ASSESSMENT OF VIBRATION INJURY TO BARTLETT PEARS

D. C. Slaughter, R. T. Hinsch, J. F. Thompson
MEMBER ASAE — MEMBER ASAE

ABSTRACT. *Laboratory tests revealed that palletized fiberboard boxes of Bartlett pears are most susceptible to bruising damage at vibrational frequencies below 40 Hz (cycles/s), which are common in refrigerated highway trailers. Damage studies indicate that of the four frequency regions observed in-transit (3.5 Hz, 9 Hz, 18.5 Hz, and 25 Hz), Bartlett pears are most severely damaged at 3.5 Hz and 18.5 Hz. Laboratory studies also show that fiberboard boxes of pears amplify vibration at frequencies below 40 Hz such that, for some frequencies, the lid of the top box in a pallet is accelerated three to four times more than the level input to the bottom box.* **Keywords.** *Vibration, Pears, Injury, Transportation.*

Fresh produce is often damaged when transported in highway trailers and the problem is particularly acute for California produce because several of the major U.S. domestic markets (e.g., Chicago or New York) are 3000 km or more from the areas of production. In a study of produce losses, Pierson et al. (1982) estimated that the losses during transport for the U.S. fresh fruit and vegetable industry in 1977 were between \$268 million and \$380 million (1977 dollars). Ceponis and Butterfield (1974) estimated that mechanical injury due to transportation caused a 4% loss in pears at the retail level.

Bartlett pears, because of their fragile nature, can be damaged when excessively vibrated in-transit. In many cases, the physical damage will lead to attacks by microorganisms and physiological changes which may increase the deterioration of these products. Sommer (1957) found that surface discoloration was caused by vibration in-transit and, although the internal flesh of the fruit was not affected, the surface damage seriously affected marketability. Vibration often causes the fruit to rotate, forming a discolored region or dark band around the fruit called "roller bruising". In addition, Sommer found that vibration-damaged fruit loses moisture more rapidly than undamaged fruit, further reducing its quality. O'Brien et al. (1963) found that the extent of bruising in fruit in-transit depended upon the frequency, amplitude, and duration of applied vibration as well as the initial condition of the fruit.

O'Brien et al. (1963) observed that in-transit vibration damage most frequently occurs in the top layers of fruit in containers without restraint from above and that the fruit in the top container of a column stack is often more severely damaged than those below. O'Brien et al. (1963) further observed that as accelerations approached 1 g, the top fruits moved freely allowing the fruit to impact against other fruit below. Researchers (e.g., O'Brien et al., 1965; Godshall, 1971; Garrett et al., 1976) found that in simulated transit tests (using sinusoidal vibration) acceleration levels were positively correlated with position in a column stack of containers, and that amplification within the column was as high as 6.7 at resonance.

Sommer (1957) studied the vibration damage in tightly and loosely packaged Bartlett pears with and without pads. He subjected pears packed in full telescope fiberboard boxes to sinusoidal vibration of 1 g (in both the horizontal and vertical directions) at a frequency of 8.5 Hz for 1.5 h. Fruit from each packaging treatment were then evaluated on a 0 to 5 scale with 0 representing no surface discoloration and 5 being severely discolored. The fruit for this study was sorted prior to testing so that only non-bruised fruit was tested (Mitchell, 1991). Sommer found that fruit which was packed tightly with a pad between the fruit and the carton top had very little discoloration (average score = 0.33), fruit which was tightly packed and without a top pad was slightly damaged (average score = 1.51), and fruit which was not tightly packed and without a top pad was severely damaged (average score = 4.24). He also found that placing pads under the fruit (in the bottom of the container) did not reduce vibration injury.

O'Brien et al. (1965) determined the average natural frequency of containers of fruit by conducting bulk compression tests to determine the bulk modulus of elasticity and modeling the system after a single degree of freedom lumped mass system. They predicted that the natural frequency of pears is inversely proportional to fruit column height and that for pear depths of 24 in. to 12 in. the natural frequency was 30 Hz to 50 Hz, respectively. Chesson and O'Brien (1971) studied the vibration characteristics of bulk containers of fruit by measuring the modulus of elasticity of individual fruit and modeling the elasticity of a column of fruit after a column of identical elastic spheres. This technique allowed Chesson and

Article was submitted for publication in September 1992; reviewed and approved for publication by the Power and Machinery Div. of ASAE in June 1993. Presented as ASAE Paper No. 92-6034.

Mention of a proprietary product does not constitute an endorsement or recommendation for its use by the University of California or the USDA.

The authors are **David C. Slaughter**, Assistant Professor, University of California, Davis; **R. Tom Hinsch**, Agricultural Marketing Specialist, USDA-Agricultural Research Service, Fresno, CA; and **James F. Thompson**, Extension Agricultural Engineer, University of California, Davis.

O'Brien to estimate a single resonant frequency for a bulk container of fruit; however, they had limited success validating their model with actual vibration tests.

Objective

The objective of this study was to characterize the frequency response of palletized fiberboard boxes of fresh market Bartlett pears to vibration, and to investigate the relationship between specific vibration frequencies observed in-transit and physical damage to Bartlett pears.

Procedure

Palletized loads and individual boxes of Bartlett pears were vibrated in the laboratory using the American Society of Testing and Materials (ASTM, 1989) Standard Test Method D999-86. The pears were packaged in nominal 36 lb "tight-fill" (Mitchell et al., 1968), full telescope boxes constructed of 275 lb test, curtain-coated, corrugated fiberboard. Each box had outside dimensions of 30.48 cm × 23.50 × 45.72 cm (12 in. × 9.25 in. × 18 in.) and had ten 2.54 cm × 8.89 cm (1 in. × 3.5 in.) vertical vent holes, three in each side and two in each end. The boxes were commercially volume filled and vibration settled, and were closed with a single strap encircling the middle of the box. A single macerated paper pad 35.6 cm × 29.2 cm × 0.85 cm (14 in. × 11.5 in. × 0.33 in.) was placed on the top of the fruit after filling and before vibration settling and box closure. No padding was placed between the box bottom and the fruit. The average moisture content of the fiberboard in the boxes ranged from 13% to 14.2% at the time of testing. The boxes were palletized in cross-stacked configuration shown in figure 1, with nine boxes per layer, stacked six layers high. The first three layers were column-stacked in register and the top three layers were cross-stacked. This pattern provides a central "chimney" for temperature management of the fruit. The boxes were held in place by "palletizing glue" which is strong in shear but not in tension. No straps or wrapping material were used to consolidate the pallet. The average pulp temperature of the pears during testing was 5° C (41° F). The palletized loads of pears were transported from the cold storage facility in the California Bartlett pear river district to the laboratory, a distance of approximately 112 km (70 miles). The individual boxes of pears were transported from the California Bartlett pear lake district to the laboratory a distance of approximately 339 km (130 miles). All treatments, including the controls, were subjected to the same base level of damage incurred in harvest and post-harvest handling and transportation.

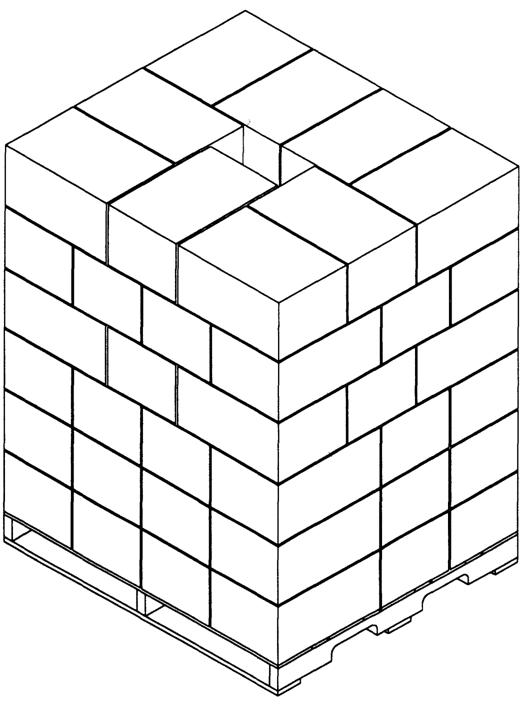

Figure 1–Cross-stacking pattern used to palletize shipments of Bartlett pears.

Vibration Sweep Tests

A vibration sweep test was conducted on each of four replicate pallets (fruit size was 135 fruit per box) of Bartlett pears according to the ASTM Method C of Standard Resonance Test D999-86. A pallet of pears was placed on a foundation-mounted, servo-hydraulic vibration table (Lansmont Corp., Pacific Grove, CA) in a room with an average air temperature of 21° C (70° F) and subjected to sinusoidal vibration of 0.25 g (zero-to-peak) acceleration at a frequency that was swept at a continuous logarithmic rate of 1 octave/min from 2 Hz to 100 Hz and back to 2 Hz. The transmissibility of vertical vibration through the pallet was measured by two accelerometers, one was mounted to the vibration table and the second was attached (using double-sided adhesive) to the lid of a box of pears on the top of the pallet.

Vibration transmissibility data from the pallet load of pears was compared with data from cross-country refrigerated transit tests conducted by Hinsch et al. (1992) using the same packaging techniques described previously. Shown in figure 2 is the acceleration spectral density versus frequency for the top box of the rear pallet in a shipment of Bartlett pears from California to New York. The 48-foot long, refrigerated highway trailer was equipped with a steel spring suspension (Series 7600-7700-7800, Hutchens Industries, Inc., Springfield, MO). The tractor also had a steel-spring suspension.

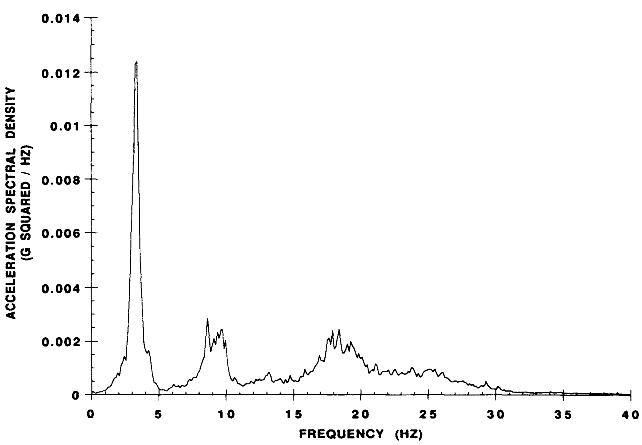

Figure 2–In-transit vertical vibration of the top rear box in a refrigerated trailer equipped with a steel spring suspension and loaded with pears, California to New York, 1991.

Vibration Dwell Tests

Following the suggestion of Harris (1988), vibration dwell tests at specific frequencies were then conducted at frequencies where the refrigerated trailer floor exhibited high acceleration spectral density levels and where the pallet load exhibited vibration amplification. Two separate tests were conducted. The first test was set up in a randomized complete block design with four replicates of two sizes of pears (135 fruit/box and 100 fruit/box) and four sinusoidal frequencies (3.5 Hz, 9 Hz, 18.5 Hz, and 25 Hz), all at a peak acceleration of 1 g. The second test was set up identically to the first except that acceleration at each frequency was based upon the normalized root mean square (rms) value exhibited by the trailer within a 3 Hz band of the frequency of interest (3.5 Hz @ 1g, 9 Hz @ 0.67g, 18.5 Hz @ 0.75g, and 25 Hz @ 0.5g). In all tests, the boxes of fruit were vibrated for 30 min. The time length of the treatment was based upon observations by Guillou et al. (1962) that a dwell test at an acceleration of 1.1 g for 30 min produced damage levels in Bartlett pears similar to that observed in actual transcontinental rail shipments. A set of four boxes of fruit of each size was not vibrated to serve as a control. After the vibration treatments, the fruit was held at room temperature for about 24 h and then evaluated for damage visible on the exterior of the fruit. Damage to the interior of the fruit was not evaluated.

Twenty fruit were randomly selected from top, middle, bottom, interior, and periphery of each box, and were then visually inspected by two evaluators. Each fruit was scored on a six-point scale used by Sommer (1957) and Gentry et al. (1965) where 0 = no damage, 1 = trace, 2 = slight, 3 = moderate, 4 = severe, and 5 = extreme. Fruit with damage levels of 4 and 5 were considered unmarketable.

Results and Discussion

Vibration Sweep Tests

The vibration transmissibility of a pallet of Bartlett pears to vertical vibration is shown in figure 3. This figure shows at which frequencies the pears in the top boxes of a pallet load vibrate at higher acceleration levels than the vibration table (transmissibilities greater than one) and at which frequencies the top boxes vibrate at lower levels than the vibration table (transmissibilities less than one). The two curves on this plot show the envelope (or minimum and maximum levels) observed during the test. The large envelope at frequencies between 2 Hz and 5 Hz make interpretation of the results in this region difficult and indicate a need for further study. This figure is typical of the four replicated tests conducted. The data show that palletized pears amplify vibration from the bottom box to the top box at frequencies between 2 and 40 Hz and attenuate vibration at frequencies between 40 and 100 Hz. Whenever the transmissibility reached a level greater than or equal to 4, the top boxes of the pallet were subjected to accelerations greater than or equal to 1 g and broke free from the boxes below, becoming air borne at certain frequencies. This seems to indicate that in selecting packaging or trailer suspensions the frequencies between 2 and 40 Hz are the most critical. This data contradicts the assumption of O'Brien et al. (1965) that a pallet of pears can be modeled as a column of pears with a single resonant frequency while corroborating the observation from the cross-country tests conducted by Hinsch et al. (1992) that the top box vibrates at higher acceleration levels than the trailer floor in the frequency regions between 5 and 40 Hz. The wide range of resonant frequencies observed may be caused in part by variations in effectiveness of tight-fill packing, variability in fruit firmness, and variability in moisture content of the fiberboard cartons as well as the stacking pattern of cartons on the pallet.

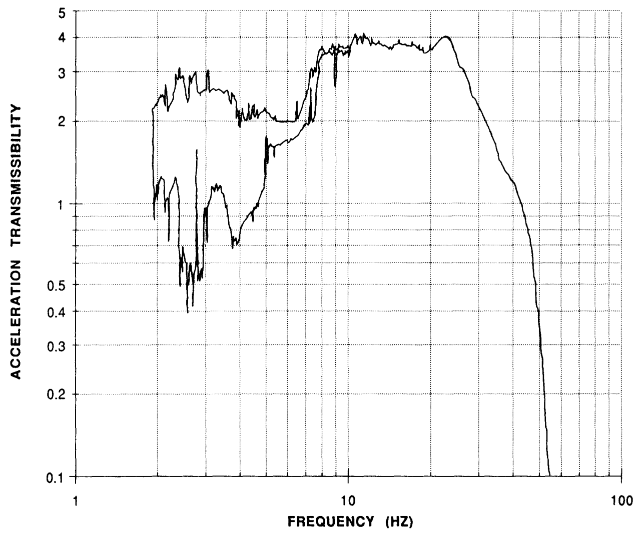

Figure 3–Transmissibility of vibration through a palletized load of Bartlett pears.

Vibration Dwell Tests

Shown in table 1 are the mean weight for two sizes of commercially packed tight-fill Bartlett pears collected for laboratory study. The standard tight-fill package for pears should be filled to a density of 616.4 kg/m^3 (38.4 lbs/ft^3) (Mitchell, 1991). The full telescope AFM (All Flaps Meet) box used had inside dimensions of 22.2 cm × 27.9 cm × 43.8 cm (8.75 in. × 11 in. × 17.25 in.) and required 16.8 kg (36.9 lb) of fruit to meet the density criteria for tight-fill. For the boxes in this study, which weighed approximately 0.9 kg (2 lb), the total weight should be about 17.7 kg (38.9 lb). As indicated in table 1, the boxes in this study were slightly underfilled. In order to reduce vibration damage by using tight-fill packaging the fruit must be immobilized; when the boxes are underfilled or if they are constructed such that the flaps do not meet, then a tight-fill will not be achieved. This problem is exacerbated by the fact that many packing lines cannot tolerate overfilled boxes without equipment failure and so there is a tendency toward underfilling. Further when the boxes are improperly constructed there is a tendency to construct boxes that are larger rather than smaller which also leads to a failure in achieving a tight-fill. Several boxes were

Table 1. Mean weight of tight-fill Bartlett pears after storage

Size	# of Boxes	Mean Wt. (kg)	S.D. (kg)	Minimum (kg)	Maximum (kg)
135	32	17.6	0.3	17.0	18.4
100	32	17.5	0.5	16.8	18.4

observed that were incorrectly assembled, with gaps between the flaps as large as 1.3 cm (0.5 in.).

Table 2 shows results from the first ASTM specific frequency test addressing the basic question of which frequencies of vibration are most damaging to Bartlett pears. All treatments in the first test were at a peak acceleration of 1 g. An analysis of variance was conducted for bruise score using a model that included the vibration treatment, the fill weight of the box, the size of the fruit in the box, and the interactions between these three. When the vibration treatment, the box fill weight and their interaction were included in the model, the addition of fruit size was not significant ($\propto = 0.05$) based on the Type II sum of squares analysis of variance procedure (SAS, 1992). Because the relationship between fruit size and vibration bruising was not significant, the effect of fruit size was ignored in all other analyses. The analysis of variance indicated that vibration treatment, fill weight, and their interaction were all significant ($\propto = 0.05$). The data in table 2 show that Bartlett pears are most susceptible to vibration bruising at 3.5 and 18.5 Hz. However, at an acceleration of 1 g all vibration treatments were significantly ($\propto = 0.05$) more damaging than the control.

In the second laboratory test the acceleration levels were adjusted to be proportional to that observed by the top box in the cross-country study, figure 2. The data in table 3 show that the 9 Hz and 25 Hz treatments were not significantly different from the control, but that the 3.5 Hz and 18.5 Hz treatments resulted in significantly more damage.

In both tests, vibration at frequencies of 3.5 Hz or 18.5 Hz was significantly more damaging to Bartlett pears than vibration at 9 Hz or 25 Hz. Reducing the acceleration at 9 Hz from 1 g to 0.67 g or from 1 g to 0.5 g at 25 Hz resulted in considerably less damage. However, pears will be damaged when vibrated at 18.5 Hz even though the acceleration is below 1 g. The damage to Bartlett pears at 3.5 Hz is of significant concern since it is difficult to attenuate low frequency vibration.

It is interesting to compare the results of this study with results published by Sommer (1957). The 9 Hz vibration treatment previously described is similar to Sommer's 8.5 Hz vibration treatment. As shown in table 2, commercially "tight-filled" packages with top pads had an average damage score of 1.17 after only 0.5 h of vertical vibration at 1 g and a frequency of 9 Hz. Sommer found that tightly packaged pears with top pads had an average damage score of 0.33 after 1.5 h of vibration at 1 g (in both the horizontal and vertical directions) and a frequency of 8.5 Hz. Since Sommer used blemish-free fruit in his test, the results of this study need to be adjusted by subtracting the damage observed in the unvibrated control (average score of 0.78) giving an adjusted average damage score of 0.39. Considering the difficulty in directly comparing subjective damage scores recorded by different researchers, the agreement between these two studies is quite good. This comparison indicates that Sommer did a better job of immobilizing the fruit because similar damage levels were obtained even while vibrating the pears three times longer and that immobilizing the fruit may significantly contribute to reducing in-transit vibration damage.

Table 2. Assessment of vibration bruising in Bartlett pears

Treatment*	Grouping†	Mean Bruising Score‡
18.5 Hz @ 1.0 g	A	1.72
3.5 Hz @ 1.0 g	A	1.70
25.0 Hz @ 1.0 g	B	1.41
9.0 Hz @ 1.0 g	C	1.17
Control	D	0.78

* Mean fruit firmness = 68.5 N (standard deviation = 7.6 N, probe diameter = 2.8 mm), mean soluble solids = 11.2% (standard deviation = 1.1%).

† Tukey's Studentized Range Test, $\alpha = 0.05$, MSD = 0.24. Means with the same letter are not significantly different.

‡ Bruising scores ranged from 0 = none to 5 = extreme.

Table 3. Assessment of vibration bruising in Bartlett pears

Treatment*	Grouping†	Mean Bruising Score‡
3.5 Hz @ 1.0 g	A	1.70
18.5 Hz @ 0.75 g	B	1.06
25 Hz @ 0.50 g	B, C	0.98
Control	C, D	0.78
9 Hz @ .67 g	D	0.72

* Mean fruit firmness = 68.5 N (standard deviation = 7.6 N, probe diameter = 2.8 mm), mean soluble solids = 11.2% (standard deviation = 1.1%).

† Tukey's Studentized Range Test, $\propto = 0.05$, MSD = 0.23. Means with the same letter are not significantly different.

‡ Bruising scores ranged from 0 = none to 5 = extreme.

Conclusion

Laboratory studies indicate that vertical vibration amplification can occur in a pallet of Bartlett pears between the frequencies of 2 and 40 Hz. For example, when the floor of the pallet was vibrating at an acceleration of 0.25 g, the top boxes of the pallet were subjected to accelerations greater than 1 g and broke free from the boxes below, becoming air borne at certain frequencies below 40 Hz. This is consistent with the observations made by Hinsch et al. (1992) in cross-country transit studies, that Bartlett pears vibrate at four frequency regions while in-transit (3.5 Hz, 9 Hz, 18.5 Hz, and 25 Hz). Vibration damage studies show that of these four frequency regions, pears are more severely damaged at 3.5 Hz and 18.5 Hz than at 9 Hz and 25 Hz. In summary, pallet loads of Bartlett pears are most susceptible to vibration damage at frequencies below 40 Hz, which are common vibration frequencies in refrigerated highway trailers.

Future work should concentrate on methods of reducing the amount of vibration reaching the bottom boxes, particularly at frequencies of 3.5 Hz and 18.5 Hz, and evaluating methods of packaging which will reduce bruising damage at these critical frequencies.

References

ASTM. 1989. Standard methods for vibration testing of shipping containers. Method D 999-86. Annual book of ASTM standards. Vol. 15.09:188-191.

Ceponis, M. J. and J. E. Butterfield. 1974. Retail and consumer losses of western pears in metropolitan New York. *HortScience* 9(5):447-448.

Chesson, J. H. and M. O'Brien. 1971. Analysis of mechanical vibration of fruit during transportation. *Transactions of the ASAE* 14(2):222-224.

Garrett, R. E., J. J. Mehlschau, L. R. Erickson, Jr., R. F. Drown, L. L. Morris and A. A. Kadar. 1976. Lettuce handling systems. Research Progress Report. California Iceberg Lettuce Research Program Advisory Board. Salinas, CA.

Gentry, J. P., F. G. Mitchell and N. F. Sommer. 1965. Engineering and quality aspects of deciduous fruits packed by volume-filling and hand-placing methods. *Transactions of the ASAE* 8(4):584-585, 589.

Godshall, W. D. 1971. Frequency response, damping, and transmissibility characteristics of top-loaded containers. USDA Forest Service Research Paper, FPL 160.

Harris, C. M. 1988. Shock and Vibration Handbook, 3rd Ed. 20-7 to 20-9. New York: McGraw-Hill.

Hinsch, R. T., D. C. Slaughter, W. L. Craig and J. F. Thompson. 1993. Vibration of fresh fruits and vegetables during refrigerated truck transport. *Transactions of the ASAE* 36(4):1045-1048.

Mitchell, F. G., N. F. Sommer, J. P. Gentry, R. Guillou and G. Mayer. 1968. Tight-fill fruit packing. California Agricultural Experiment Station Extension Service. Circular 548.

Mitchell, F. G. 1991. Personal communication. Pomology Department, University of California, Davis.

O'Brien, M., L. L. Claypool, S. J. Leonard, G. K. York and J. H. MacGillivray. 1963. Causes of fruit bruising on transport trucks. *Hilgardia* 35(6):113-124.

O'Brien, M., J. P. Gentry and R. C. Gibson. 1965. Vibrating characteristics of fruits as related to in-transit injury. *Transactions of the ASAE* 8(2):241-243.

Pierson, T. R., J. W. Aleen and E. W. McLaughlin. 1982. Produce losses in the U.S. food distribution system. Michigan State University Agricultural Economic Report. 442.

Sommer, N. F. 1957. Surface discoloration of pears. *California Agriculture* 11(1):3-4.