minimize slippage on the bark. Normal stress exerted on the tree by the shear pads to keep them from slipping over the bark surface was from 150 to 225 psi (pounds per square inch). Stresses applied to the tree were determined from hydraulic pressure developed by a hand-driven pump.

For radial tests, a rubber disc of 60 durometer hardness was originally placed under each compression pad to distribute the load. However, preliminary tests indicated that the rubber would flow out from under the pads, and that stresses resulting from tangential movement would cause the bark to split under the center of the disc and longitudinally with the limb. Cork discs lessened this problem, and mylar 3-mils thick placed between bark and rubber pad also helped. The thin member reduced the tangential flow, the slick surface minimized the transmission of tangential forces from the rubber to the tree, and the rubber permitted distribution of the force over the desired area. Results on almond limbs showed that injury occurred at 50 psi lower stress without mylar than with mylar. Therefore, mylar was used in all subsequent tests with the bark tester.

Radial tests were conducted on prunes, peaches, almonds, apricots, and olives. Injury to the bark and cambium was evaluated by visual observation and by inoculation of the test areas with a solution containing *Ceratocystis* fungi.

For comparison with radial tests, tangential tests designed to determine the



Fig. 28. Compression test area showing discoloration occurring at cambium with the application of high stresses. Four tests were conducted on the strip, with stress increasing from top to bottom.

total ability of bark to resist failure in a direction tangential to the limb were conducted. This strength includes tension, compression, and shear reactions within the bark, as well as shear at the cambium.

Visual observations at failure. In examining limbs after radial force tests, it was discovered that when stress became sufficiently high the inner bark became discolored. As stress increased the discoloration extended to the cambium, the amount increasing with increase in force (fig. 28, table 6). Apparently, stress caused hairline cracks in the bark and air entered, causing oxidation which was visible as browning. In tangential shear tests, injury occurred only when the bark failed completely; this failure occurred at a significantly lower stress than that which caused darkening in the compression tests (table 6).

Table 7 lists radial stresses causing browning at the cambium and tangential stresses causing bark failure in several species. (With the exception of Dixon peaches all trees were in University orchards.)

Susceptibility to infection. To deter-

TABLE 6
STRESSES CAUSING VISIBLE INJURY TO
THE BARK OF 6-YEAR-OLD PRUNE TREES

Test	Stress	Type of injury
	<i>psi</i>	
Radial.....	300-350 400-600 600-750	Faint browning in bark† Marked browning in bark† Marked browning in cambium†
Tangential.....	145-175	Failure of bark
Tensile*.....	640 (applied longitudinally) 160-180 (applied tangentially)	Failure of bark Failure of bark

* Tensile tests made on bark specimens 1/4" thick and 1" wide.

† Inspection made by cutting open the bark 5 minutes after the test (longer intervals were unnecessary).

mine correlation between visible injury and infection by *Ceratocystis*, thirteen trees were subjected to different compression pressures on each of two limbs. Test areas on one limb were cut open to determine when darkening occurred; test areas on the second limb were inoculated with fungus spores and wrapped with masking tape.

Results of inoculation tests on 20-year-old trees indicated that *Ceratocystis* canker infection occurred on mature prune trees when the radial stress exceeded 1000 psi. On young trees, critical stresses were about 75 per cent of this value. This correlated closely with the magnitude of stress which visibly cracked the bark to the cambium. Considering

Ceratocystis infection only, a pad design which allows a maximum stress of 500 psi radial and 100 psi tangential on the limb would give a safety factor of 2 to allow for tree variability. However, a radial stress of 500 psi resulted in visible discoloration of the inner bark and cambium, indicating some tissue injury and the possibility of future problems; therefore, a conservative radial design stress would be 250 psi. A total clamping and shaking force of 2500 pounds would then require 10 square inches of contact on each side of the limb.

SHAKER CLAMP DEVELOPMENT

The results of the preceding study indicate the importance of minimizing tangential forces and distributing radial load. Tangential forces can be minimized by eliminating the need for centering on the limb, or by using a pad that can easily center as the clamp closes. The radial load can be distributed by increasing pad depth and width, and by using a pad made from material that will conform to limb shape without stretching in a direction tangential to the limb—for example, a flexible, nonstretchable pad filled with a noncompressible fluid or granular material; centering would not be required and attachment would be rigid after conforming to the limb by clamping.

Magnetic clamp. To test the possibili-

TABLE 7
COMPARISON OF RADIAL STRESS
CAUSING BROWNING AT CAMBIUM
AND TANGENTIAL STRESS
CAUSING FAILURE FOR
VARIOUS CROPS*

Crop	Radial	Tangential
	<i>psi</i>	
Tilton apricots†.....	800-900	250-265
Blenheim apricots†.....	800-900	215-245
Dixon peaches.....	700-800	200-230
Nonpareil almonds.....	550-600	.....
Peerless almonds.....	550-600	.....
French prunes†.....	600-650	145-155
French prunes.....	700-800	200-225
Olives.....	500-600	140-160

* Results for each crop from tests on two to six trees with six to twelve measurements per tree.

† Trees approximately 6 years old; other trees tested were mature.

ties of a pad filled with iron particles, a magnet was designed to saturate iron particles placed in a small metal box. BB shot and 8- and 3-micron carbonyl iron particles were mixed in different proportions with light machine oil. The combinations were tested for relative stiffness by pressing plungers of various sizes and shapes into the magnetized particles.

In general (1) the larger particle size resulted in the greater stiffness; (2) as the force applied to the BB shot alone approached its upper limit the individual particles rapidly shifted, causing a fluctuation in the resisting force; (3) the mixture of small and large particles prevented the sudden shifting of large particles, resulting in an appreciable increase in strength at large deflections; (4) resisting strength increased with an increase in current, and was affected not only by the cross-sectional area of the plunger but also by the shape of the plunger; (5) an optimum mixture of oil and particles was observed.

The force resisting deformation of the particle mass was increased by magnetization as much as 15 times. However, large deformations which would allow loosening on the limb if used for a clamp were encountered with larger applied forces. The weight of coils, cores, and other parts required for the electromagnet present another disadvantage. Because of these problems, the principle was not investigated further.

Belt-type pad. To meet established criteria, a pad consisting of a continuous flat belt located on two parallel rollers spaced more than limb diameter distance apart was designed so that a portion of the flat surface of the belts would contact the tree and wrap partially around the limb as the clamp closed. Centering was accomplished automatically by the movement of special cable-reinforced belts 2 inches wide and $\frac{1}{4}$ -inch thick. (Laboratory tests indicated the necessity of using

steel reinforcing in the belts to eliminate stretching on the limb during shaking, and also to provide sufficient strength to resist the high-tensile forces encountered for this type of loading.) Two rubber-covered belts were used on each pad, and a rubber tubing of 60-durometer hardness was placed over each roller to reduce impact loads and to distribute loads more equally on each belt. To allow freedom for attachment on limbs which were not perpendicular to the shaker axis, each pad (two rollers and two belts) was mounted on a pivot. (Preferably, the pivot axis should be perpendicular to the roller axis and tangent to the limb midway between roller ends to reduce relative motion of the limb and belts while clamping.) The first unit constructed had the preferred axis location with pivots positioned at each end of each pad, but the over-all width of the pad was too large for movement through the limbs. On the second unit the pivots were positioned 2 inches behind the roller: thus, the clamp was reduced to approximately two-thirds the width of the original clamp. However, with this arrangement the pad was unstable when shaking a limb that was more than 30° from perpendicular. To attain stability a pad was designed to incorporate an effective pivot at the preferred location (fig. 29). Pads were equipped with detents to hold the belt surface perpendicular to the shaker axis before contact with the limb. If limb and shaker were not perpendicular during clamping, the force exerted on the belt edge overcame the detent and the pad aligned with the limb. As the clamp opened, a stop on the moving pad returned it to the initial perpendicular position and two cables, connected from the roller ends on the moving pad to the roller ends on the other pad, returned the latter pad to a perpendicular position.

Field tests with the belt-type pad showed no visible bark injury, and inoculation tests showed no evidence of fungus infection for shaking limbs that were not



Fig. 29. C-clamp using belt-type pads with effective pivot tangent to limb.

more than 25° to 30° from perpendicular to the shaker. Increased pad depth and wrap of the belt on the limb gave sufficient contact area to maintain radial stresses below the critical magnitude, and the rolling action of the belts limited the tangential stresses during clamping. Table 8 shows the effect of limb size on the radial stress exerted on the limb by the pads. Contact area was measured by clamping onto circular steel tubing and noting the arc length in contact between the belts and tubing. Shaking force was determined from data taken during the 1957 and 1958 tests, and the clamping stress was calculated for a pressure of 100 psi in the clamp cylinder. Results demonstrate that stress exerted on the limb is

substantially greater on small limbs than on large limbs.

At angles greater than 30° the bark usually sheared at the cambium in a longitudinal direction. Initial observations indicated the longitudinal failure might be caused by the clamp coming loose and moving along the limb. More detailed studies with a high-speed camera showed that when the clamp was too loose appreciable movement caused damage as a result of impact and abrasion; when too tight, bark sheared at the cambium, permitting relative motion there. A narrow range of clamping pressures permitted the belts to move back and forth on the limb without a large change in position and without failure at the cambium.

TABLE 8
EFFECT OF LIMB SIZE ON STRESS EXERTED
ON LIMBS BY THE BELT-TYPE CLAMP

Limb diameter	Contact area	Shaking force*	Stress on limb		
			Shaking	Clamp†	Total
<i>inches</i>	<i>square inches</i>	<i>pounds</i>	<i>psi</i>		
5½.....	11.0	1470	134	45	179
3½.....	5.0	860	172	98	270
2½.....	4.0	720	180	133	313

* Shaking force determined from 1957 and 1958 tests.

† Clamp pressure assumed to be 100 psi in clamping cylinder.

Controlling the clamping pressure to permit some movement of the belts did not seem practical, because occasional injury was still encountered and desired clamping pressure would vary greatly with variation in bark smoothness. Therefore, consideration was given to (1) directing the shaking force more nearly perpendicular to the limb, (2) limiting the longitudinal component of force by modifying the clamp design, and (3) increasing the area of contact. The first two possibilities were investigated, but the third possibility did not seem practical because of difficulty of finding locations on limbs which would permit more contact area. Limiting of the longitudinal force is discussed immediately below.

Limiting longitudinal force by clamp design. When the shaker is attached to a limb at other than a 90° angle, elimination of the longitudinal component of the shaking force would dampen out some of the desired motion of the limb, but injury will occur if the longitudinal component causes greater stress on the bark than the ultimate strength. Therefore, it is desirable to keep the longitudinal component as high as possible without exceeding the ultimate strength of the bark.

Pads were modified to permit relative motion of the belts and rollers with respect to the main structure of the clamp. The motion was parallel to the roller axis and was restricted by a series of Belleville springs which provided a centering force which increased rapidly as the rollers were displaced a small distance off center, but which was limited as the motion approached its maximum. Tests indicated friction of the roller sliding on the shaft to be a practical limitation.

A second pad, developed to limit the longitudinal force, used thick rubber to permit relative motion longitudinally between the limb and the shaker. Possible pad designs would be a straight or a curved rigid support with a rubber pad

having either a straight or a curved front surface. The design used (fig. 26) combined a curved support with a straight rubber surface; the flat rubber reduces the need for centering as compared to a curved rubber surface, and the curved support gives more uniform force distribution and more contact area than a straight support.

Field tests showed this method of limiting longitudinal shear force to have practical applications. No bark injury was encountered when shaking limbs at angles of up to 45° with respect to the shaker, although some reduction of stroke was observed particularly when shaking at poor angles.

COMMERCIAL DEVELOPMENT

Most pads incorporate some of the desirable features discussed previously. Many limb-pads are made of a flexible member 4 to 5 inches deep and supported at each end to permit wrapping on the limb. Some trunk-shaker pads use a flexible, rubber tubing partially filled with granular material and pressurized with air, which serves to straighten the tube and thus to redistribute the granules. With operator care and proper equipment adjustment, there is little bark injury.

PERPENDICULAR ATTACHMENT OF SHAKERS ON LIMBS

The best way to avoid failure of bark in a direction longitudinal to the limb is to attach the shaker perpendicular to each limb. Two approaches to this were studied. First, a small remote-controlled shaker was designed for mounting on a powered-arm assembly having several directions of motion. This allowed the shaker to be positioned perpendicular to each limb (fig. 30). Second, a study was

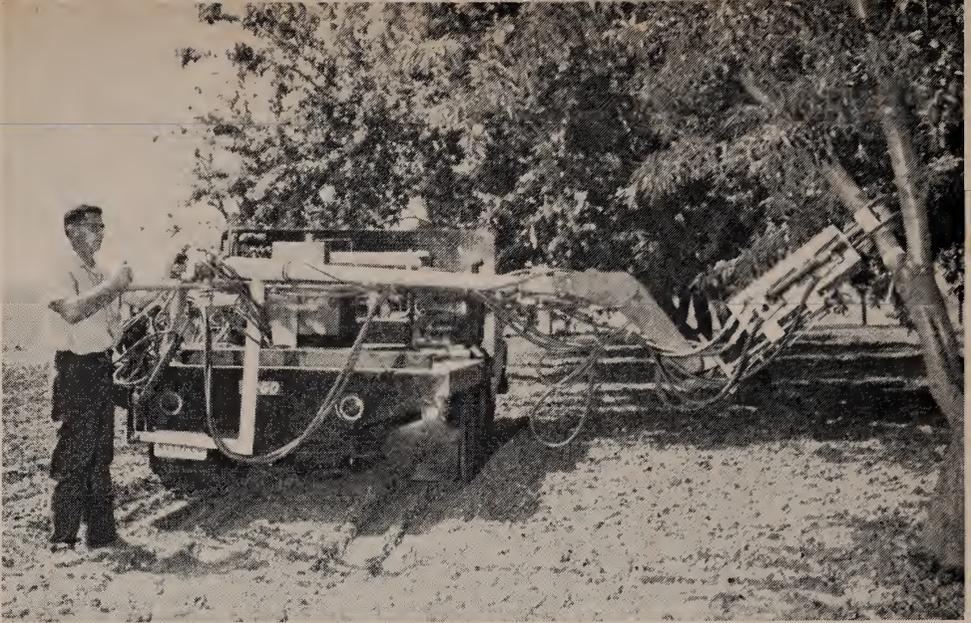


Fig. 30. Remote-controlled shaker for perpendicular attachment on limbs achieved by folding of the arm and by rotation and elevation of the entire arm and shaker assembly. Force developed by the shaker is isolated from the arm by mounting with linear bearings.

made to determine the optimum position and mounting dimensions for the inertia-type shaker.

Remote controlled limb-shaker for perpendicular attachment. For developing and applying the shaking force perpendicular to the limb, a more compact mechanism was designed (fig. 31); the "folding" weights rotate in opposite directions, thus providing counterbalance perpendicular to the longitudinal shaker

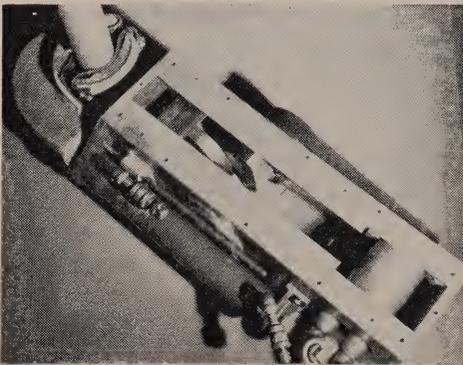


Fig. 31. Closeup of shaker for perpendicular attachment.

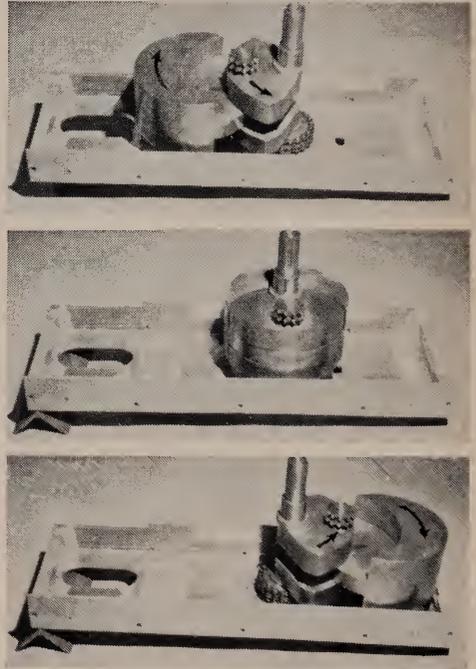


Fig. 32. Shaker for perpendicular attachment, showing motion of "folding" weights.

axis but producing an additive effect along that axis (fig. 32). The unit required less power than the slider-crank as a result of the rotary motion (yielding less friction) and the flywheel effect of the weights (reducing peak power requirements).

Positioning of the shaker is accomplished by a series of pivoted arms controlled by hydraulic cylinders and rotary actuators. A single control handle with micro-switches was designed to operate five solenoid valves which directed oil flow for the actuators, cylinders, and motor. This single control provided simplicity of operation.

Tests with the shaker indicated that remote positioning requires some experience to get near perpendicular attachment on limbs. Also the straight pad (page 28) was used in place of the curved pad (fig. 31), as centering on the limbs was difficult. The perpendicular attachment when the shaker was positioned with reasonable care produced no injury to bark. Isolation of the shaking force from the arm assembly by use of linear ball bushings proved successful.

Angle of attachment of frame-mounted shakers on tree limbs. For commercial harvesting operations, two shaker placements are generally used—one positioned to shake the whole tree, or two shakers positioned about 180° apart, each to shake half of the tree nearest the operator. To determine optimum position and construction dimensions, as indicated by the angle of attachment of the shaker on the limb, measurements were made to check the effect of (1) the support-arm length, (2) the height of the shaker boom, (3) the distance (or radius) from the center of the tree to support-arm standard, and (4) the angles of the limbs relative to the horizontal.

A "model tree" was constructed to facilitate taking data. The tree crotch was 18" above the ground and the angle of the limb with the horizontal was 40° , 50° ,

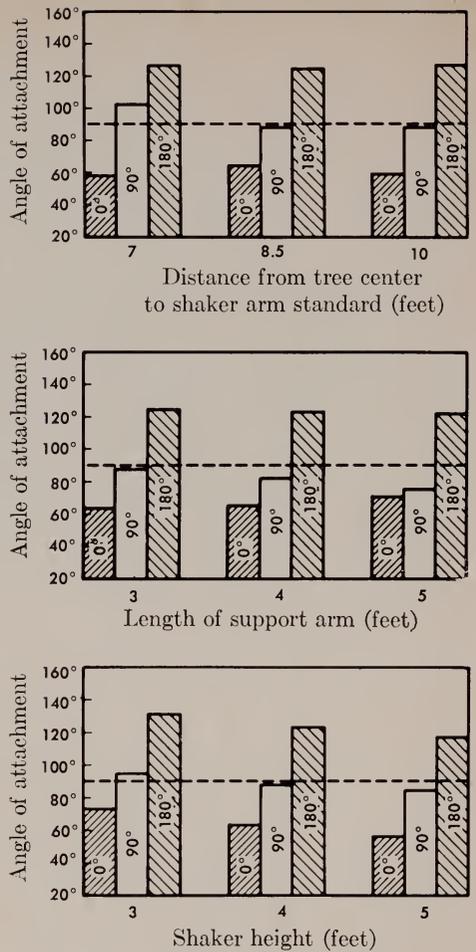


Fig. 33. Angles of attachment of shakers on limbs leaning toward (0°), to the side (90°), and away from (180°) the operator. The top chart shows the effect of mounting the shaker 7', 8.5', and 10' from the tree center, using a 3' support arm with a shaker height of 4' and a limb inclined 60° above the horizontal. The middle chart shows the effect of various support arm lengths with shaker mounted 8.5' away from the tree, a shaker height of 4', and a limb inclined 60° above the horizontal. The bottom chart shows the effect of various shaker heights, using a 3' support arm mounted 8.5' from the tree on limbs inclined 60° above the horizontal. Dotted line gives the desired perpendicular attachment.

60° , and 70° . The shaker was always attached 4 feet above ground. The model limb was rotated through 360° and meas-

measurements of the angle of attachment were taken at 30° intervals.

The support-arm lengths and heights tested were 3, 4, and 5 feet; radii tested were 7, 8, 8½, 9 and 10 feet. Length of the shaker, 8½ feet, measured from the shaker support to the middle of the clamp, was not varied. This dimension was the same as that used on the inertia-type shaker discussed earlier.

The results on a limb inclined 60° above the horizontal (fig. 33) demonstrate that the mounting dimensions giv-

ing most nearly perpendicular attachments for the use of one shaker on an entire tree were: shaker height, 4 feet; shaker arm length, 4 feet to 5 feet; and radius, 8 feet 6 inches. Although these dimensions result in some poor angles of attachment, other dimensions resulted in poorer angles on limbs directed towards or away from the shaker. In some cases, it was impossible to reach such limbs if they were inclined less than 60°.

The mounting dimensions found best for two shakers, each used on the half of

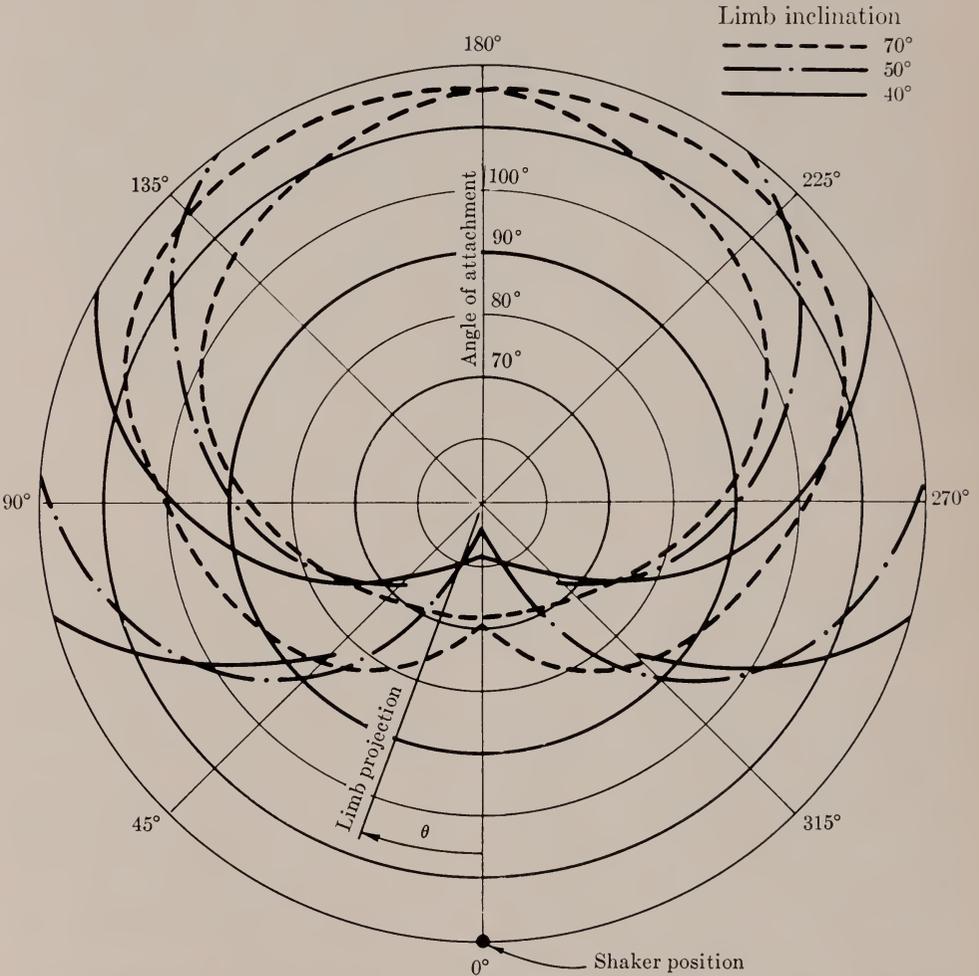


Fig. 34. Effect of limb inclination on the angle of attachment with limb shakers mounted 8.5' away from tree center at a 4' height. The radial coordinate indicates the angle of attachment on limbs; the angular position of the radii indicates the projection of the limb on the ground. The two families of curves shown result from two support-arm positions possible for attachment on any limb; the support arm (fig. 18) may extend to the operator's right as well as to his left.

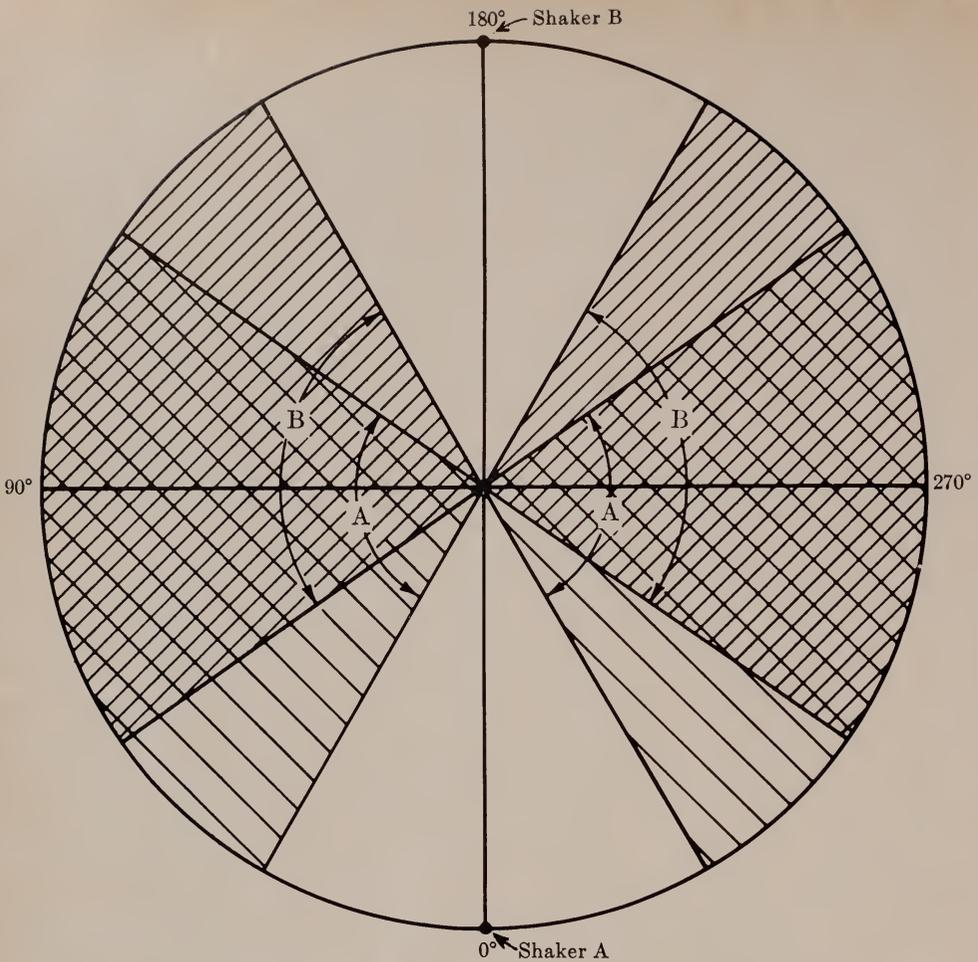


Fig. 35. Portions of the tree where a good angle of attachment can be attained with two shakers positioned 180° apart. The two shaded sectors A and B provide good angles of attachment for shakers A and B, respectively. Unshaded sectors give poor attachments for shakers.

the tree nearest the operator were: shaker height, 3 feet; support arm length, 4 feet to 5 feet; and radius 10 feet.

Figure 34 shows the angles of attachment which can be obtained on limbs inclined at various angles. As would be expected, the more nearly vertical the limb the better the angle of attachment.

Although the study indicated optimum mounting dimensions and limb inclination, a more important finding was that best angles of attachments can be attained in the two side quadrants—45° to 135°, and 225° to 315°. Figure 34 shows that on limbs inclined 50°, angles

of attachments not more than 20° from perpendicular occurred on limbs 30° to 125° away from the shaker. This is shown schematically in figure 35, in which the sectioned areas A and B represent portions of a tree where satisfactory attachments ($\pm 20^\circ$) can be made by shakers positioned 180° apart.

Figure 36 gives similar information for the location of shakers 95° apart; the increased area where favorable attachments can be made demonstrates the desirability of placing shakers 95° to 110° apart. Considering the interference encountered when attempting to attach to limbs at

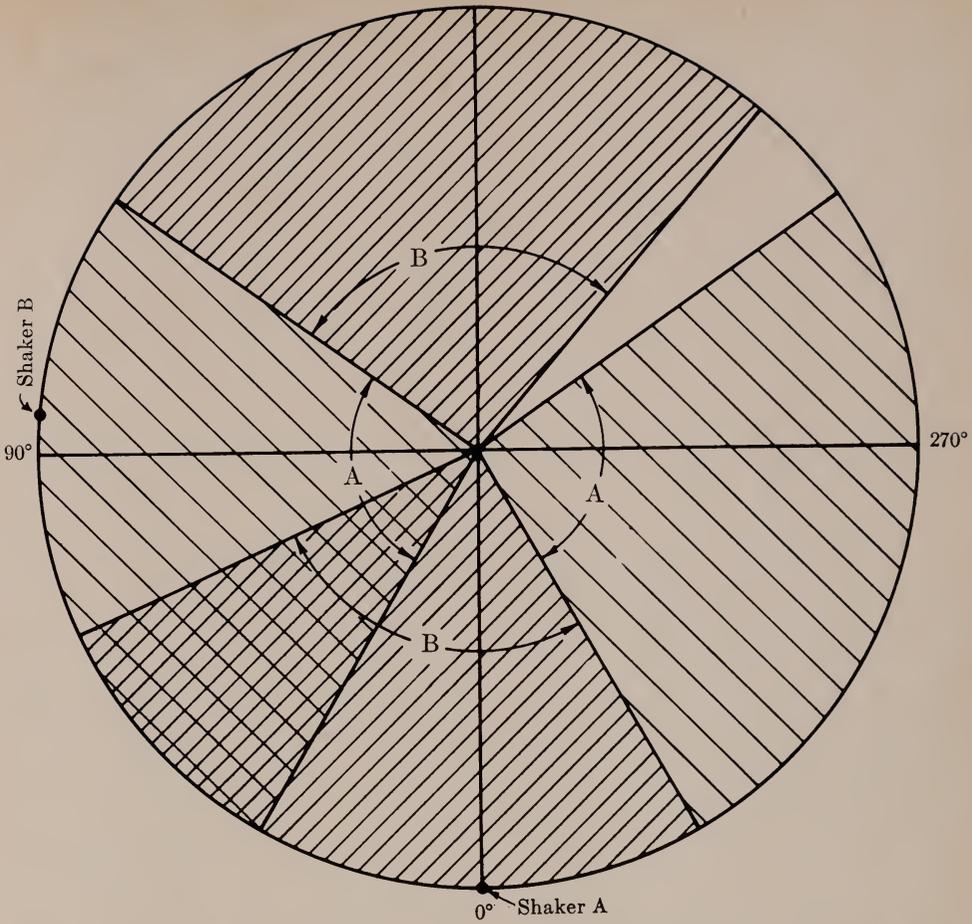


Fig. 36. Portions of the tree where a good angle of attachment can be attained with two shakers positioned 95° apart. Sectors A and B provide good angles of attachment for shakers A and B, respectively. Small unshaded sector indicates the only part of the tree where good attachments cannot be made.

positions of 220° to 235°, placing shakers 110° apart seems best.

MODIFIED ATTACHMENT OF SHAKERS

Modifying shaker attachment by the use of bolts, screws, or other fasteners has the basic advantage of transmitting force directly from the shaker through the fastener to the heartwood of the tree, rather than transmitting it through bark and

tissue; a disadvantage is the cost of materials and labor.

In studying this method, first considerations were the direction to apply force relative to the fastener, the strength of the fastener, and the strength of the tree. If the force was to be applied perpendicular to the fastener in the tree, the bending of the bolt and splitting of the tree would be limitations; also, the shaker would have to be attached to a fastener on each side of the tree if the resultant force was to be directed through the center of the trunk or limb. If the force was

TABLE 9

ACTUAL AND CALCULATED WITHDRAWAL RESISTANCE FOR
EYE SCREWS AND NAILS IN GREEN ALMOND WOOD

Type of fastener	Hole diameter	Actual resistance*		Calculated resistance
		Yield force	Ultimate force	Ultimate force
	<i>inches</i>	<i>pounds</i>		
1/2" lag screw.....	5/16	3250	3400	3420
	3/8	3550	3950	....
	7/16	3350	3570	....
5/8" lag screw.....	7/16	5450	5720	5030
	1/2	5770	6250	....
	9/16	5200	5600	....
3/4" lag screw.....	5/8	6000	6500	6960
1/2" screw nail.....	1/2	2500	2700	1450
5/8" screw nail.....	5/8	2800	3020	2280
3/4" screw nail.....	3/4	....	3450	3250

* Averages of two measurements.

to be applied in line with the fastener axis, the fastener would have to withstand any bending resulting from misalignment, and there would have to be sufficient resistance to withdrawal.

Laboratory tests. To determine their feasibility as permanent fasteners, bolts, lag screws, and screw nails (made by twisting square bar stock) were tested in the laboratory for withdrawal resistance. The tests were conducted on almond wood mounted in a tensile testing machine, and ultimate withdrawal force was determined for different fasteners placed in various sizes of prebored holes; each fastener was installed to a depth of five times the outside diameter. Table 9 gives results and calculated values, as determined from the equations (Neubauer and Walker, 1961), $P = 7500 G^{3/2} D^{3/4} C$ for lag screws, and $P = 6900 G^{5/2} D C$ for screw nails, where P = maximum withdrawal force in lbs. per in. of penetration, G = specific gravity of oven dry wood, D = diameter of fastener, inches, and C = 0.75 correction for wet rather than dry wood (and assuming almond wood to be a group 2 hardwood with $G = 0.55$).

The correlation of the actual and calculated results is fair, in view of the fact that depth of penetration was 5D (5

diameters), and the formulas are for 10D and 7D for nails and lag screws, respectively.

Results of the laboratory study indicate that the limiting factor is bending of the fastener, which can happen when shaking other than colinear with the fastener. This is shown in table 10, which gives the allowable withdrawal force for lag screws and screw nails, assuming a safety factor of 3 on the ultimate strength. (Use of factor of 3 prevents the force from exceeding the proportional limit, which would result in loosening of the fasteners.) Also tabulated is the maximum misalignment permissible for application of the allowable withdrawal force,

TABLE 10
ALLOWABLE WITHDRAWAL LOAD
AND MAXIMUM MISALIGNMENT
WITHOUT EXCEEDING
ALLOWABLE BENDING STRESS
OF FASTENERS

Type of fastener	Withdrawal load	Maximum misalignment
	<i>pounds</i>	<i>degrees</i>
1/2" lag screw.....	1320	1.7
5/8" lag screw.....	2080	2.6
3/4" lag screw.....	2170	4.7
1/2" screw nail.....	900	9.7
5/8" screw nail.....	1010	17.0
3/4" screw nail.....	1150	25.0

assuming a design stress for the fastener of 15,000 psi and assuming that shaking force is applied 2 inches from the periphery of the limb.

An analysis of resistance of bolts to withdrawal indicated that if $\frac{3}{4}$ -inch or 1-inch bolts were installed in clearance holes and held by flat washers and nuts, the stress under the washer would be close to the proportional limit of the wood. However, the resistance to withdrawal could be increased appreciably by threading the bolts into an undersized hole.

Preliminary field tests. The first field tests were conducted on 1-inch and $\frac{3}{4}$ -inch threaded rod installed during early spring in clearance holes and undersized holes in the trunks of 22 prune and 4 peach trees ranging from small to large (approximately 14 inches diameter). Rods were placed at approximately a 45° angle to the tree row to minimize the chance of hitting the bolt with equipment. A spur drill was used to produce a flat surface in the wood for the washers to bear against. Rods were placed at a maximum height possible below the crotch, and a trailer-hitch ball was placed on one end of each rod to attach the shaker.

By harvest time a thin layer of callus had formed over the edge of many washers; this was not disturbed during shaking. The $\frac{3}{4}$ -inch bolt had sufficient strength for all shaking forces, provided the attachment was no more than 2 to 3 inches from the tree. The clearance holes were adequate, and added withdrawal strength (obtained by threading the bolts into the trees) was unnecessary. Some of the very old trees which had decayed internally, collapsed when shaken.

Tests of different fasteners. During the preliminary field tests installation was slow and difficult. To correct this, bolts, lag screws, and screw nails were installed in 42 limbs and 16 trunks of both mature and young prune trees. In trunks, $\frac{5}{8}$ - and

$\frac{3}{4}$ -inch diameter fasteners were used; in limbs, $\frac{1}{2}$ -, $\frac{5}{8}$ -, and $\frac{3}{4}$ -inch diameter fasteners were used. Lag screws and screw nails were placed in predrilled holes having a diameter equal to the minor diameter of the fastener; approximate depth of penetration was 5D. All fasteners were made of mild steel and were positioned so the force would be directed approximately colinear ($\pm 15^\circ$) to the fastener.

Holes were drilled with an impact wrench, which was much easier to use than the drill used in preliminary tests. Lag screws were the easiest to install provided hole size was at least equal to the minor diameter. The screw nails were hard to drive, especially in limbs which were not sufficiently rigid. On small limbs drilling holes for threaded rod and washers weakened the limbs.

All limb fasteners were fitted with an eye, and a shaker clamp (fig. 37) was designed to attach to them. With screws and nails the center of the eye was about 3 inches from the limb; with threaded rod the distance was about five and a half inches. Trunk fasteners were again fitted with a trailer-hitch ball. The center of the ball was located about seven and a half inches from the edge of the trunk.

Table 11 summarizes the results. With the exception of one screw nail all fasteners were satisfactory on the young prune trees. On mature trees, misalignment of 5° to 10° caused $\frac{1}{2}$ -inch and $\frac{5}{8}$ -inch



Fig. 37. Limb shaker attached to eye in screw nail.

TABLE 11
RESULTS OF SHAKING IN LINE WITH
FASTENERS PLACED IN TREE LIMBS AND TRUNKS

Location and type of fastener	Young trees		Mature trees	
	Number tested	Problems encountered	Number tested	Problems encountered
Limbs:				
1/2" lag screw	12	None	2	None
5/8" lag screw	3	None	2	None
3/4" lag screw .....	..	.....	2	None
1/2" screw nail	3	None	2	One pulled out
5/8" screw nail	3	One pulled out	2	One pulled out
3/4" screw nail .....	..	.....	1	Gumming at nail
1/2" threaded rod .....	..	.....	7	Four bent*
5/8" threaded rod .....	..	.....	4	One bent*
Trunks:				
5/8" lag screw	1	None	2	Two bent*
3/4" lag screw	2	None	2	One loosened
1/4" screw nail	1	None	2	Nail failed at weld
5/8" threaded rod .....	..	.....	2	One bent*
1/4" threaded rod	2	None	2	None

* All bent fasteners occurred when shaker was misaligned about 5 to 10 degrees.

diameter lag screws and threaded rods to bend, and some screw nails were pulled out. On trunks of mature trees, misalignment caused loosening of one 3/4-inch lag screw and bending of most of the 5/8-inch fasteners. This indicates that if misalignment of the shaker is no more than 5°, the minimum diameter of mild-steel fasteners required for use in limbs and trunks of mature trees is 5/8-inch and 3/4-inch, respectively. Accurate alignment is essential, and the force should be applied to the fastener at a point about 2 to 3 inches from the tree.

Removal of fruit was observed to be at least equal to removal obtained when using conventional clamps. Shaking the bolts in the trunks was as effective as shaking the trunk in one direction using a clamp. Where bolts were placed in each primary limb, fruit removal was as good as when clamping onto and shaking each primary limb.

Perpendicular attachment to fasteners. Removal of fruit by trunk-shak-

ers was improved by shaking in more than one direction, therefore limited tests were conducted on mature almond trees to investigate the possibility of shaking perpendicular to the fasteners as well as in line with them. Tests were first made on mild-steel threaded-rod 1 inch in diameter installed through the trunk and extended out 4 inches on each side. For this test, the trunk-shaker was equipped with a set of V-shape grips to clamp on the ends of the rod.

Mild-steel rods did not have sufficient strength for the application of force perpendicularly to the rod. Accordingly, tests were conducted with 1-inch diameter lag screws, hand forged and heat treated to strength of 150,000 psi (three times that of mild steel) and inserted into each end of a hole drilled through the trunk.

Field tests on three trees produced satisfactory results when the lag screws did not extend out of the tree more than 2 inches. When extended more, the wood's bearing strength was insufficient to support the screws and they became loose.

SELECTIVE SHAKING OF COASTAL AREA PRUNES

Prunes grown in the central valley of California tend to mature uniformly, thus lending themselves to a single harvest with catching-frames, but in coastal valleys there is a long ripening season and fruit loosens and falls as it matures. The long season necessitates a selective harvest to maintain quality (Claypool, L. L. *et al.*, 1962). Additionally, the natural drop associated with decrease in bonding force as the fruit matures makes selective harvesting essential to minimize wind-falls if catching-frames are to be advantageous.

In 1958 a study to determine the feasibility of selective harvest of prunes grown in the coastal valleys of California was initiated. Tests used pulsating air blowers, the inertia-shaker designed for use on primary limbs, and the inertia-shaker designed for use on tree trunks.

PULSATING AIR BLOWER

Preliminary blower tests were conducted with a conventional orchard sprayer having a louver in the air outlet. The louver was oscillated at 50 to 60 cpm to develop air pulsations at the tree. Results were encouraging because selectivity comparable to hand shaking was produced.

In 1959 and 1960 the effect of air velocity and rate of pulsations were studied, using centrifugal blowers capable of developing air velocities of 50 mph to 200 mph at the outlet of tubes having a diameter of 12 and 5 inches, respectively (Brewer, *et al.*, 1961). The tube conveyed the air close to the surface of the tree to minimize velocity losses. In 1959, pulsations were developed by oscillating the tube up and down; in 1960 they were developed by rotating a damper in the tube. Observations indicated that the rate

of pulsations should be about 60 to 70 cpm, as pulses were not distinct above this rate. The amount of removal was significantly affected by the ease of removal, but in general the lower velocity removed about 10 per cent of the fruit on the tree at the time of harvest and the higher velocities removed about 50 per cent. In addition to the effect of average F/W (ratio of removal force to fruit weight) on removal, the frequency of occurrence of F/W is of major importance. This finding led to making measurements of F/W on 100 individual fruits for all subsequent tests.

In 1962, more extensive tests were conducted with a blower having a 6' propeller and capable of developing 500 pounds of thrust. Louvers which could be oscillated or rotated were placed over the exit (fig. 38). Oscillation of the louvers resulted in moving the air stream up and down over the surface of the trees. For rotation, louvers were set to converge the air stream first toward the bottom of the tree, and then to the top; it was thought that this might produce better results



Fig. 38. Blower, showing louvers set to converge air stream.

because the impulse on all elevations of the tree would be more uniform. The pulsation rate for both methods was approximately 60 per minute. The 6-foot diameter exit and the louvers permitted shaking the entire side of the tree by driving past a tree instead of scanning its side, as was the case with small-diameter tubes.

Tests with the 6-foot blower were conducted a year later in one of the orchards used for the mechanical shaker tests. Variables studied included rotating and oscillating louvers, and ground speeds of $1\frac{1}{4}$ and $2\frac{1}{2}$ mph. Since the use of a blower permitted continuous down-the-row harvest, the equipment could harvest at a relatively fast rate; accordingly, the interval between pickings was set at 4 days to permit a maximum number of pickings. Each plot had about 60 trees, young and old.

Selectivity was determined by measuring the flesh firmness and soluble solids (indices of maturity) of the fruit on the tree before and after harvest, and the amount fruit removed. The F/W was also determined for the fruit on the tree before harvest and after harvest. An additional measure of selectivity was the windfalls occurring between harvests.

MECHANICAL SHAKERS

Two orchards were selected for tests with mechanical shakers. Although hand harvest should be (and for these tests was) on a 3-pick basis, mechanical shaking tests were conducted on a single and 2-pick basis only, as two pickings were all that could be economically justified. Hand shaking was done with hand-carried poles, and each treatment was made on five trees.

To check the effect of seasonal variation, the 2-pick harvests were started at 4-day intervals with the second pick 8 days later. The 8-day period between first and second pick was thought to be a practical limit—allowing sufficient time

to cover enough acreage to justify equipment costs, yet minimizing windfall condition between harvests.

Selectivity was evaluated as for blower tests.

Preliminary runs were conducted to evaluate the effect of frequency and stroke so that they could be held constant during the remainder of the test. Results of these tests indicated that if the frequency or stroke were too great considerable immature fruit was removed; if they were too little, excessive mature fruit was left in the tree. For the conditions encountered the limb-shaker gave the best results when operated at about 450 to 550 cpm with about a 1-inch stroke. The trunk-shaker yielded best selectivity at about 570 to 680 cpm at a $\frac{3}{8}$ -inch stroke. The shaking time was 5 seconds and 15 seconds with limb- and trunk-shakers, respectively.

RESULTS

Table 12 summarizes results. Results given for mechanical shakers are the average for the trunk- and limb-shakers, as there was no appreciable difference in selectivity between them. Pulsating-air results for the $1\frac{1}{4}$ mph speed are the average of results obtained with louvers rotating and oscillating, as no significant difference was detected between the two methods. The $2\frac{1}{2}$ mph speed was used only with louvers rotating.

From the standpoint of flesh firmness and soluble solids, mechanical shakers and the blower were selective for all treatments. (It is generally accepted that an average flesh firmness of $1\frac{1}{2}$ pounds or less, and soluble solids of 24 per cent or more, for harvested fruit is good.) A comparison of the maturity indexes for fruit on the tree before blowing, fruit blown off, and fruit still on after blowing, indicates that firmness is lower and soluble solids higher for harvested fruit than for fruit on the tree before harvest. Blower tests also demonstrate that firm-

TABLE 12
MATURITY AND REMOVAL FORCE DATA FOR
SELECTIVE HARVEST OF SANTA CLARA COUNTY PRUNES

Treatment	Status of fruit	Selective harvest early in season			Selective harvest in middle of season		
		Flesh firmness	Soluble solids	F/W†	Flesh firmness	Soluble solids	F/W
		<i>pounds</i>	<i>per cent</i>		<i>pounds</i>	<i>per cent</i>	
Blower at 1¼ mph...	On tree before	3.7	25	39	2.3	28	43
	Removed	1.5	28	..	1.0	30	..
	On tree after	4.0	25	43	2.4	28	43
Blower at 2½ mph...	On tree before	3.8	25	40	2.1	22	37
	Removed	0.8	27	..	0.8	30	..
	On tree after	3.8	25	46	2.4	28	45
Mechanical shakers...	On tree before*	2.4	25	31	2.4	25	24
	Removed*	1.8	24	..	1.4	29	..
	On tree after*	...	..	29	...	..	29
Mechanical shakers...	On tree before*	2.0	21	34	2.3	22	19
	Removed*	1.3	23	..	0.8	24	..
	On tree after*	...	..	22	...	..	28
Hand shaking.....	On tree before*	2.5	20	19	2.3	24	33
	Removed*	1.0	24	..	1.3	26	..
	On tree after*	...	..	21	...	..	31

* Readings from samples from lower portion of tree.
† Ratio of removal force to fruit weight.

ness of fruit remaining on the tree was higher and soluble solids lower than in harvested fruit. In most cases the average F/W was increased, due to removal of fruit with a lower F/W.

Figure 39 shows the frequency of occurrence of flesh firmness and removal force for the mechanical shaker test in the second orchard listed in table 12, for blower tests in 1962 at speeds of 1¼ mph, and for the blower tests in 1960. The pulsating-air shakers produce somewhat more selective results than do mechanical shakers, as indicated by the smaller amount of firm fruit removed and by the smaller amount removed with a high removal force.

Table 12 shows that the 2½ mph ground speed produced more selective results than did the 1¼ mph speed; however, it also resulted in less total removal—and this proved to be the main problem with the pulsating air method. The removal shown in figure 39 is the total

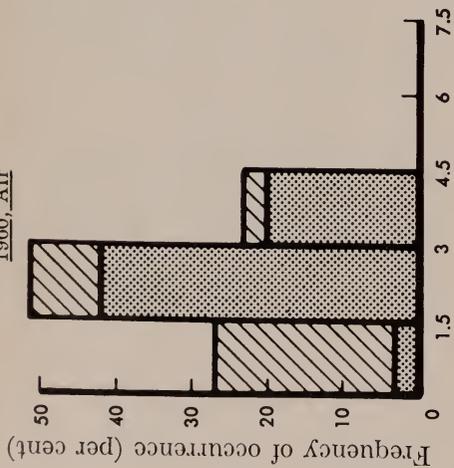
obtained with the blower in four pickings, but mechanical shakers are capable of removing 90 to 98 per cent of the fruit at any time.

Table 13 summarizes fruit removal and windfall results. Results for the blower are for four pickings; mechanical shaker results are for two pickings. Variations from year to year make the prob-

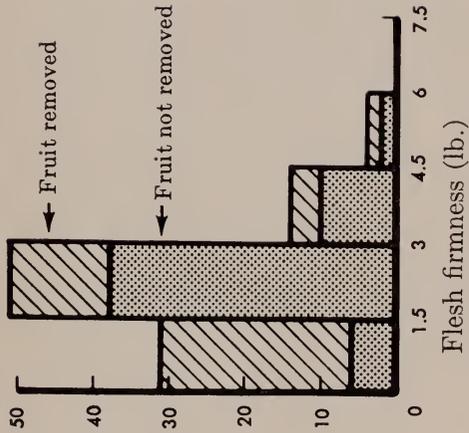
TABLE 13
WINDFALL AND FRUIT REMOVAL
DATA FOR SELECTIVE HARVEST
OF SANTA CLARA COUNTY PRUNES

Method	Wind-falls	Total fruit removed	Fruit removed per picking
	<i>per cent of total fruit</i>		
Blower at 1¼ mph.....	10	56	14
Blower at 2½ mph.....	9	49	12
Mechanical shakers....	10	88	37-50
	21	76	44-33
Hand shaking.....	8	93	18-44

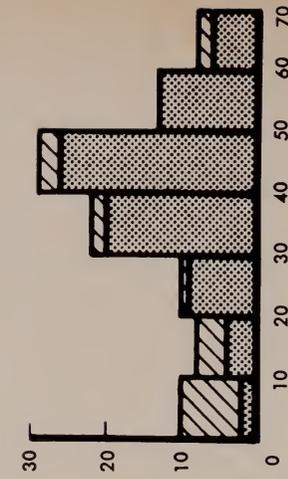
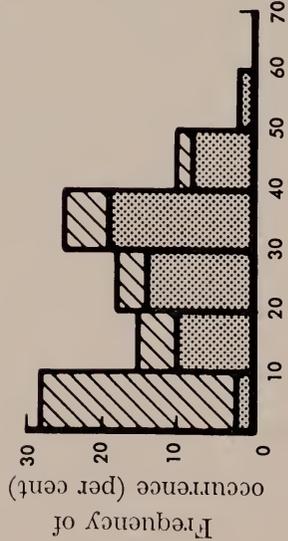
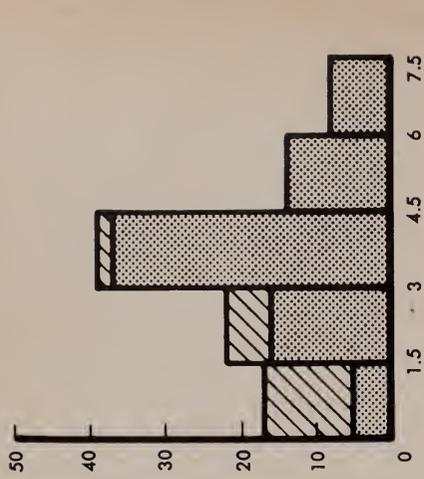
1960, Air



1961, Mechanical



1962, Air



Removal force (oz.)

Fig. 39. Selective harvest results with pulsating air (1960, 1962) and mechanical shakers on coastal area prunes. Area in each diagram is total fruit on tree at harvest. Columns represent per cent of fruit in flesh firmness (or removal force) range indicated; cross-lined portion at top of

each column shows fruit removed by shakers. Good selectivity is indicated in top diagrams by removal of fruit with low flesh firmness, and in bottom diagrams by removal of fruit with a low removal force while not removing fruit with a high flesh firmness or removal force.

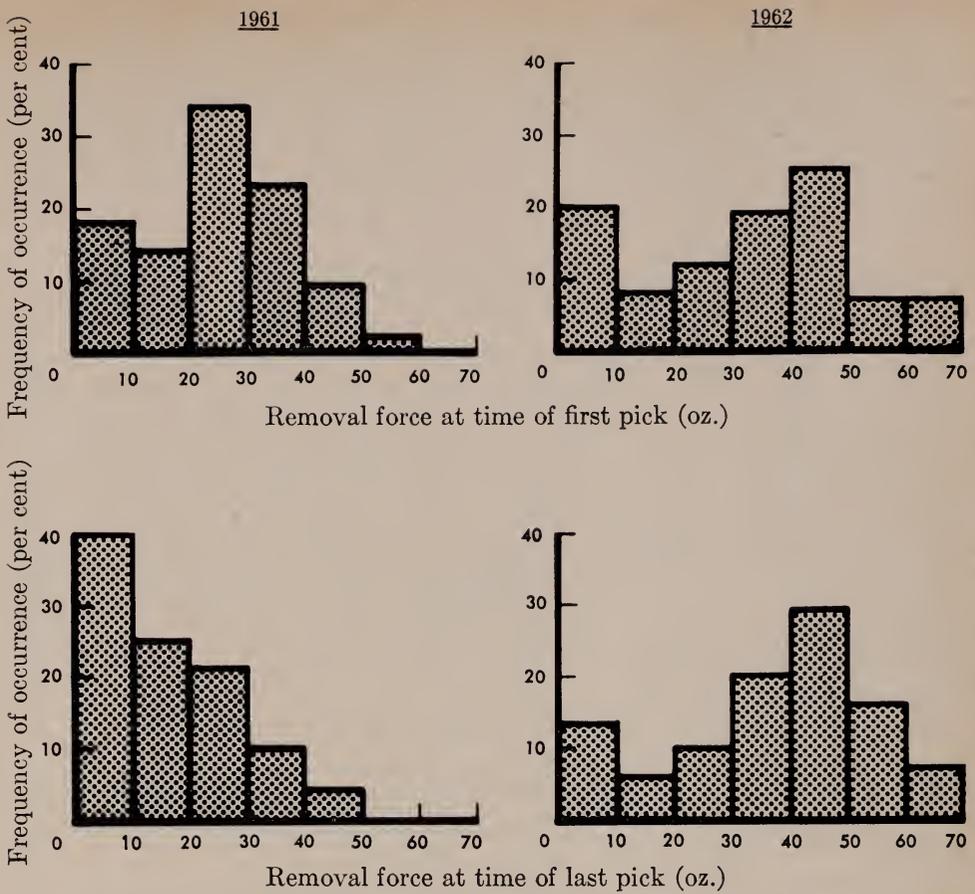


Fig. 40. Comparison of removal force in "easy" and "hard" years, 1961 and 1962 respectively. The total area in each diagram represents total fruit on tree and each column represents the per cent of fruit within the removal force ranges indicated. In 1961, fruit was easier to remove than in 1962 since it loosened appreciably as it matured, particularly late in the season.

lem of total removal with the blower particularly difficult. Figure 40 shows typical differences in distributions of the removal force early and late in the season for "easy" and "hard" years. Blower tests during the hard year resulted in a total removal during the season of about 55 per cent (table 13), which is not practical.

The blower method of harvest resulted in 6 to 7 per cent windfalls, while mechanical shakers resulted in 8 to 10 per cent windfalls in one orchard and 14 to 21 per cent in the second orchard. The high number of windfalls in the second orchard harvested by mechanical shakers

was caused by a strong wind removing loose fruit before the first pick. The primary difference between the two methods of shaking seems to be the interval between pickings and the natural drop before the first picking. With the blower, the first picking can be scheduled early and consequently few windfalls will have occurred before harvesting; also, the shorter interval between harvests yields fewer windfalls.

The above results demonstrate that both pulsating-air blowers and mechanical shakers can selectively remove prunes in the coastal areas of California. But there are two inherent problems: the first

is that when fruit continues to loosen as it matures, windfalls associated with use of mechanical shakers become excessive for catching-frame harvest; secondly, when fruit does not continue to loosen as it matures throughout the season total

removal with blowers is not practical. A solution might be to do early pickings with a blower and a cleanup with a mechanical shaker, if harvest costs are not excessive. This combination might be satisfactory for use with catching frames.

PICKUP MACHINE DEVELOPMENT

Mechanical harvesting of figs and coastal area prunes has proved to be difficult because the fruits ripen over a long period and usually drop to the ground upon maturing, which necessitates more than one picking. Considering the potential problems of considerable windfalls, the use of pickup machines has an advantage of minimum risk.

Pickup machines used prior to 1956 were usually either mechanical or vacuum-type devices. Mechanical devices were less complicated and required less power, and so the principles applied in constructing various mechanical pickup machines were analyzed. The analyses involved laboratory tests in which high-speed movies were taken of the pickup action of each principle (Fridley and Adrian, 1959). The units, which were all basically reel-type devices similar to a leaf-sweeper reel, were tested by duplicating field conditions.

High-speed movies of these units revealed presence of characteristics impossible to observe on a machine in the field. Small reels, rotating with the direction of travel and gauged close to the ground, exert downward force on the fruit because the fingers are traveling downward when they first come into contact with it. But large reels, rotating against the direction of travel, roll the fruit which has windrowed in front of the reel. The windrow is the result of two things: (1) if the fingers of the reel are radial, they are nearly vertical at the time of contact with the fruit, and consequently the force applied to the fruit is essentially horizontal;

(2) if curved fingers are used to develop a force on the fruit at a more desirable angle, there is an appreciable interval during which the finger will contact only the top side of the fruit, rolling it ahead. Figure 41 shows the interval of contact between the finger and the fruit and the angle of the finger (θ) when contacting the fruit. These two factors depend on the ratio of reel diameter to fruit diameter ($\frac{D}{d}$, fig. 42), and results are improved by decreasing this ratio.

NEW PRUNE PICKUP PRINCIPLE

A reel (or roller) diameter about equal to the fruit diameter would be optimum. However, using a roller of this diameter results in an upward force being applied on one side of the fruit. To produce a resultant force which passes upward through the center of gravity, a second roller was placed above and in front of the first roller. Thus the new pickup principle (fig. 43) consisted of a small roller rotating against the direction of travel, and a second roller above and in front of the first and rotating in the opposite direction. (The second roller is flexible, to prevent damaging the fruit as it passes between rollers.)

The first machine incorporating the pickup principle discussed above consisted basically of the pickup head which lifted fruit off the ground and threw it onto the flat section of an L-shaped con-

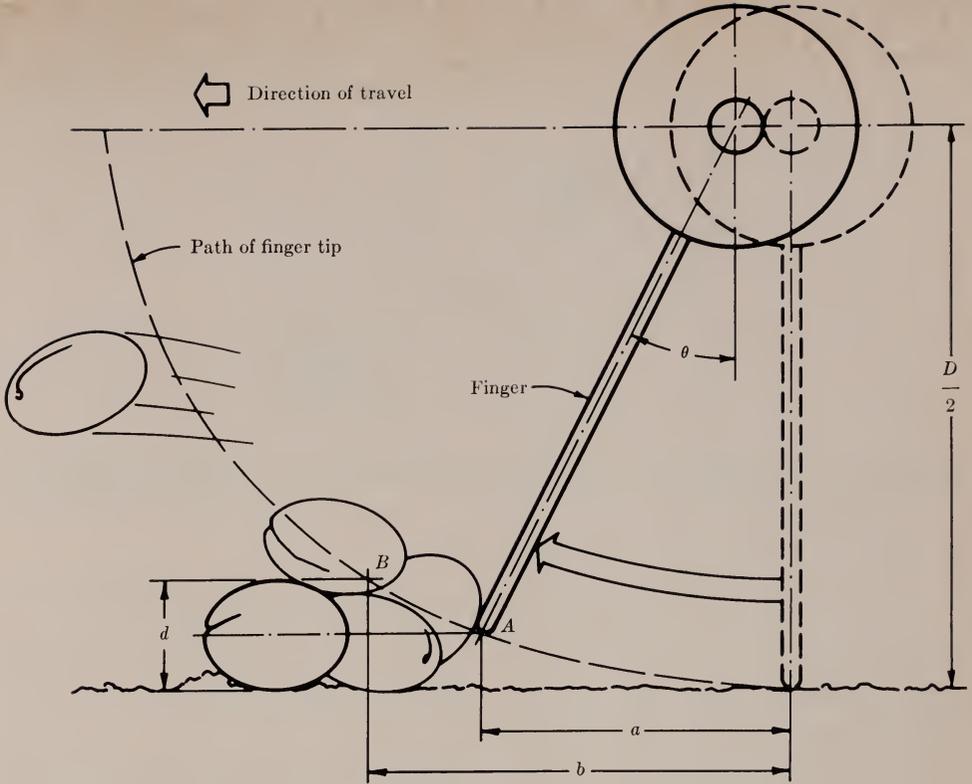


Fig. 41. Fruit pickup with a reel-type device rotating against the direction of travel. Contact between the fingers of the reel and the fruit is best during interval a . Travel of the finger tip from A to B results in rolling the fruit. Percentage of fruit rolled can be reduced by increasing the ratio of a to b .

veyor. Satisfactory floatation of the pick-up head was achieved by gauge wheels and rubber augers used to clear a path for the wheels. An attempt was made to float the pickup head on runners, but on a

cloddy surface clods were crowded into the path of the pickup unit.

Front pickup rollers from 2 to 4 inches diameter and rear roller from $\frac{3}{4}$ to $1\frac{1}{4}$ inch diameter were tested; a 3-inch roller and a 1-inch roller combination were found to be most suitable. Several materials were tried for the rear rollers, and fluted garden hose proved to be satisfactory; flutes were necessary to maintain sufficient friction for positive fruit pickup.

In general, best results were obtained with the rear roller about $\frac{1}{4}$ to $\frac{1}{2}$ inch above the ground, with the front roller just low enough to touch the smallest fruit on the ground (about $\frac{3}{4}$ to 1 inch above ground). The best distance between the rollers was achieved when the front roller was compressed slightly as small fruit passed between the rollers.

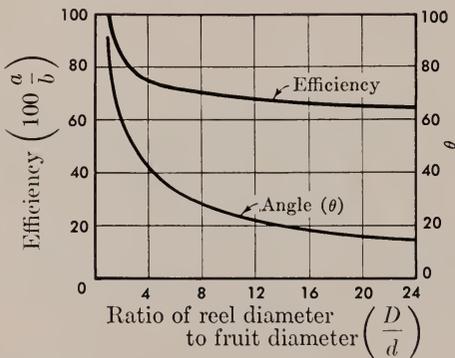


Fig. 42. Theoretical pickup performance as affected by the ratio of reel diameter to fruit diameter. (For details see page 42.)

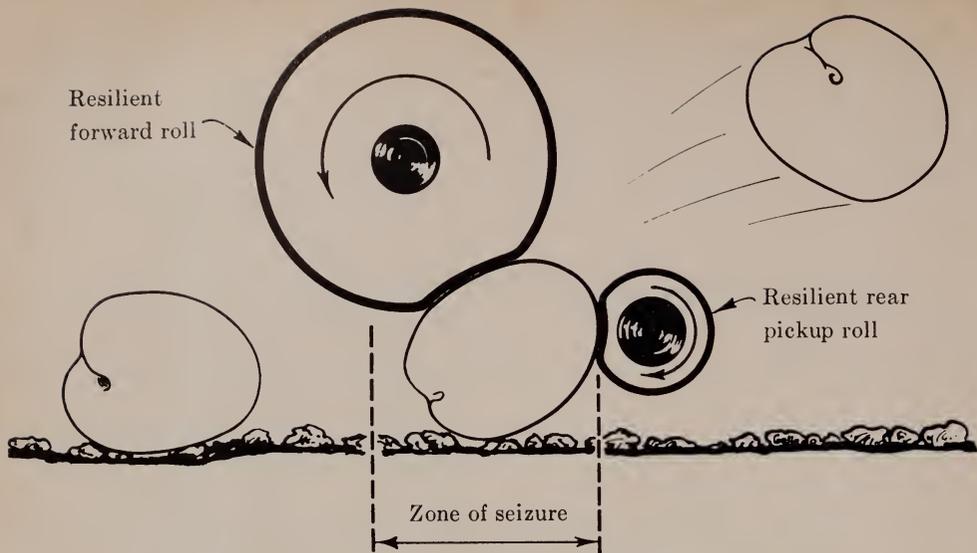


Fig. 43. New pickup principle for picking up fruit from ground.

Field tests of the principle revealed two problems: the absence of a positive transfer of fruit from the pickup mechanism to the conveying system, and the poor wearing qualities of the resilient forward roller (a steel shaft covered with foam rubber and enclosed with a skin of gum rubber).

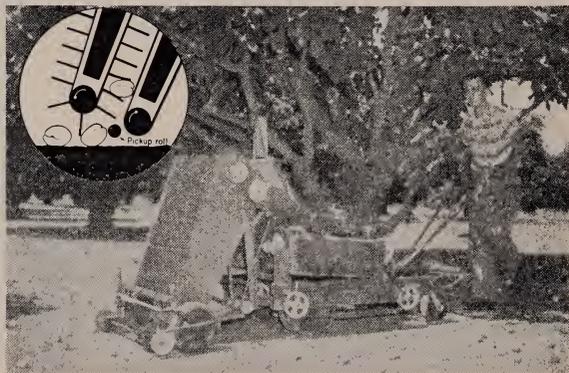
A second model was then designed which incorporated the pickup rollers into the elevating system (fig. 44). Foam rubber was replaced with a rubber-fingered belt which served in both pickup and elevation capacities; the fingers were $1\frac{1}{4}$ inch long, $\frac{3}{16}$ inch in diameter and $\frac{1}{2}$ inch apart—a wider spacing would also be satisfactory. The pickup roller was

constructed by slipping a 1-inch water hose over a $\frac{5}{8}$ -inch shaft.

Results. The average rate of harvesting prunes with the 3-foot-swath machine was 18 boxes per hour (about four times the average rate of hand pickup).

The new pickup principle caused no visible damage to harvested fruit, compared to no damage by hand pickup but 1 to 11 per cent damage for existing pickup machines. The picking up of dirt and missing fruit was found to be affected by soil preparation (as is the case with other harvest methods). With good preparation, negligible fruit was missed by either the new machine or hand harvest.

Fig. 44. Second pickup machine field testing. Insert shows the pickup principle incorporated with conveyor system.



Existing machines missed about 2 per cent of the fruit under similar conditions. About $\frac{1}{2}$ to 3 per cent of the material picked up by the new machine was dirt. Hand harvest averaged $\frac{1}{2}$ per cent, and existing pickup machines averaged 4 to 13 per cent.

Proper ground preparation was essential for best performance with this unit, although preparation was not as critical as with most other machines. Preparation consists of leveling surface ripples, filling holes, and rolling the ground in order to push clods into the surface. On a well-prepared surface, all fruit should be at substantially the same elevation.

COMMERCIAL DEVELOPMENT

In 1963 a study of commercial pickup machines using the new principle on prunes was conducted on two soil types. The first, a gravelly loam soil, was prepared by rolling four times with a smooth-roller after the growers conventional preparation for hand harvest. The second, a loam soil, was prepared by two passes with a ring-roller smooth-roller combination, but this was not sufficient for good machine performance and the soil was rolled two more times. After rolling four times the machine did a fair job on both soils, despite pronounced undulations in the surface. However, a landplane would have improved results by reducing the number of prunes missed and the amount of dirt picked up.

Time and travel studies were conducted for harvesting two-thirds of an acre with a 5-foot-swath machine which had been designed for bulk handling. The times required for various operations were:

- picking—35 seconds per tree
- turning at end of row—24 seconds
- changing bins—2 minutes.

The average yield was one box per tree per picking. Rows were 18 trees long and 4 passes of the machine were required for each row; total time for all operations was 45 seconds per tree. Assuming a field efficiency of 75 per cent, the average harvest rate would be 60 trees per hour and 60 boxes per hour. Adding one man for shaking, the output of the two-man crew would be 30 boxes per man-hour.

Improvement in harvest rate could be expected when harvesting larger blocks. With 18 trees per row and 4 passes of the machine per row as in this trial, an average of approximately 12 per cent of the total time was required for turning.

On properly prepared land, machines using the new principle had the following advantages: a positive pickup of fruit as the machine moved into it, a low impact force on fruit, and no soil disturbance by the pickup roller. Use on prunes and figs has demonstrated that the positive pickup and small impact force results in little or no fruit damage. The machines perform equally well on walnuts.

CLOD SIZE REDUCTION

A conical roller was built and tested to determine if it produced more reduction in clod size than did a comparable cylindrical roller. Theoretical analysis indicated that a conical roller would develop a torsional stress when a clod was in contact with the roller at two points, due to the velocity differential along the length of the roller. The performance of each roller was determined by comparing clod size before rolling to clod size after two passes with the roller. Soil samples were taken at four locations in the path of the roller and contained the top 1 inch of soil. Comparisons were based on a sieve analysis similar to that used for concrete aggregates (Henderson, 1955) and failed to indicate any advantage resulting from use of the conical roller.

CATCHING-FRAME DEVELOPMENT

Progress in tree shaking led to the need for a high-capacity, efficient catching-frame for fruit collection, and in 1958 a program was initiated to determine what type of catching apparatus would best fit these needs. An ideal catching-frame should have sufficient capacity to handle the output of a shaker, it should require a low labor input, and it should not interfere with shaker operation.

Frames in use up to 1958 were of three basic types: two-plane surfaces sloping toward the tree, two-plane surfaces sloping away from the tree, and an inverted umbrella wrapped around, and sloping toward, the tree trunk.

Existing catching-frames that sloped toward the tree were high at the outside on two sides of the tree, and this interfered with boom-shaker operation. In addition, delay was caused by the necessity of removing the fruit before moving to the next tree. However, these frames had the advantage of being low at the trunk, thus permitting a good seal below the tree crotch.

Sloping-out frames were low on their outer periphery, thus making tree limbs easily accessible to the shaker; however, their inside was high and a poor seal resulted due to interference of the limbs which branched out below the elevation of the seal. Good drainage of these frames was a problem.

Inverted umbrella frames had two disadvantages: their high outside periphery interfered with boom-shaker operation, and they had to be completely drained before moving.

The primary disadvantages of all three types were the high portions of the frames, which were about 4½ to 5 feet at their highest point.

LOW-PROFILE CATCHING-FRAME

The factors just discussed were considered in determining the main components to be incorporated into a catching apparatus. A low-profile machine had many advantages, such as ease of positioning a boom-shaker on tree limbs, ease of maneuvering the catching-frame under interfering branches, and a low seal for eliminating fruit losses (flexibility for different trunk sizes would be the only requirement).

A low-profile self-propelled frame was constructed and field tested in 1958 (Adrian and Fridley, 1959). The frame was designed to have individual units on each side of the tree. Each unit was self-propelled and moved straight down the tree row to minimize time loss in moving (there was less maneuvering, and no time was required to wrap frame around tree). The wide conveyor (fig. 16) was chosen because in addition to producing a low profile, it need not be drained before moving, thereby increasing efficiency. Results of limited tests on prunes were favorable. Output was 30 boxes per man-hour, with a shaker speed of 30 trees per hour—twice the output of any operation previously observed, and six times the average hand-harvest rate. Filling and handling of standard field boxes was a problem, however.

More extensive tests were conducted in two prune orchards in 1959 (Adrian, *et al.*, 1960). One was a typical prune orchard with many scaffolds and low branches. The second orchard was pruned for mechanical shaking—few primary limbs were left, (in order to minimize the number of hookups) and few low branches (in order not to interfere with operator visibility). Field boxes were used in the first orchard and bulk



Fig. 45. Trees properly pruned for mechanical harvesting.

bins in the second. A tractor-mounted boom shaker was used in both orchards.

Field test results. Table 14 shows the times required for the various operations of the catching-frame and tree-shaker under the two orchard conditions. Tree structure in the specially pruned orchard

reduced the time needed for several operations—moving shaker from limb to limb, moving shaker into tree, moving frame—and resulted in a harvest rate of 60 trees per hour (compared to 23 trees per hour in the typical orchard). For shaking limbs, the tree should have three or four scaffold limbs to minimize



Fig. 46. Low-profile catching frame incorporating bulk handling.

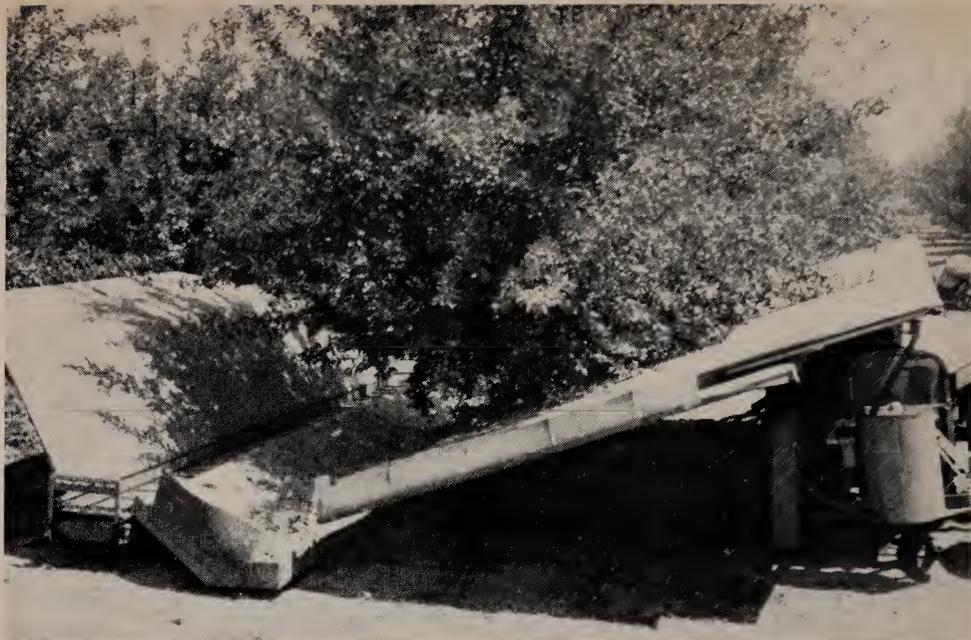


Fig. 47. Two-man harvesting frame with trunk shaker mounted under the deflecting surface on the right side. Unit on left conveys fruit to a bulk trailer in the rear. Pan in foreground is in catching position.

conveyor. The advantage of these units is low initial investment, and their use is made possible by the fact that prunes are relatively resistant to injury. They require more labor than the more mechanized units.

CATCHING-FRAME DESIGN AND FRUIT INJURY

The possible use of catching-frames for peaches, apricots, and other soft fruits led to the study of methods of minimizing injury to fruit caused by the catching operation (Claypool, L. L. 1962; Fridley *et al.*, 1964). Studies were made of protection afforded by padding material placed over hard surfaces, and of deceleration of fruit before impact with the catching surface.

The first investigation sought to develop data relative to energy relationships in fruit bruising, and the ability of certain materials to absorb a high per cent

of the kinetic energy gained by the fruit while falling. It was found that damage to fruit caused by impact on hard surfaces can be minimized by use of effective padding to absorb (or store) kinetic energy of the fruit at impact without exceeding an allowable stress of the fruit. A material which absorbs the energy—one with a high hysteresis—is preferred over one which momentarily stores the energy, as this would result in fruit being accelerated upward toward other falling fruit. A thin layer of padding is more desirable than a thick layer from a design standpoint, and therefore the shape of the stress-strain curve for the material should also be considered, as the area under this curve gives an indication of the energy it can absorb (or store).

Injury caused by fruit hitting other fruit already on the catching surface is a serious problem, particularly where fruit is concentrated in or near conveyors. Accordingly, strips of lightweight canvas webbing were suspended above



Fig. 48. Catching frame incorporating decelerator strips and expanded polyethylene padding.

the catching surface to decelerate the falling fruit (fig. 48). Tests on apricots, peaches, and olives indicated that the strips should be narrow (about 3 inches) to prevent forming pockets which will hold fruit. Spacing between strips needs to be slightly less than the fruit diameter but sufficient to prevent fruit being supported, and two or three offset layers are

required. Table 15 gives results of drop tests and fruit-injury data resulting from impacts of different energy levels on different materials and thicknesses.

In one test the combined use of padding and deceleration strips was studied on two varieties of clingstone peaches. The frames used were presumed to be one of several equally suitable commer-

TABLE 15
COMPARISON OF FRUIT INJURY RESULTING
FROM IMPACT ON DIFFERENT MATERIALS

Treatment	Blenheim apricots*		Peak clingstone peaches*	
	Drop height	Fruit severely damaged	Drop height	Fruit severely damaged
	<i>feet</i>	<i>per cent</i>	<i>feet</i>	<i>per cent</i>
Control.....	0	0	0	2
Canvas decelerator strips (2 layers).....	15	0	..	..
Fruit onto fruit on taut canvas.....	15	6	..	..
Sponge rubber $\frac{3}{8}$ -in. thick.....	15	66	7½	22
Sponge rubber $\frac{3}{4}$ -in. thick.....	10	4	7½	14
	15	12	12½	32
Polyurethane foam 1½-in. thick.....	10	7	..	..
	15	22	10	17
Expanded polyethylene ½-in. thick.....	10	10	..	..
	15	9	7½	10
Expanded polyethylene 1-in. thick.....	..	..	7½	8
	15	4	10	6

* Average of 12 apricots or 3½ peaches per pound.

cial models. Both halves of the frame were modified by covering the entire catching surface with a 1-inch layer of expanded polyethylene. As the base for the padding on one unit $\frac{3}{8}$ -inch plywood was used, and 2- \times 4-inch welded wire, tightly stretched, was used on the other unit. Laboratory studies had demonstrated that bouncing of fruit was reduced with the wire (which also provided added cushioning.)

Three layers of strips, made of woven plastic lawn-chair webbing, were installed over lengthwise conveyors on both frames. These strips were $2\frac{3}{8}$ inches wide, spaced $1\frac{1}{2}$ inches between layers and $2\frac{5}{8}$ inches between strips in the same layer; layers were offset $1\frac{5}{8}$ inch. Each layer of strips was cross-tied at 24-inch intervals to help maintain proper spacing

and to prevent strips from turning on edge. Mountings for the strips, installed on the ends of the catching frame, were designed to permit individual tightening, as effectiveness of the strips is greatly reduced if they are allowed to sag. Plastic strips did not sag appreciably due to temperature or humidity changes, but they did occasionally loosen.

The maximum drop for fruit falling from the decelerator strips onto other fruit was 16 inches, and from the strips onto the conveyor was 6 inches. Evaluation of fruit injury indicated a 3 to 7 per cent increase over that resulting from hand harvesting. Most of this injury was caused by fruit hitting limbs as it fell through the tree. Deceleration of fruit on padded catching-surfaces resulted in little or no injury.

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APPENDIX A

STATISTICAL ANALYSIS OF FRUIT REMOVAL

For the purpose of multiple regression analysis the equation

$$\text{Per cent removed} = 100 - 100e^{-kS^pN^\mu},$$

was changed into the form,

$$\frac{\text{Per cent not removed}}{100} = e^{-kS^pN^\mu}$$

$$\text{or } \ln \left(-\ln \frac{\text{per cent not removed}}{100} \right) = \ln k + p \ln S + \mu \ln N$$

$$\text{or } Y = C + pX_1 + X_2$$

The statistical results are shown in Appendix table A. The exponent p varied from 1.83 to 1.23, with an average value of 1.6. The value of μ ranged from 0.80 to 1.39, with an average value of 1.1.

The significance of the relationship was checked by determining the correlation coefficient between the measured removal and the calculated removal for $p=3/2$ and $\mu=1$.

The results were:

$$\begin{aligned} x_1x_2 &= 10,227 \\ x_1^2 &= 9,710 \\ x_2^2 &= 10,878 \\ r &= 0.993 \end{aligned}$$

where,

- x_1 = deviations of calculated values from mean
- x_2 = deviations of measured values from mean
- r = correlation coefficient.

This is significant, as the 1 per cent significance level is $r = 0.641$ for 13 degrees of freedom.

APPENDIX TABLE A
RESULTS OF MULTIPLE
REGRESSION ANALYSIS OF
FRUIT REMOVAL STUDY
CONDUCTED ON PRUNES

Item	1957	1958	
		Grower orchard	University orchard
		<i>value</i>	
Σx_1^2	1.5515	3.4508	0
Σx_2^2	1.2450	1.3872	0.5807
Σx_1x_2	-0.7257	-0.5071	0
Σx_1y	1.3294	5.4572	0
Σx_2y	0.0371	1.3272	0.6571
n	33	14	6
p	1.23	1.83	.....
r	0.80	1.39	1.13
k	0.0084	0.000088	0.00112

NOTE: $X_1 = \ln(\text{stroke})$
 $X_2 = \ln(\text{frequency})$
 $Y = \ln \ln \left(\frac{\text{per cent not removed}}{100} \right)$
 x_1 = deviation of X_1 from mean
 x_2 = deviation of X_2 from mean
 y = deviation of Y from mean
 n = number of runs

APPENDIX B

ANALYTICAL ANALYSIS OF SHAKER DESIGN

To describe many complex systems mathematically it is possible for most engineering purposes to make qualifying assumptions. In the case of vibration problems it is frequently sufficient to describe a system with few or possibly even one degree of freedom. This has been done for the following analysis.

Assumptions made for analysis (Jacobsen and Ayre, 1958; Thomson, 1954):

1. The system has a single degree of freedom.
2. The exciting force varies sinusoidally.
3. The restoring force is proportional to displacement.
4. Damping is viscous (damping force is proportional to velocity).
5. Steady-state vibration occurs.
6. Energy is conserved by the shaker.

The following differential equation then applies.

Differential equation of motion: From Newton's second law of motion, $F = ma$, it can be seen that:

Spring force + damping force + applied force = inertia force

$$\text{or} \quad -kx - c \frac{dx}{dt} - m \frac{d^2x}{dt^2} (x + r \cos \omega t) = (M_t - m) \frac{d^2x}{dt^2} \quad [1]$$

Where x = instantaneous displacement from equilibrium position—ft.

k = spring stiffness—lb./ft.

c = coefficient of viscous damping—lb./ft.—sec.

r = eccentricity—ft.

m = mass of unbalance—slugs

M_t = total mass of the system including m —slugs

t = time—sec.

ω = exciting frequency—rad/sec.

Differentiating the third term with respect to t , we obtain:

$$-kx - c \frac{dx}{dt} - m \frac{d^2x}{dt^2} + mr\omega^2 \cos \omega t = (M_t - m) \frac{d^2x}{dt^2} \quad [2]$$

And rearranging and simplifying,

$$M_t \frac{d^2x}{dt^2} + c \frac{dx}{dt} + kx = mr\omega^2 \cos \omega t \quad [3]$$

The solution of equation [3] is of the form

$$x = \frac{S}{2} \cos(\omega t - \alpha) \quad [4]$$

where S = limb displacement, ft., and α = phase angle (amount the displacement lags impressed force).

From which

$$\frac{dx}{dt} = -\frac{S}{2} \omega \sin (\omega t - \alpha) \quad [5]$$

and

$$\frac{d^2x}{dt^2} = -\frac{S}{2} \omega^2 \cos (\omega t - \alpha) . \quad [6]$$

By substituting these values into equation [3] and analyzing the resulting expression, it can be shown that for $\omega \gg \omega_n$ (where ω_n is the fundamental mode frequency):

$$S \cong \frac{2mr}{M_t} \quad [7]$$

Force. The exciting force in the differential equation [3] which describes the system, does not actually exist internally in the vibrator unit, since the center of rotation oscillates. If the force resulting from this oscillation is subtracted, the actual physical force applied on the rest of the system by the unbalanced mass is:

$$mr \omega^2 \cos \omega t - m \frac{d^2x}{dt^2} .$$

This can also be seen in equation [1] and [2]. Therefore, substituting for d^2x/dt^2 , the internal force is $F = m \omega^2 [(S/2) \cos (\omega t - \alpha) + r \cos \omega t]$, and by differentiating to determine the maximum the design force is found to be:

$$F_d = mr \omega^2 \left[\left(\frac{S}{2r} \right)^2 + 1 + \frac{S}{r} \cos \alpha \right]^{\frac{1}{2}} . \quad [8]$$

Power. The power required to vibrate the system is equal to force times velocity. Therefore, the instantaneous power (P_i) can be expressed as:

$$P_i = [mr \omega^2 \cos \omega t] \left[-\frac{S}{2} \omega \sin (\omega t - \alpha) \right] \quad [9]$$

The average power (P_a) for one cycle extending over the period (T_f) is then

$$\begin{aligned} P_a &= \frac{\Sigma(P \Delta t)}{T_f} = \frac{1}{T_f} \int_0^{T_f} P dt \\ &= \frac{1}{T_f} \int_0^{T_f} [mr \omega^2 \cos \omega t] \left[-\frac{S}{2} \omega \sin (\omega t - \alpha) \right] dt \end{aligned}$$

$$P_a = \frac{mr \omega^3 S}{4} \sin \alpha .$$

Torque. An important consideration in the design of shaker units is the maximum torque requirements. The maximum power (P_m) is found by differentiating equation [9]:

$$P_m = \frac{mr \omega^3 S}{1} (\pm 1 - \sin \alpha)$$

and since torque = power \div angular velocity the maximum torque (T_m) is given by:

$$T_m = \frac{mr \omega^2 S}{4} (\pm 1 - \sin \alpha) . \quad [11]$$

In practice, variations of the above assumptions and analyses are experienced. For example, damping includes shaker friction as well as internal limb friction and air drag on the branches and leaves. Sometimes, when the frequency of the exciting force coincides with one of the normal mode frequencies of the system, a resonance is encountered and amplification in the stroke results. Although solutions of the idealized systems may not be exactly descriptive of the behavior of actual systems, they do give enough information for most design purposes.

To simplify the information, it is sometimes necessary to use trade names of products or equipment. No endorsement of named products is intended nor is criticism implied of similar products not mentioned.