Full-Power-Positioning Limb Shaker for Harvesting Oranges

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THE Florida citrus industry processed 7.9 million tonnes of fruit in 1975 (Fla. Agr. Statis.). The fruit was harvested almost entirely by hand labor. The development of mechanical harvesting systems for this operation has become necessary because of labor problems and the high cost of performing the operation. Several systems have been developed (Coppock, 1974; Coppock, 1976), but their acceptance has been limited primarily because of their low economic efficiency.

Limb-shaker systems have been used for the harvesting of early and midseason oranges for several years &Coppock and Hedden, 1968; Hedden and Coppock, 1968). The development of a self-propelled, single-operator shaker was reported by Coppock (1974) for use in a shake-pickup harvesting system. The shaker was crank-driven, pendulously hung, and controlled remotely from the operator's handle on the shaker. A similar limb shaker was also used on catch frames developed for harvesting citrus (Coppock 1976). The limb shaker was effective in removing a high percentage of fruit without the use of abscission chemicals for loosening of the fruit. However, its harvesting rate was increased when abscission chemicals were used.

Unbalanced rotating-weight mechanisms have been used on trunk shakers to produce large shaking forces and small displacements at high shaking frequencies. The International Harvest Company (Patent No. 3,392, 517) proved that a large limb displacement could be obtained at a low frequency by use of unbalanced rotating weights. However, the couple generated between the rotating weights caused excessive boom deflection during shaking.

In an effort to overcome some of the disadvantages of earlier shakers and to improve the economics of the harvesting system, researchers at Lake Alfred, Florida, developed a shaker that used unbalanced rotating weights. The limb shaker had full hydraulic power for positioning of the shaker and required one operator. The objective in the design of the limb shaker was to reduce operator fatigue and increase harvesting rates by increasing the force developed by the shaker mechanism compared to present limb shakers. The design and performance of the limb shaker is given in this paper.

FIG. 1 Limb-shaker unit with full-powered positioning mechanism.

DESIGN OF LIMB SHAKER

The design requirements of a self-propelled, crank driven, limb shaker for citrus, reported by Coppock (1974), were applied to the design of the full power positioning limb shaker with unbalanced rotating weights, which will hereafter be referred to as the FPP-RW limb shaker. Other design considerations were required due to the automated feature of the shaker. Fig. 1 shows the FPP-RW limb shaker unit and Table 1 gives specifications of the machine components. The limb shaker unit consisted of a hydraulically driven, three-wheel transport system with a steerable rear wheel. The hydraulic drive was connected to a four-speed transmission and to the front axle differential for the purpose of propelling the machine. The transmission gave a grove travel speed of 4.2 km/h (2.6 mph) and a road travel speed of 14.5 km/h (9 mph). The shaker

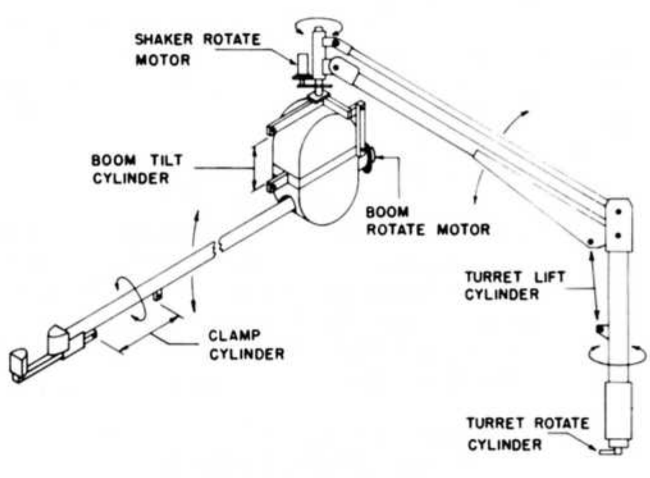

FIG. 2 Mechanism for full-powered control of shaker positioning.

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TABLE 1.
SPECIFICATIONS OF MACHINE COMPONENTS FOR THE FPP-RW LIMB SHAKER

Complete machine			Specifications
Weight			2812 kg (6200 lb)
Height			2.50 m (8.2 ft)
Length			4.66 m (15.3 ft)
Width			2.23 m (7.3 ft)
Transport unit			**Specifications**
Tires			Three-12.5-15
Engine			45 kW (60 hp) at 2400 rpm
Hydraulic drive motor, 188 cm^3/rev (11.5 $in.^3$/rev)			1261 cm^3/s (20 gpm) at 14 MPa (2000 psi)
Ground speed (4-speed)			4 to 15 km/h (1 to 9 mph)
Torque on wheels (max)			10,670 N·m (7875 ft-lb)
Shaker mechanism			**Specifications**
Total mass			317 kg (21.8 slugs)
Rotating mass			109 kg (7.5 slugs)
Eccentric of C. G.			15.9 cm (6.25 in.)
Boom length (hanger to clamp)			3.1 m (10 ft)
Hydraulic drive motor, two-117 cm^3/rev (two-6.2 $in.^3$/rev)			2142 N·m (1580 in.-lb)
Positioning mechanisms		**Specifications**	
	Range	Distance	Speed
Turret rotate	3.15 rad (180°)	8 m (27 ft)	0.3 m/s (0.1 fps)
Turret lift	0.7 rad (40°)	2.9 m (9.5 ft)	0.21 m/s (0.7 fps)
Rotate shaker	3.15 rad (180°)	9.6 m (31 ft)	0.7 m/s (2.3 fps)
Boom tilt	0.7 rad (40°)	2.1 m (6.8 ft)	0.43 m/s (1.4 fps)
Boom rotate	6.3 rad (360°)	——	2.1 rad/s (20 rpm)
Cylinder clamp	31 cm (12 in.)	31 cm (12 in.)	0.1 m/s (0.32 fps)

positioning system consisted of six mechanisms: a turret that rotates 14.3 rad (90 deg) to each side of the transport unit, a parallel-linkage turret lift arm, a shaker-rotation mechanism, a shaker hanger linkage and boom tilt cylinder, a shaker boom rotation mechanism and a limb clamp (Fig. 2).

Three double-function levers were arranged and connected such that they would give lever movements (up, down, rotate, etc.) that corresponded to the six positioning movements. The left and center control levers activated motions that would position the shaker boom in the tree, and the right control lever rotated the limb clamp and clamped it to the limb.

The operator's station was located near the ground and at the rear of the machine. This position allowed the operator to view the limb attachment point by sighting along the shaker boom. He was low enough to see under the tree canopy and to select the sequence of limb attachment points.

A 45 kW (60 hp), air-cooled engine provided power for operation of the shaker and the hydraulic components on the machine. A hydraulic schematic is shown in Fig. 3. The 1577 cm^3/s (25 gpm) pump furnished hydraulic power to the shaker and transport motors through a series control circuit. The flow from a 441 cm^3/s (7 gpm) pump was divided into two parallel circuits that operated the shaker positioning function and steering function of the transport unit. Recharge oil for the limb clamp cylinder was metered with a one-way check valve from the shaker motor and adjusted at a pressure of 6.9 MPa (1000 psi). The recharge oil kept the limb clamp tight during shaking.

DESIGN OF ROTATING-WEIGHT SHAKER MECHANISM

The rotating weight mechanism which consisted of four 27.2 kg (1.8 slugs) weights mounted on two shafts, was timed (with gears) such that it would produce a combined force in the horizontal plane and zero net force in the vertical plane. The design provided a shaker motion horizontal or parallel to the shaker boom.

The theoretical displacement amplitude of the shaker mechanism was determined by the following equation (Marrill 1957):

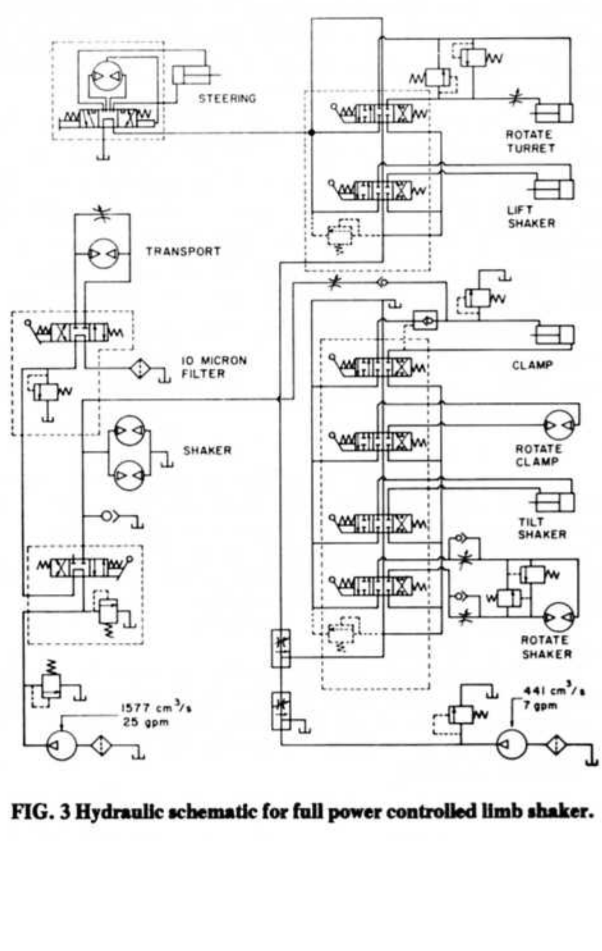

FIG. 3 Hydraulic schematic for full power controlled limb shaker.

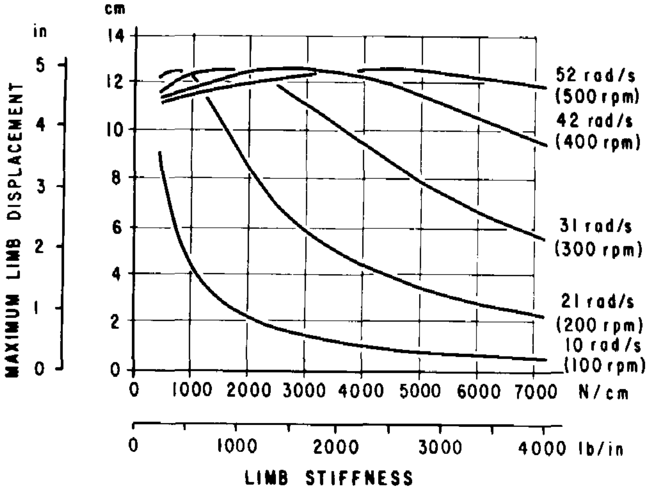

FIG. 4 Maximum theoretical limb displacement as influenced by limb stiffness.

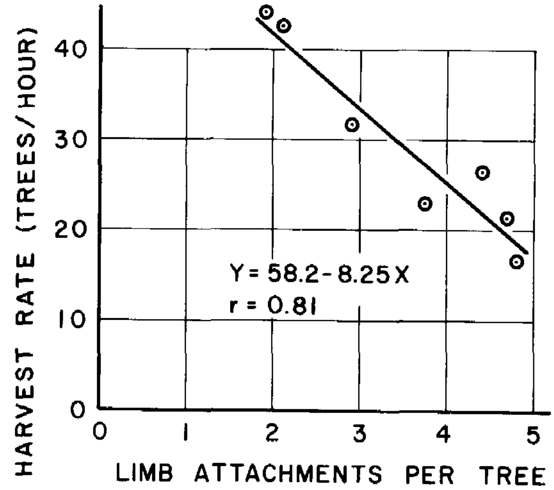

FIG. 5 Harvesting rate as influenced by limb attachments per tree.

$$x = \frac{2m_1ef^2}{k} \cdot \frac{1}{\sqrt{(1-B^2)^2 + (2\,EB)^2}}\ ;\ B = \frac{f}{f_n}\ ;\ f_n = \sqrt{\frac{k}{m}}$$

Where

- x total displacement amplitude, cm (in.)
- m_1 = mass of rotating weight, kg (slugs)
- e = eccentric distance of m_1, cm (in.)
- f = frequency of rotation, rad/s
- E = damping ratio
- f_n = natural frequency of system, rad/s
- k = spring constant, N/cm (lb/in.)
- m = total mass of system, kg (slugs)

One of the objectives in the design of the shaker was to obtain a large displacement amplitude at a frequency below 42 rad/s (400 rpm). The above equation shows that an increase in m_1, e, and f would increase displacement and that a small total mass would be an advantage.

The completed shaker had a total mass of 317 kg (21.8 slugs), rotating mass of 109 kg (7.5 slugs), and an eccentric of 15.9 cm (6.25 in.).

Fig. 4 shows the calculated, maximum, theoretical limb displacement as influenced by limb stiffness at given shaker speeds, assuming a damping ratio of 0.5. The limb displacement was reduced by an increase in limb stiffness and increased by an increase in shaker frequency. Limb displacement was large enough (7.5 cm (3 in.) or above) for harvesting oranges at a shaker frequency of 31 rad/s (300 rpm) over a wide range of limb stiffness.

PERFORMANCE

The shaker's propelling system performed well in a variety of orange grove conditions and on the road. However, turning at the end of the tree rows was difficult in very deep sand. The problem was caused by the large amount of weight on the rear wheel (nonpowered) when the shaker was in the center position. Also, the left wheel slipped on some occasions when the shaker was extended all the way to the right as it was positioned into the tree. When the shaker was moved back to the center position, the weight added to the left wheel alleviated the slippage.

Table 2 gives the shaker performance data for the

TABLE 2. RESULTS OF FIELD PERFORMANCE WITH FPP-RW LIMB SHAKER

Variety treatment no. trees	Orange variety, treatment, and no. of trees						
	Parson Brown*		Parson Brown†		Valencia‡		
	Acti-Aid 12	Check 12	Acti-Aid 24	Release 24	22	Release 25	22
Limb attachments/ tree, No.	2.9	4.4	1.9	2.1	4.8	3.7	4.7
Shake time/limb, min	0.06	0.07	0.06	0.09	0.09	0.08	0.07
Preharvest fruit drop, percent	15.3	0	26.2	9.3	9.5	29.3	13.2
Fruit removal, percent	94.9	91.6	98.3	96.2	96.1	98.0	92.1
Harvesting rate,§ trees/hr	31.6	26.7	43.8	42.3	16.6	22.8	21.3
Detachment force, N (lb)	30.7 (6.9)	83.6 (18.8)	— —	— —	33.8 (7.6)	14.7 (3.3)	22.2 (5.0)

*4.6 x 9.1 m (15 x 30 ft) spacing, 4.6 m (15 ft) tree height, yield 164 kg (360 lb)/tree.
†4.6 x 9.1 m (15 x 30 ft) spacing, 5.5 m (18 ft) tree height, yield 184 kg (404 lb)/tree.
‡7.6 x 7.6 m (25 x 25 ft) spacing, 5.5 m (18 ft) tree height, skirts pruned and water sprouts removed, yield 270 kg (615 lb)/tree.
§Harvesting rate does not include delays, time for minor repairs, or turning time.

treatments in three grove locations. The same operator harvested all trees with the FPP-RW limb shaker, which shook at a variable speed up to 37 rad/s (350 rpm). The trees were sprayed with abscission chemicals for loosening of the fruit. The effectiveness of the abscission chemicals used is reflected in the fruit detachment force and preharvest fruit drop. In the Acti-Aid (a commercial abscission agent) vs. check test, fruit removal efficiency and harvesting rate were greater with a lower fruit detachment force than with a greater fruit detachment force.

Trees in which the fruit had a greater detachment force and a lower percentage preharvest fruit drop required more limb attachments per tree than did those that had less fruit detachment force and higher percentage preharvest fruit drop. The linear regression between limb attachments and harvesting rate is shown in Fig. 5 for the groves reported in Table 2. The relationship points out the importance of the number of limb attachments per tree on harvesting rate. Trees in the 'Valencia' grove were larger and had more limbs than those in the 'Parson Brown' grove. Therefore, they required more limb attachments per tree.

Average fruit removal efficiency ranged from 92 percent to 98 percent. With the best fruit loosening the average removal was 98 percent. Tree structure, particularily the amount of space between limbs, the density of the foliage, and visibility of the limbs by the shaker operator, were found to be the most important factors influencing harvesting rate and fruit removal efficiency. Relatively small trees were shaken from one side with almost no forward or backward movement of the transport unit required between limb attachments. However, in large, dense trees with a wide limb structure, more movement of the transport unit was required and, on some trees, the shaker was backed between trees in the row to attach to limbs located away from the shaker.

The fruit deflector and cover on the transport system aided in preventing falling fruit from being run over by the wheels. However, a laborer was required for the hand raking of fruit that fell in the path of the wheels. The addition of wheel sweeps is needed ahead of each wheel, for the raking of fruit from the path of the wheels.

Although the shaker was operated by the same operator in test results reported here, other operators used in the shaker outside of these controlled conditions. It was observed that a new operator required about 2 hrs to obtain an acceptable harvesting rate with the FPP-RW shaker. All operators liked the "double function" control levers and having their direction of movement the same as required by the shaker positioning movements.

SUMMARY

A rotating-weight limb shaker, with a full-power-positioning mechanism was designed and field tested. Three "double function" control levers that activated the six motion functions in the positioning mechanism and the location of the operator were assets in getting the shaker clamped to the limbs. Tree structure was an important factor in the ease with which limb attachments were made. The rotating weight limb shaker was effective in producing a shaking motion that removed 92 to 98 percent of the fruit from orange trees. Harvesting rate and fruit removal efficiency were influenced by tree structure, fruit detachment force, and the number of limb attachments required per tree. An average of 17 and 44 trees per hour were harvested in groves that had 5 and 2 limb attachments per tree, respectively.

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