

# A Self-Propelled Air Shaker for Citrus Fruit Removal

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## ABSTRACT

A self-propelled air shaker for citrus fruit removal was designed, constructed, and field tested. The 4-wheel prime mover was hydraulically powered with all-wheel steering. The air shaking pattern was generated by two 1.37 m diameter vane axial fans delivering air to a discharge with center pivot plates. The prime mover performed quite satisfactorily, but the fruit removal capability of the machine was not better than that of previous air shakers. On chemically loosened oranges, 160 to 340 kg of fruit were removed per liter of consumed diesel fuel.

## INTRODUCTION

Research has been underway at Lake Alfred for over two decades to address the problems related to harvesting the citrus crop. The most recent research has concentrated on mechanizing the harvest, which today remains a manual arduous task.

In a feasible mechanical harvesting system, removal of citrus from the tree has been the most difficult function to mechanize. The most successful concept for removing Florida citrus has been shakers, one of which is the air shaker.

Previous reports (Whitney and Patterson, 1972; Whitney, 1977, 1978) have outlined the major advantages and disadvantages of the air shaker concept. Some of the most recent reports (Whitney 1977, 1978) described the performance of an air shaker with three fans. It was designed to remove citrus by making two passes per tree or one pass on each side and parallel to the tree row. The air shaker was effective in removing citrus which had been loosened to a bonding strength of 20 N. Operation of this and other air shakers in the field have indicated that improvements were needed in the following areas: (a) machine stability, (b) height of tree which could be effectively shaken, (c) maneuverability, (d) cost and (e) efficiency in the use of power to shake trees. The objectives of the air shaker design discussed in this paper were to give improvements in the above areas.

## DESIGN FEATURES

The major design features of the air shaker described in this paper were those which were felt would be improvements over existing air shakes. These features were:

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FIG. 1 Right front view of self-propelled air shaker.

1 Unit was self-propelled and 4-wheel hydraulic drive with continuously variable ground speed control and steering on both axles for a high degree of maneuverability.

2 Unit was relatively narrow in width (profile width of 2 m immediately above the axles) so that it could be used in narrow middles between canopies of adjacent tree rows.

3 Height of air discharge was approximately 6.4 m and was greater than existing units in an attempt to produce better shaking action in the tops of trees approximately 6.4 high.

4 Air discharge width was 76 cm and was wider than discharges of existing air shakers to generate air shaking action with a larger area of exposure at a reduced velocity (less pressure) to reduce tree damage, especially near the outside of the tree canopy.

5 Unit had cab to reduce operator exposure to acceptable levels of noise and dust.

6 Unit had low center of mass even with greater height of air discharge for greater stability than most existing air shakers.

7 Engine and fan inlet compartment was designed to attenuate some of the noise generated by the engine and fans, to shield the engine, belts, and fans from fruit and limbs, and to provide sufficient cooling of the engine without the radiator fan.

TABLE 1. AIR SHAKER SPECIFICATIONS

1. Overall length		7.77 m
2. Overall width	a. axle	2.44 m
	b. upper profile	2 m
3. Overall height	a. road travel	4.04 m
	b. in grove	6.32 m
4. Wheelbase		6.4 m
5. Weight		9910.0 kg
6. Fans	Two Joy Manufacturing Co.* Axivane, Series 2000, 1.37 m blade tip diameter, 0.66 m hub diameter.	
7. Engine	Caterpillar 3408 (18 L displacement) rated at 317 kw intermittent duty at 2100 rpm and 224 kw continuous duty at 1800 rpm.	
8. Wheel drive	Four Fairfield W3C3 Torque Hubs with 18.75 to 1 planetary gear ratio, each driven by Hydreco variable volume, hydraulic piston motor, 0.079 L/rev.	
9. Brakes	Hydrostatic except emergency and parking brake was Ausco No. 27972 between Hydreco motor and Torque Hub on each rear wheel.	
10. Tires	Four 14.7 x 17; 14 ply rating.	
11. Hydraulic pumps	a. Ground drive — Hydreco variable volume piston, 0.197 L/rev.	
	b. Auxilliary — Hydreco gear, 0.052 L/rev.	
12. Steering	Power steering on front and rear axles. Total steering angle on both axles was 90°. Turning radius to outside tires was 6.1 m.	

\*Reference to a company or product name is for specific information only and does not imply approval or recommendation of the product by the University of Florida to the exclusion of others that may be suitable.

water temperature-low oil pressure safety switches of the engine fuel shutoff system so that a low level in the oil reservoir or loss of pressure in the charge pump circuit would stop the engine.

The auxiliary pump provided oil for all other functions. Its output was delivered to a gear flow divider which divided the pump flow into four equal circuits. Maximum pump flow was 90 L/min at 2100 engine rpm or 22.5 L/min per circuit. The four circuits supplied oil to (a) the power steering system and the hydraulic motor driving the ventilation blower for the cab, (b) the two motors which drove the center pivot (air manipulating) plates (Whitney, 1978), (c) the hydraulic cylinders for raising and lowering the top duct and the motors driving the front wheel fruit sweepers and, (d) the motors driving the rear wheel fruit sweepers.

In the selection of the engine as well as all the heavier components on the air shaker, weight was a primary consideration because of the mobile application on sandy soils. The engine selected for this application had a high power-to-weight ratio and was compact. It was mounted inside the main frame immediately in front of the rear axle and as low as practical to maintain a low C. G. of the machine. The engine was capable of delivering 317 kW on intermittent duty, 261 kW of which would be used for fan power and the remaining for the prime mover and auxiliary functions.

Engine power was transmitted from the front of the crankshaft to the inlet side of the fans through a series of jackshafts, sheaves, and V-belts. Expanded metal covered the top and sheet metal covered the bottom of the engine and fan compartment. On the sides, tubular framework contained removable 76 cm × 76 cm doors which were covered with sheet metal or expanded metal. The removable doors allowed access to the compartment and placement of the expanded metal doors could be changed to get proper air entry into the fans.

The vane axial, adjustable pitch, fans were selected

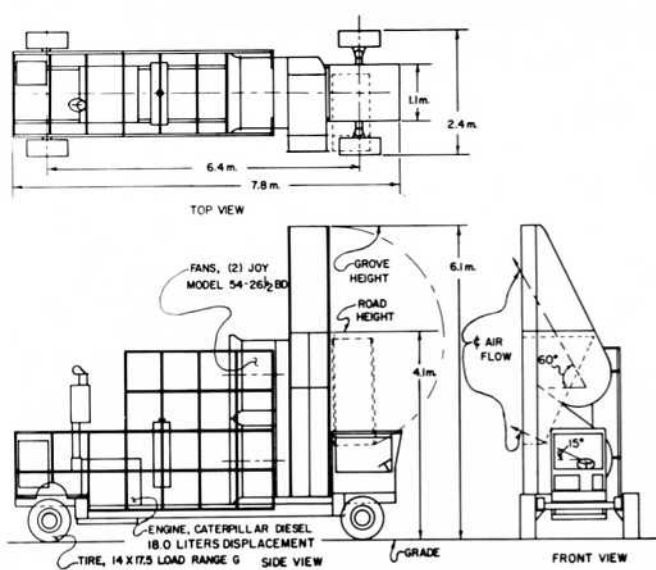


FIG. 2 Schematic views of self-propelled air shaker.

## CONSTRUCTION

Figs. 1 and 2 show the general layout of the air shaker that was constructed in 1977. Table 1 lists its specifications. Placement of major components from the rear to the front were the (a) hydraulic reservoir and pumps over the rear axle, (b) engine with radiator displaced vertically to accommodate coupling of jackshaft to front of crankshaft for fan drive, (c) belts and sheaves to drive jackshafts coupled to inlet side of fan shafts, (d) fans and ducting to convey air around 90 deg turn from fan outlet to rectangularly-shaped discharge and (e) the operator's cab over the front axle. All of the components were mounted on a steel channel frame which was suspended over the front and rear axles by leaf springs.

The hydraulic pumps were direct-driven off the rear of the engine and provided all power **except** for the fans which were belt-driven off the front of the engine. The ground drive or prime mover system used a closed-loop hydraulic drive, and the drive motors were connected in parallel. The displacement of the pump was controlled by a push-pull cable for forward, reverse and speed adjustments. Three distinct hydraulic volume displacements of each wheel motor were controlled by a small, hydraulic cylinder operated from the charge pump pressure through a solenoid valve. The maximum (0.079 L/rev) and medium (0.052 L/rev) displacements were intended for grove travel while the minimum (0.028 L/rev) displacement was for hard-surface road travel. At an engine speed of 2100 rpm, the maximum road speed in the minimum displacement position was 29 km/h.

The brakes on the two rear wheels were also operated off the charge pump pressure. The circuit was designed so that the brakes could be activated in an emergency or a parking situation. If pressure was lost in the ground drive (hydrostatic system) or power input from the engine failed, the vehicle could be stopped by activating a 2-way valve in the cab to gradually release the pressure (brakes were pressure release, spring applied) and apply the brakes to stop the machine.

Two safety switches were included in the hydraulic systems. An oil level switch was mounted in the hydraulic oil reservoir and a low pressure switch sensed the charge pump pressure. These switches were wired into the high

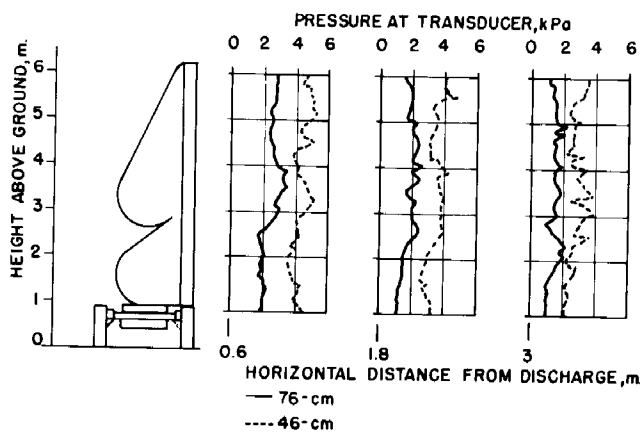


FIG. 3 Peak air pressures at the centerline of the 76 cm and 46 cm wide discharges as a function of height above ground and distance from discharge.

based on manufacturers curves because they would each deliver an air volume flow rate of  $42 \text{ m}^3/\text{s}$  at 27.9 cm total water pressure with less than 150 kW input power. Air from the fans was turned 90 deg through a smooth transition before entering a rectangular discharge 5.5 m high and 76 cm wide, and this was different from the fan orientation of the 3-fan air shaker (Whitney, 1977, 1978) in which case the air from the fans did not require turning before entering the discharge. The bottom fan supplied air to the bottom 2.4 m of the discharge and top fan supplied air to the top 3.1 m of the discharge. The uppermost part of the top fan casing was 4 m high and the air from this fan was ducted to maximum height of 6.4 m above ground.

To develop the air shaking pulses, 18 rectangularly-shaped center pivot plates, 29.8 cm by 75 cm, were spaced on 30.5 cm centers and rotated by a timed chain drive powered by two hydraulic motors. This plate system has been described in earlier reports (Whitney and Schultz, 1975; Whitney, 1978). For road travel, the top 2.4 m of the duct system and plates was folded down with hydraulic cylinders to a height less than the legal limit of 4.1 m.

The operator's cab was mounted over the front axle on the front of the air shaker. Outside mirrors assisted the operator in viewing toward the rear of the machine. Controls in the cab included steering, engine throttle, displacement of variable volume pump and motors on ground drive, speed of front and rear sweepers, speed of air discharge center pivot plates, cab ventilation blower, and emergency brake actuator.

#### AIR PRESSURE MEASUREMENTS

Previous experience with air shakers had indicated that the shaking energy required to remove citrus from the tree was greatest in the top of the tree (Whitney, 1977, 1978). For this reason, the blade pitch on the top and bottom fans were set on 2 and 3.5, respectively. At these settings according to the manufacturer's curves, the top fan should have delivered 30 to 40 percent more air volume than the bottom fan. Maximum power required at 1770 rpm was 149 kW and 112 kW on the top and bottom fans, respectively. The speeds of the top and bottom fans for all tests were approximately 1720 and 1740 rpm, respectively. The center pivot plates were rotated at 30 rpm which generated cyclic air pulses at 1 Hz. Adjacent plates were set 10 deg out of phase.

Air pressure measurements were made in a horizontal

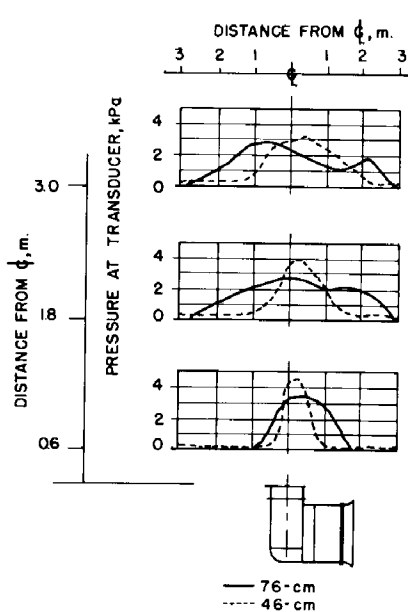


FIG. 4 Peak air pressures of the 76 cm and 46 cm wide discharges at 3.4 m above ground as a function of horizontal distance from the discharge centerline.

plane in 1977 with a pressure transducer and recorded on a storage oscilloscope as has been described elsewhere (Whitney, 1977, 1978). Figs. 3 and 4 show vertical and horizontal profiles of the peak air pressures emanating from the 76-cm wide discharge. Peak air pressures at 3 m from the discharge were about one-half those at 0.6 m. The air pressure was generally greater at midheight than in the upper height of the discharge. The divergence of the pattern (Fig. 4) in the horizontal plane was similar to the previous air patterns (Whitney, 1977).

Preliminary tests in the field indicated that generated air pressures were generally not high enough for vigorous shaking action and that the air shaking action above the midheight was not as great as desired. To increase the pressures, the discharge outlet was decreased in width to 61 cm and then to 46 cm by blocking an equal width on each side of the original 76 cm wide outlet. This created a sharp-edged orifice (containment walls perpendicular to air flow) at discharge opening.

Figs. 3 and 4 also show the peak air pressures of the vertical and horizontal profiles of the 46 cm outlet. Pressures obtained with the 61 cm outlets were between those of the 76 cm and 46 cm outlets and are not shown. Pressures for the 46 cm outlet were about twice those of the 76 cm outlet, but at the expense of horizontal pattern width.

In 1978, the discharge was narrowed to a width of 38 cm by making the containment walls parallel to the air flow (as in original 76 cm wide discharge). This was done to reduce the losses of the sharp-edged discharges tested in 1977. Results with this discharge were similar to those with the 46 cm wide discharge (Figs. 3 and 4). Fig. 5 shows the air pressure pulses from the 38 cm discharge as a function of time and position with respect to the discharge. These results, along with those in Fig. 3, illustrate why the air shaker did not generate an effective shaking action in the top of trees. That is, the pressures in the air pulse at the upper level, which should be higher than that at lower levels, were not any greater than those at midheight.

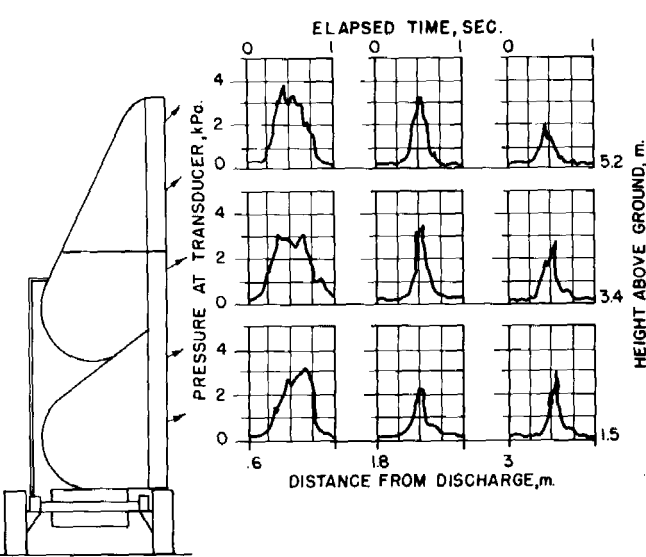


FIG. 5 Peak air pressures at the discharge centerline as a function of time, distance from the discharge, and height above ground.

## FIELD PERFORMANCE

### Prime Mover

Maneuverability of the air shaker in the grove was very satisfactory. Turning at row ends was accomplished without stopping in 9.1 m middles and in 7.6 m middles whenever there was 9 to 12 m of turning spacing at the ends of the grove.

Both the hydrostatic and auxiliary hydraulic systems functioned satisfactorily. A relief pressure of 20,670 KPa in the hydrostatic system was adequate to spin the tires in sandy conditions with the wheel motors at maximum displacement. Reduction in tire pressures to 276 KPa was sometimes required to move through loose and dry sand conditions. A hydraulic system pressure of 6890 KPa was usually adequate to move the prime mover through the grove. With the wheel motors in the minimum displacement position, grades of up to 7 percent on hard surface roads could be negotiated. Sustained road speeds were limited to about 16 km/h because of excessive heat build-up in the planetary wheel hubs. The hydraulic oil temperature in the field or on the road never exceeded ambient temperature by more than 17 °C. The engine water temperature never exceeded 82 °C when operating in the field under full load with the radiator fan inoperative.

The air shaker was very stable. The leaf-spring suspension system accommodated most of the terrain satisfactorily. One situation was encountered where the weight and thus the traction on one of the four wheels was inadequate to assist in propelling the machine.

The cab provided good visibility for the operator. A window in the roof of the cab was required for the operator to have good observation of the fruit removal operation.

### Fruit Removal

The first removal tests were conducted in 1978 with the 76 cm wide discharge. Mature 'Hamlin' orange trees 6.1 m high and spaced 6.1 m × 9.1 m were sprayed with abscission chemicals 4 to 5 days before harvest. Preharvest drop from loosening by the abscission chemical ranged between 15 and 50 percent. The trees were air shaken with both the 3-fan unit (Whitney, 1978) and the self-propelled unit. Average fuel consumption for the 3-fan and self-

propelled shaker averaged 72 and 70 L/h, respectively. Percent fruit removal averaged about 95 percent for both machines. However, the kg of fruit removed per liter of fuel was 480 for the 3-fan unit and 340 for the self-propelled unit because the former could move at a faster ground speed.

In another 1978 test, 'Hamlin' oranges were sprayed with abscission chemicals and a 30 to 80 percent preharvest fruit drop resulted. Fan power was reduced so that the fuel consumptions of the 3-fan and self-propelled air shakers were 43 and 51 L/h, respectively. Fruit removals averaged more than 95 percent for both machines but the kgs of fruit removed per liter of fuel were 530 and 320 for the 3-fan and self-propelled shakers, respectively.

A comparative test was conducted in 1979 with 38 cm wide discharge on the self-propelled air shaker and the 3-fan air shaker. Parson Brown trees were sprayed with several abscission chemicals and by several sprayers. Generally, the fruit did not loosen satisfactorily for air shaking, but the trees were air shaken about seven days after spraying. Preharvest drop range from 0 to 10 percent. With both shakers operating under similar but widely varying fruit loosening conditions, the average fruit removal percentages of the 3-fan and self-propelled units were 87 and 75 percent, respectively. Fuel consumption was comparable for both air shakers at 160 kg of fruit per liter.

## DISCUSSION

In general, the prime mover functioned satisfactorily. The tires, however, were marginal from a flotation viewpoint, especially if the vehicle had to negotiate grades of 4 to 5 percent in loose, dry sand on a regular basis. Road travel speeds were only 50 percent of the capability of the hydraulic system because of the wheel hub heating problems. Noise and dust levels in the cab were acceptable to the operator. Temperatures in the cab ventilated by the blower were maintained near ambient in the summer (up to 32 °C) and could be maintained in the comfort region by off-on operation of the blower in the winter (down to 2 or 3 °C).

In general, the fruit removal capability of the air shaker was less than what had been expected. The air shaking pattern generated by the bottom 2.4 m of the discharge (air furnished by bottom fan) was fairly aggressive and usually adequate to shake the bottom portion of the trees. However, the air shaking pattern developed by the top section of the discharge (air furnished by top fan) was not aggressive enough for the tops of most trees. Apparently the fan was unable to generate sufficient air pressure and volume, even though the fan blade pitch on the top fan was set to develop considerably more air volume and pressure than the bottom fan. A fan with greater pressure capability would be desirable. Mainly because of the inadequate performance of the top fan system, the power efficiency of this design (based on fruit removal performance) was not as good as the 3-fan air shaker (Whitney, 1978). Only with the proper fan selection and duct design does it appear feasible to duct air above the general vicinity of the fan to gain the benefits of better stability. It appears that similar fans with less air volume and greater pressure capabilities would be more desirable for this application than the fan that was selected here.

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## Self-Propelled Air Shaker for Citrus

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In the final analysis, most of the design features worked out except numbers 3 and 4—namely the effective shaking action in the tops of trees was not increased over existing shakers and the 76 cm width discharge was too wide to use with the design input.

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