Correct Project Number: 00-KS-o0

Final Report: Reducing Shaker Barking Injury in Almonds (Almond Board Project: 00-KS-00)

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Objective: To summarize and compare the levels of forces that occur during almond shaking under field conditions for a number of commercially available shakers.

Background:

Shaker damage (barking) during almond harvest can reduce tree health and productivity, and it is widely recognized that incorrect pad design or improper shaker operation can cause barking under most conditions. It is also widely believed that well irrigated trees are more susceptible to barking than water stressed trees, but in 1997 and 1998 we irrigated almond trees very close to harvest (36 - 48h) and found no damage, indicating that water stress at harvest is not a required condition for safe shaker harvesting of almonds. In 1999 we found that shaker damage was limited to one row of trees, indicating that either the shaker or shaker operator was a significant factor. Since all of the shakers were of the same manufacture, and all of the shaker operators were experienced, we proposed to compare the levels of forces that occur during almond shaking under field conditions for a number of different commercially available shakers.

Procedures:

A high speed data acquisition system for shock and vibration measurements was obtained on loan from the USDA post-harvest laboratory in Fresno, and two tri-axial accelerometer packages capable of withstanding shaking forces were fabricated at UCD. A series of studies using a vibrating table and a precision laser micrometer were used to confirm that accelerometer data could be reliably converted into displacement, using appropriate mathematical techniques. A number of field tests were performed using the commercially available harvesters indicated in Table 1.

Table 1. Shakers tested as part of this study (in alphabetical order).

AGH (American Grape Harvester)
Compton Enterprises
ENE (Erick Nielsen Enterprises, inc.)
FMC (Food Machinery Corporation)
OMC (Orchard Machinery Corporation)
Orchard-Rite

By agreement with the manufacturers, letters were randomly assigned to each manufacturer to maintain confidentiality in the reporting of the test results. Each test consisted of at least two replicate 3 second shakes using a free wooden post in place of the tree (called a "free shake"), to determine the shaking forces in the absence of any tree influence. Forces were measured both on the shaker arm and on the post, and an example of this kind of test is shown in Fig. 1. All three directions of movement were recorded by the accelerometer packages (Fig. 3) and are labeled as the shaker operator would observe them while looking at the tree: "Right/Left," "In/Out" and "Up/Down." The free shake test was followed by one 3 second shake applied to each of five individual trees down a row, with forces measured on the shaker arm and on the tree, and an example of this test using the same shaker as shown in Fig.1 is shown in Fig. 2. In all cases, the shakers were operated by experienced employees who were instructed to apply the same kind of shake as they normally would apply for the trees being harvested, with the exception that only 3 seconds of shaking would be given. In some cases, new harvesters were tested at the manufacturers shop in the free shake mode to evaluate whether shaker age was an important factor, and additional tests were also performed to determine the effects of engine RPM and pad type.

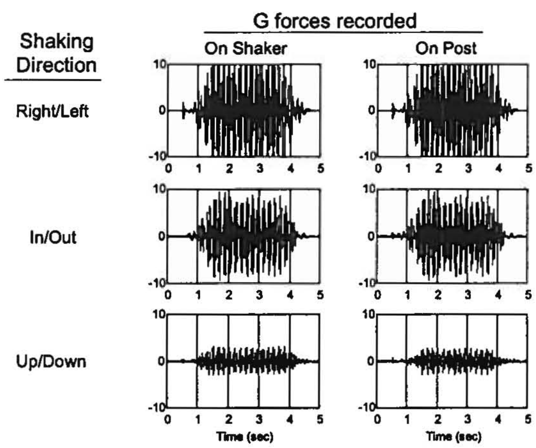


Figure 1. G forces recorded in three directions on the shaker (left graphs) and the post (right graphs) during a "free shake" (no tree).

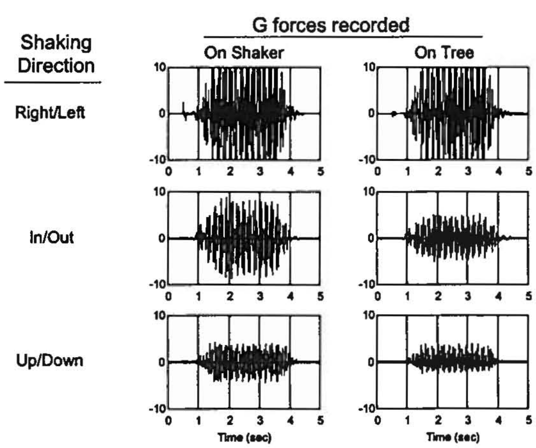
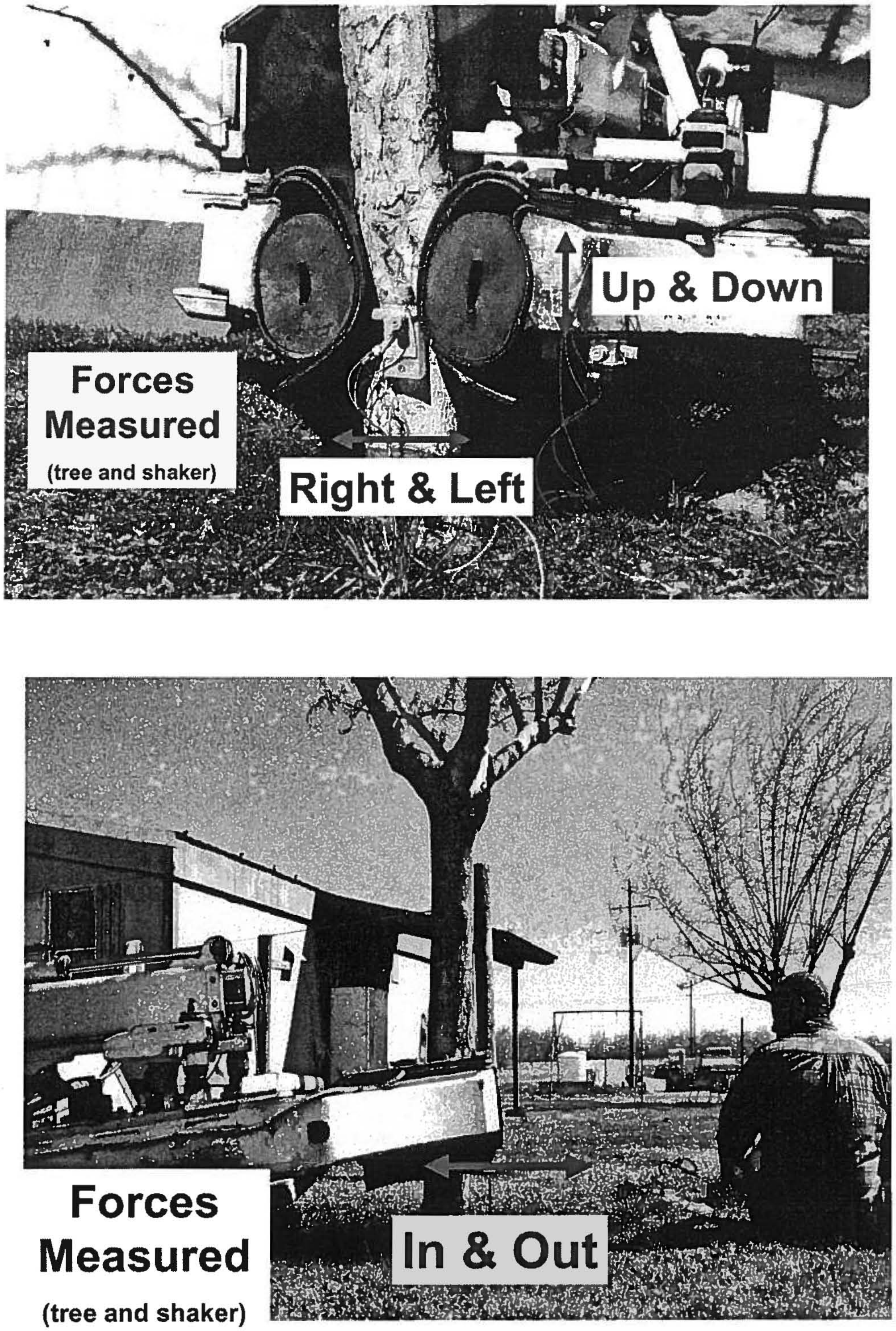


Figure 2. G forces recorded in three directions on the shaker (left graphs) and the tree (right graphs) during normal shaker harvest

Figure 3. Directions of forces measured both on the tree and on the shaker arm.



Results and discussion:

Using a prescision laser micrometer, the motion of a vibrating table could be measured directly, and was found to have a total displacement of about 4 mm (Fig. 4). At the same time, the accelerometer data showed a reasonable pattern in measured acceleration (Fig. 5 A), but when velocity (Fig. 5 B) and displacement (Fig. 5 C) were calculated from the acceleration data, it became clear that mathematical errors were compounding, and that there was substantial drift in

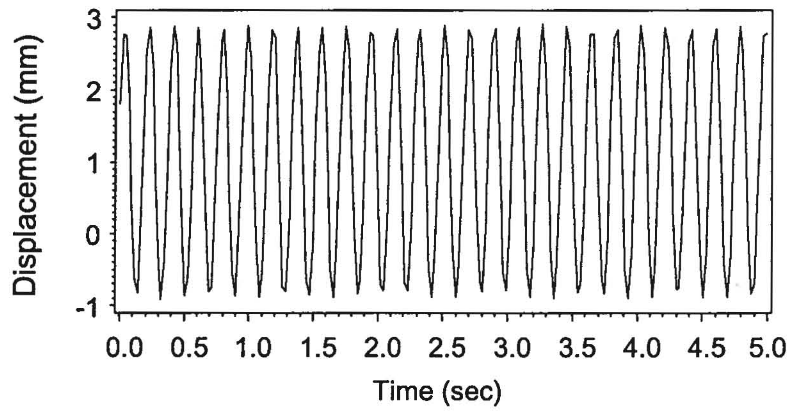


Figure 4. Displacement of a vibrating table as measured by a precision laser micrometer.

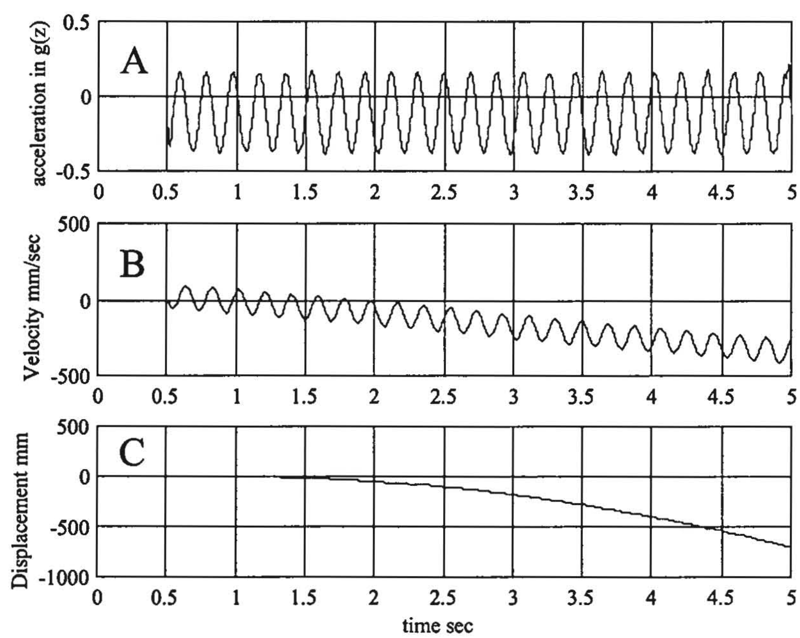


Figure 5. Acceleration measured by the accelerometers (A), and velocity (B) and displacement (C) calculated from the acceleration values, for the same test as shown in Fig. 4.

the calculated displacement (i.e, as much as 700mm, Fig. 5 C). A moving average approach was used to correct this error however (Fig. 6), and this gave displacement values of about 4 mm (Fig. 6 C), in good agreement with the measured displacement (Fig. 4).

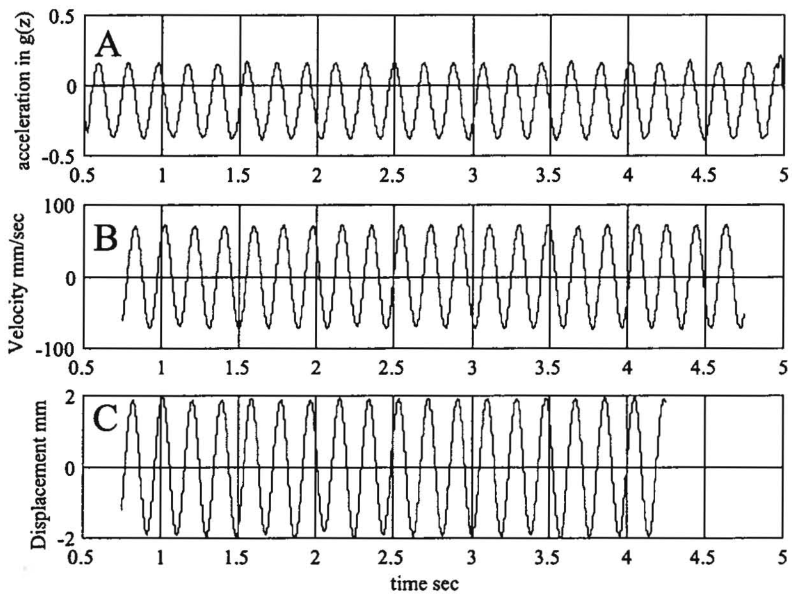


Figure 6. Acceleration, velocity and displacement for the same data of Fig. 5, but using a moving average mathematical correction to remove signal drift.

In the free shake mode (Fig. 1), both accelerometer packages measured the same forces, which is as expected. Typically, most of the force was experienced in the Right/Left direction, with somewhat less force in the In/Out direction, which is also as expected based on the mechanics of how the shaking motion is created in these shakers. A measurable amount of force was also recorded in the Up/Down direction however, which was not expected. When a tree was shaken (Fig. 2) the forces on the tree were generally less than those on the shaker arm, particularly in the In/Out and Up/Down direction. Presumably, lubrication of the flexible slings (slip belts) that cover the pads allows for slippage in the In/Out and Up/Down directions to minimize the shearing forces that could damage the bark. Despite this however, we were able to measure significant forces in the Up/Down direction.

Tables 2 and 3 summarize the data collected for all of the shakers evaluated in the free shake mode. In general the variation between shakers for the same manufacturer was similar to the variation between manufacturers, indicating that all shakers were similar in their behavior in the absence of a tree. If the shaker pattern is designed to shake in all directions more-or-less equally, then we would expect the In/Out displacement to be about the same as the Right/Left displacement, and the average for all the shakers showed the Right/Left displacement to be the highest, with an In/Out displacement of 74% of that value. The average Up/Down displacement

Table 2. Displacement in all directions for almond shakers in the free shake mode (no tree). Each value is the average of two replications, which in most cases were essentially identical.

Manufacturer	Shaker	Direction and Displacement (mm)		
		Right/Left	In/Out (% of Right/Left)	Up/Down (% of Right/Left)
A	Used	13.1	10.6 (81%)	4.1 (32%)
B	New	10.0	8.7 (87%)	2.2 (22%)
	Used #1	7.6	5.7 (75%)	5.1 (67%)
	Used #2	11.1	8.4 (76%)	3.1 (28%)
	Used #3	10.1	9.2 (91%)	9.4 (92%)
	Used #4*	14.4	12.5 (87%)	2.5 (18%)
C	Used*	13.9	9.2 (67%)	1.7 (12%)
D	New #1	9.1	7.0 (76%)	5.1 (56%)
	New #2**	14.6	12.2 (84%)	6.9 (47%)
	Used #1	10.3	7.1 (69%)	3.1 (30%)
	Used #2	9.2	6.6 (72%)	3.8 (41%)
E	Used	13.7	6.5 (48%)	3.7 (27%)
F	Used	14.9	14.1 (95%)	6.1 (41%)
AVERAGE		11.8	8.7 (74%)	4.3 (37%)

* Prune shaker **Walnut shaker

Table 3. Frequency in all directions for almond shakers in the free shake mode (no tree). Where a range of values is given, this indicates that there was substantial energy applied over the entire range. In some cases there was a dominant frequency however, and this is indicated by an underlined value.

Manufacturer	Shaker	Direction and Shaking frequency (Hz)		
		Right/Left	In/Out	Up/Down
A	Used	29.1	28.9	28.9
B	New	14.8 - 20.3	15.2 - 20.3	15.4
	Used #1	<u>16.0</u> - 20.3	<u>16.0</u> - 22.3	<u>16.0</u> - 20.3
	Used #2	14.5 - 25.0	15.6 - 25.0	17.5 - 20.0
	Used #3	16.3 - 21.3	14.9 - 21.4	14.8 - 21.4
	Used #4*	14.3 - 18.2	14.3 - 18.2	14.3 - 18.2
C	Used*	13.8 - <u>18.0</u>	<u>13.8</u> - 18.0	<u>0.4</u> - 18.0
D	New #1	<u>15.8</u> - 22.1	<u>15.8</u> - 22.1	<u>15.8</u>
	New #2**	15.0 - 20.7	15.0 - 20.7	15.0 - 20.7
	Used #1	20.2 - 27.6	20.0 - 27.6	20.0 - 27.6
	Used #2	15.6 - 21.3	15.6 - 21.3	15.6 - 21.3
E	Used	20.9 - 26.3	20.7 - 26.8	22.6 - 27.3
F	Used	14.2 - 24	16.0 - 24.2	24.3 - 29.5

* Prune shaker **Walnut shaker

was also substantial however, being 37% of the Right/Left value. The frequency data (Table 3) is more complex to interpret, because in most cases the data covered a wide range of frequencies.

Based on the literature, the typical almond trunk shaker vibrates at 15 - 25 Hz with a displacement of 8-12 mm, with higher frequencies and larger displacements considered as potentially damaging to the tree. We have found no research information regarding the acceptable range in the vertical direction (Up/Down), although it is reasonable to assume that any displacement in this direction would be unproductive for the purposes of harvest and also potentially detrimental to tree health. For vibration in the horizontal plane (Right/Left and In/Out), most shakers were within the 8-12 mm (Table 2) and 15-25 Hz (Table 3) range.

Table 4 presents the average of all tests performed on individual almond trees in the field during shaking for both displacement and frequency. In general, the frequency range experienced by the tree was similar to that applied by the shaker, which is to be expected. Also as expected, the displacements experienced by the tree are less than those applied by the shaker, with the Right/Left displacement being the highest. The average Up/Down displacement was 3.3 mm, which represents a significant proportion (44%) of the average Right/Left value. From the standpoint of the tree, then, it can be said that it experiences lifting displacements that are close to half of the value of shaking displacements.

Table 4. Average displacement and frequency measured on all trees tested.

Manufacturer	Shaker	Tree age (& Diameter)	Displacement (mm) Frequency (Hz)		
			Right/Left	In/Out	Up/Down
A	Used	5 yr. (7.2")	10.5 12.0 - 20.3	6.7 12.0 - 20.3	2.7 12.0 - 20.3
B	Used #2	12 yr. (10.7")	7.2 18.0 - 23.1	6.4 18.0 - 23.1	5.5 18.0 - 37.0
	Used #3	12 yr. (11.5")	5.7 15.2 - 22.6	6.1 14.5 - 22.6	3.9 13.6 - 34.8
D	Used #1	4 yr. (7.5")	9.0 20.3 - 28.1	3.3 20.1 - 28.1	2.4 20.2 - 28.1
	Used #2	5 yr. (7.1")	8.6 15.6 - 21.1	5.1 15.6 - 21.1	1.3 15.6 - 36.3
E	Used	2 yr. (4.9")	10.9 12.5 - 20.0	6.1 13.6 -17.2	5.5 12.5 - 20.0
		6 yr. (8.0")	13.7 14.0 - 19.2	6.1 19.0 - 21.1	3.9 13.6 - 19.2
F	Used	24 yr. (13.5")	4.4 16.4 - 20.7	2.3 16.4 - 20.7	1.5 16.4 - 33.2
Average displacement			7.6	5.2	3.3

We did not consider it a valid approach to compare shaker manufacturers based on displacement values alone, because it was clear that the lowest Right/Left displacements recorded were associated with the largest diameter trees, and the highest Right/Left displacements were associated with the smallest diameter trees (Table 4). Hence, our statistical analysis of the data was based on expressing the In-Out and Up-Down motion as a percent of the Right-Left motion (Table 5). The data indicated that there were statistically significant

Table 5. Ranked means of displacement (expressed as a percent of the Right/Left displacement to account for differences in tree size) for the different manufacturers and shakers used in this study. All data was collected under field conditions, for the shakers indicated in Table 4. The most important direction of displacement for a comparison of damaging potential is probably the Up/Dowm displacement. Means followed by the same letter are not different at the 5% level of DNMRT.

In/Out		Up/Down	
Manufacturer/Shaker	Displacement (% of Right/Left)	Manufacturer/Shaker	Displacement (% of Right/Left)
B (Used #1)	107 a	B (Used #2)	75 a
B (Used #2)	90 a	B (Used #1)	66 a
A (Used)	66 b	E (Used, 2yr. trees)	50 ab
F (Used)	60 b	E (Used, 6yr. trees)	30 b
E (Used, 2yr. trees)	56 bc	F (Used)	30 b
D (Used #2)	51 bc	D (Used #1)	28 b
E (Used, 6yr. trees)	45 bc	A (Used)	27 b
D (Used #1)	37 c	D (Used #2)	17 b

differences between manufacturers in both In/Out and Up/Down directions. High levels of displacement in both of these directions may indicate a potential stress on the tree bark, but because trees must be shaken evenly in all directions to get good nut removal, a high value for In/Out may be necessary. A high level of Up/Down displacement however, should not be necessary from the standpoint of harvest, and any value in this direction should be considered undesireable. One manufacturer (B) was significantly higher in this value than most of the others, having an Up/Down displacement of around 70%.

A number of additional tests and preliminary analyses were performed as part of this project, to determine what shaker properties might be obtainable from the data collected. For instance, it should be possible to determine both the shaker and the tree pattern of displacement. One example of this analysis is shown in Figs.7 - 10. By combining the Right/Left and In/Out displacements calculated for the shaker (Fig. 7) or tree (Fig 8), the shaking pattern for the shaker

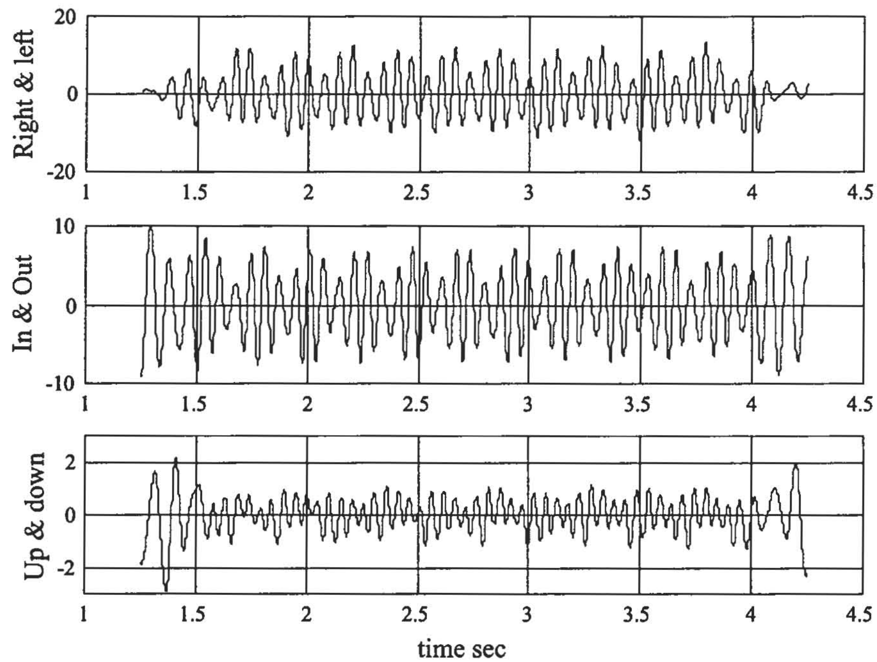


Figure 7. Displacements calculated on the shaker arm during a tree shake. The shaker used was B (Used #1).

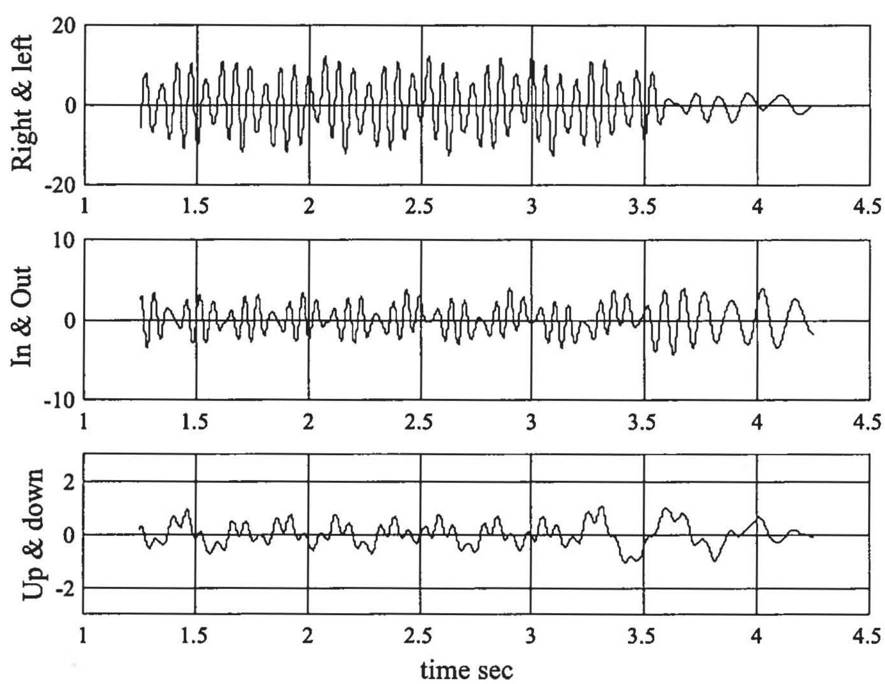


Figure 8. Displacements calculated on the tree trunk during the same shake as shown in Fig. 7.

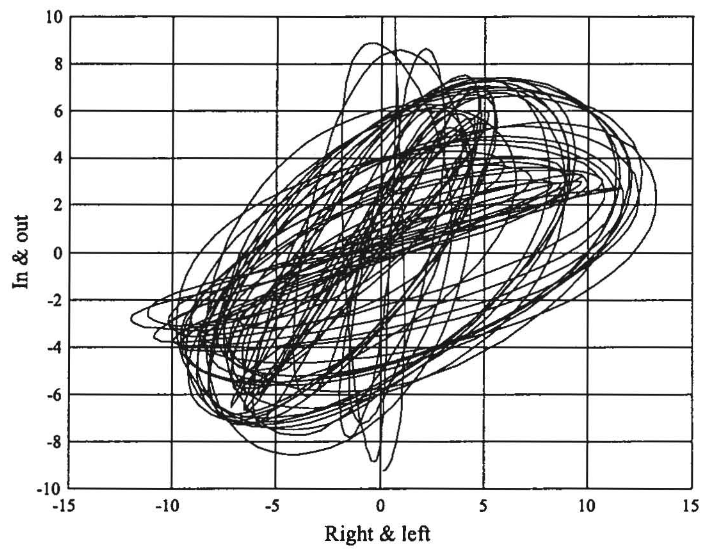


Figure 9. Shaking pattern calculated from the displacement data on the shaker (Fig. 7).

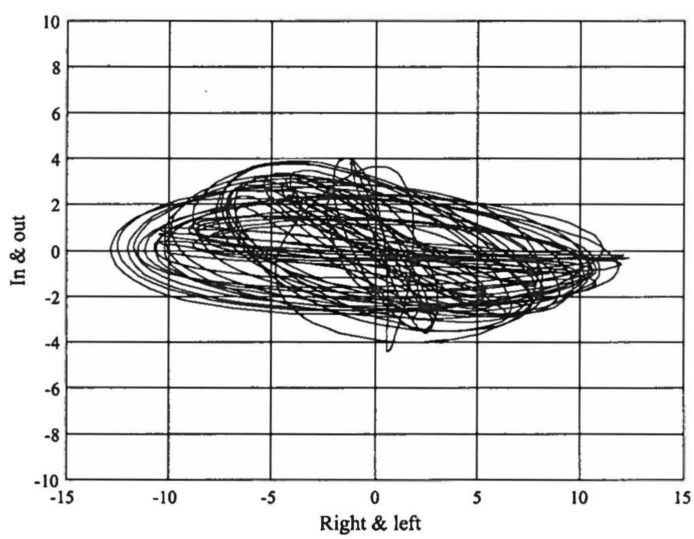


Figure 10. Shaking pattern calculated from the displacement data on the tree (Fig. 8).

(Fig. 9) or tree (Fig 10) could be obtained. This example suggests that the tree itself can substantially influence its own pattern of shaking, and determining this influence may allow a more accurate comparison between different shakers under typical field conditions. Further work is needed in this area. Most shakers can be adjusted to achieve different shaking patterns, but the patterns that we measured during a free shake and for the same shaker on the tree could be substantially different (Fig. 11).

Another important factor in shaking is the transfer of power from the shaker to the tree, and it was possible to calculate a power spectrum for both the shaker (Fig. 12) and tree (Fig. 13).

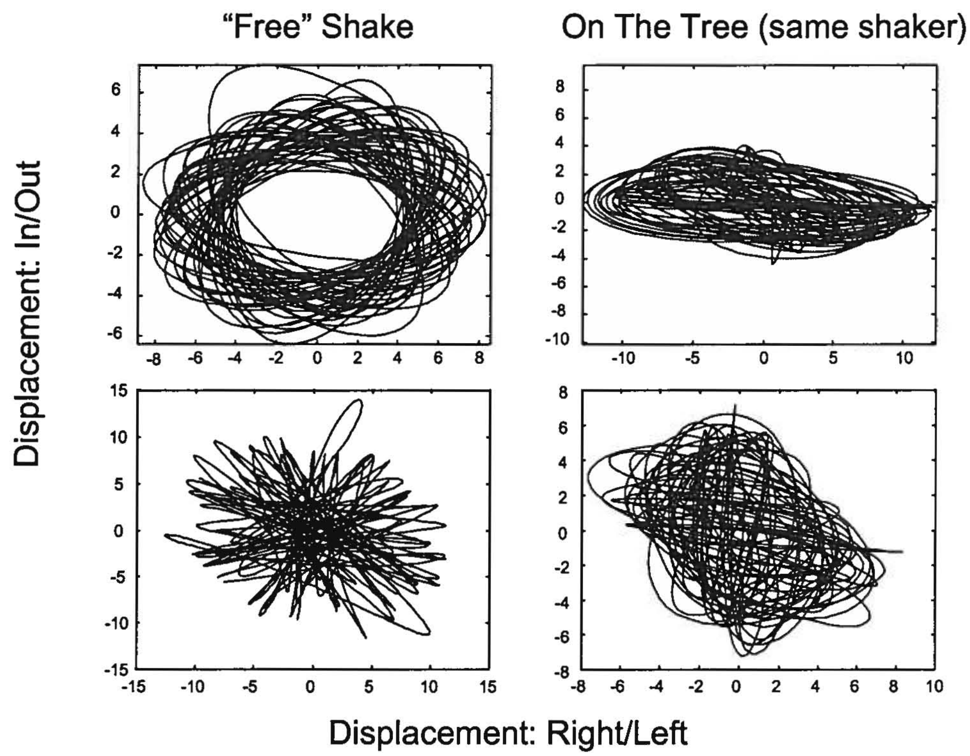


Figure 11. Examples of shaking patterns exhibited by shakers during a "free" shake (no tree) and those exhibited by a tree using the same shaker.

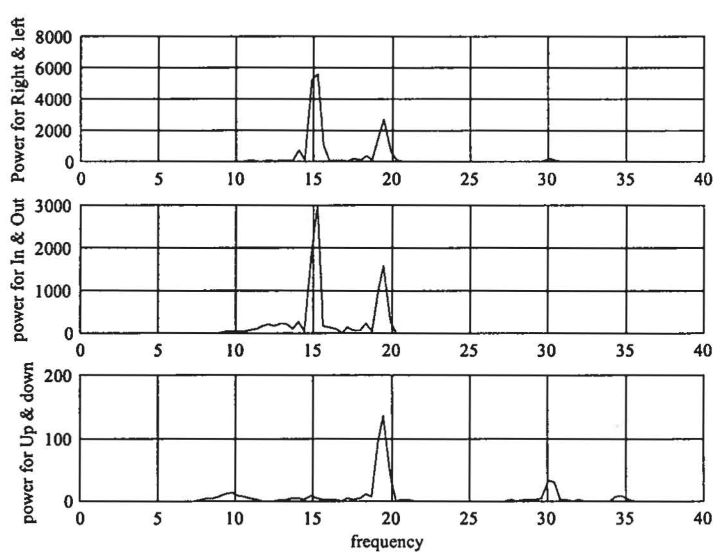


Figure 12. Power spectrum calculated for the shaker data shown in Fig. 7.

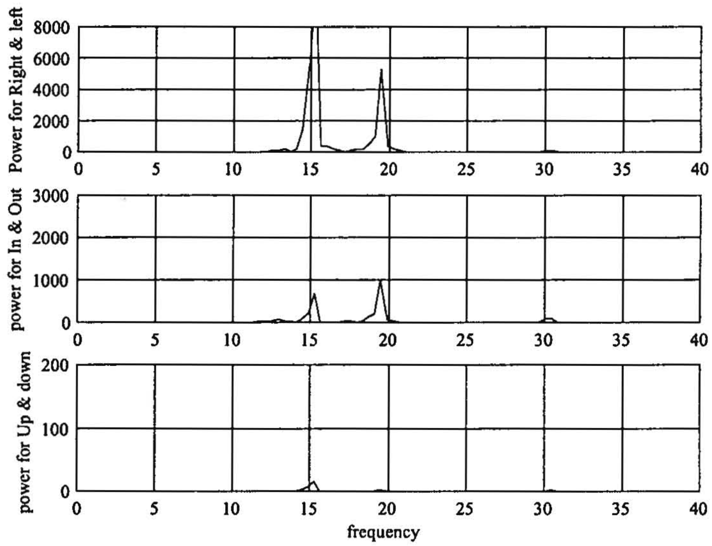


Figure 13. Power spectrum calculated for the tree data shown in Fig. 8.

Other factors that are under the control of the operator are engine RPM and pad choice. Engine RPM may be an important factor in shaker behavior, but over a wide range of RPM we found a relatively small influence on frequency and almost no influence on displacement in the free shake mode (Table 6). There was a trend towards higher frequencies and smaller displacements as engine RPM increased, and based on the mechanics of shaker operation this was the expected result. However, RPM had little influence in the amount of Up/Down displacement relative to Right/Left displacement.

Table 6. Effect of engine RPM on shaker arm displacement and frequency using the same shaker (Manufacturer B, shaker "New") in the free shake mode (no tree).

Engine Speed (rpm)	Direction and displacement on shaker arm (mm)			Direction and shaking frequency (Hz)		
	Right/Left	In/Out	Up/Down	Right/Left	In/Out	Up/Down
1400	9.9	8.4 (85%)	2.7 (27%)	14.6-19.2	14.6-18.8	14.2
1700	10.0	8.7 (87%)	2.2 (22%)	15.2-19.9	15.4-19.9	15.4
2000	9.4	7.7 (82%)	2.1 (22%)	18.2-24.4	18.9-24.4	19.0

On one occasion (Manufacturer A) we were able to test the effect of pad type on the displacemet and frequency observed in the tree, as well as calculate how much of the power (as in Figs. 12 and 13) was transmitted to the tree. The results of these tests (Tables 7 and 8), showed that pad type had essentially no effect on shaking frequency, which is not surprising, but also had very little effect on tree displacement (Table 7). In this test, pad III was a "filled" pad, and it was expected that this pad would transmit power more efficiently to the tree. There was a much higher effeciency of power transfer in the Right/Left direction using this pad (Table 8), but also a higher effeciency in the Up/Down direction, which is probably undesireable. With further study into this area, we should be able to develop a sound set of criteria for the evaluation of potential shaker injury by different shaker and pad systems.

Table 7. Effect of different pad types (III = "filled" pad) on displacement and frequency during shaking on the tree. The shaker manufacturer was "B."

Pad Type	Direction and tree displacement (mm)			Direction and frequency (Hz)		
	Right/Left	In/Out (% of R/L)	Up/Down (% of R/L)	Right/Left	In/Out	Up/Down
I	10.1	1.35 (13.6%)	0.57 (5.6%)	13.2	13.2	12.9 - 27.2
II	10.2	1.29 (13.1%)	0.63 (6.4%)	13.3	13.3	12.9 - 27.0
III	9.5	1.22 (11.6%)	0.71 (7.5%)	13.5	13.5	13.7 - 27.5

Table 8. Power transfer from the shaker to the tree for the pad test shown in Table 7.

Pad Type	Direction and % of power		
	Right/Left	In/Out	Up/Down
I	41.8%	2.5%	1.7%
II	49.9%	2.4%	1.8%
III	96.1%	4.0%	9.3%

Conclusions:

All of the shakers tested were within the range that has been recommended for frequency and displacement in the horizontal plane (Right/Left and In/Out), but in addition, all exhibited a significant displacement in the vertical direction (Up/Down). The averaging of this Up/Down displacement for all shakers was 44% of that in the horizontal plane, but there also appear to be significant differences between shaker manufacturers, covering a range of 17% - 75%. This direction appears to have been ignored in the scientific literature, and could be responsible for some of the barking damage that occurs in orchards. It is also possible that displacement in this direction causes some damage to the root system, which may have consequences for disease and other related problems in the long term. It may be possible to develop alternative shaker designs in the future that minimize this problem, but in the meantime these findings underscore the importance of maintaining shaker pad slip-belts in good operating condition, since they are critical to minimizing shearing forces on the bark. A standardized instrumentation system would be very helpful in making objective, scientific comparisons of the potential for barking injury from different shaker and pad systems.