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The evaluation of vibration damage in fresh apricots during simulated transport

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Abstract: The transportation of fruits over longer distances could lead to damage fruits such as apricots. The present study was conducted to evaluate the effect of transportation factors including the vibration frequencies (17 and 20 Hz), the vibration time (15 and 30 minutes), the fruit cultivar (Shahroudi and Urdoobad), and the package type (2 types) on the apricot damage. An electro-dynamic lab vibration simulator was used to simulate the road transportation and a fruit damage index (FDI) was used as a criterion to evaluate the damage based on the classifying bruises into five different categories. The statistical analysis indicated that, except for the package type, the other factors (apricot cultivar, frequency, and vibration duration) had a significant effect on the FDI ($P < 0.01$). The vibration damages considerably changed by the apricot cultivar and increased by the frequency and duration. The results indicated that the Urdoobad cultivar was more resistant to the damage and could be used for export purposes to transport in distances more than 1,000 km. The maximum damages occurred at a frequency and duration of 17 Hz and 30 min in the Shahroudi cultivar, respectively.

Keywords: transportation; bruising; fruit damage index; package design; packaging transmissibility

The globalization of the trade in fresh fruit has created the need for more transport systems and efficient handling methods that can maintain a product's quality over longer distances. During transportation, around 30–40% of the agricultural products become decayed due to mechanical damage (Opara, Pathare 2014). Mechanical damage mainly occurs from the orchard to the market in the transportation process, and the vibration during transportation is the main cause of the mechanical damage to the fruits and vegetables (Remón et al. 2003). Vibration injuries take place when fruits are subject to vibratory forces, such as those during transportation. Therefore, there has been increasing attention being paid to improving transportation features and the development of appropriate packaging to minimize product damage (Lu et al. 2008). For this reason, more research has been carried out to investigate the effect of vibration on the mechanical damage to different fruits, such as kiwifruits (Wei et al. 2019; Tabatabaekoloor et al. 2013), watermelons (Shahbazi et al. 2010), apples (Soleimani, Ahmadi 2015), and pears (Li et al. 2011; Zhou et al. 2007). Many researchers reported that the main reason for the in-transit fruit injury is a vertical vibration, because the vertical vibration levels are much higher than the others (Chonhenchob et al. 2010). Therefore, they have neglected the lateral and longitude vibration components in their investigations in the past (Van Zeebroeck et al. 2006; Vursavus, Özgüven 2004). Besides, the best method to perform vibration tests is under real road conditions, but it is quite difficult to control the variables under the real conditions; so, random or sinusoidal

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vibration signals have been used in the laboratory-controlled conditions (ISO 2001/FDIS-13355).

Research on many types of fruit and vegetables has revealed that the majority of the vibration damage occurs in a very narrow range around the resonant frequency (Eissa, Hafiz 2012), which makes the fruit to become virtually weightless in their boxes, and makes the fruits rub against each other and push together as they rotate (Mahajerin, Burgess 2010).

The quantity and quality of the fruit vibrational damage depends on the imposing vibration characteristics (frequency, amplitude, and duration), the fruit properties, the container design (size, material, etc.), the truck suspension system, the fruit placement pattern in the package, and the depth of the fruit packages (Acıcan et al. 2007; Van Zeebroeck et al. 2006). Among these factors, the fruit response to the vibration inputs is influenced by the cultivar, the maturity stage, and other factors (Woodroof 2012). For example, Tabatabaekoloor et al. (2013) evaluated the effect of the frequency, acceleration, fruit size, and stack height levels on the kiwifruit's vibrational damage. They reported that all the investigated factors had a significant effect on the kiwifruit damage ($P < 0.01$) and increasing each of the factors (frequency, acceleration, fruit size, and stack height) considerably increased the mechanical damage.

In some fruit like apricots, due to the thin flesh of the fruit and a hard kernel, it is very difficult to detect the fruit injuries and determine the boundaries of the affected area, as the bruise shows very little colour change in the skin of fruit (Salamolah et al. 2010). For this reason, some researchers define the severity of the bruised area by classifying, based on a visual inspection. Kappel et al. (2009) used this method and classified sweet cherries into different scales including no bruising, slight bruising, moderate bruising and severe bruising. Also, Jiménez-Jiménez et al. (2013) visually inspected olive bruising damage and put each fruit into a category with a 5-level scale according to the severity of the fruit's bruising. Iran is one of the major fresh apricot producers and has the second rating among the producers in the world after Turkey (Hazbavi 2013). Iranian apricots are well known in the world because of their quality, quantity, and colour (Ghaebi et al. 2010). Apricots are more sensitive to the damages caused by post harvesting and especially the transportation processes, because of its high moisture content and low peel resistance. Therefore, this fruit usually suffers a lot of mechanical damage during transportation. However, a review of previous studies about fruit injuries has indicated that there are not many research studies about the vibration damage of apricots, especially Iranian apricot cultivars, and there is a lack of research in this area. Therefore, the main aims of the present study were: (*i*) the simulation of real road vibrations by means of an electro-dynamic shaker in the lab (*ii*) the measurement of the apricot fruit's natural and dominant frequencies during transportation (*iii*) the measurement and compartment of the packaging transmissibility for the two types of boxes used in this study (*iv*) the investigation of the effects of the vibration parameters such as the vibration frequency and duration, and the package type on the mechanical damage of two varieties of Iranian apricots during transportation, in order to reduce the mechanical damage.

MATERIAL AND METHODS

Fruit harvesting and preparation. In the present study, all the tests were carried out with "Shahroudi" and "Urdoobad" cultivars of the Iranian apricot. All the fruits were harvested at their traditional maturity in June 2016 from Sahand Research Institute, Iran. In order to minimise any pre-bruising, all of the apricots were carefully hand-picked and placed in special packages covered with protective materials and were transferred to the laboratory. The apricots were kept in a refrigerator with a temperature of 0–4°C and 85% humidity. The physical properties of apricots and main characteristics such as mass, moisture content and major dimensions including length (L), width (W), thickness (T) and sphericity were measured. In addition, very large or small apricots were excluded from the investigation. The modulus of elasticity (as a criteria of the apricot's firmness) was measured using a compression plate test on a universal testing machine ZwickRoell Co., Z010 model (Zwick Roell Group, Germany), as shown in Fig. 1. A few apricots were randomly selected from each cultivar and their modulus of elasticity was measured using the following equation (Mirzaee et al. 2009; Hacıseferoğulları et al. 2007; O'Brien et al. 1965):

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$$E = \frac{F}{\pi\delta^2} \quad (1)$$

where: E – the elasticity modulus of the fruit (MPa), F – the compression force (N), and δ – the deformation of one side of the fruit

(a) (b)

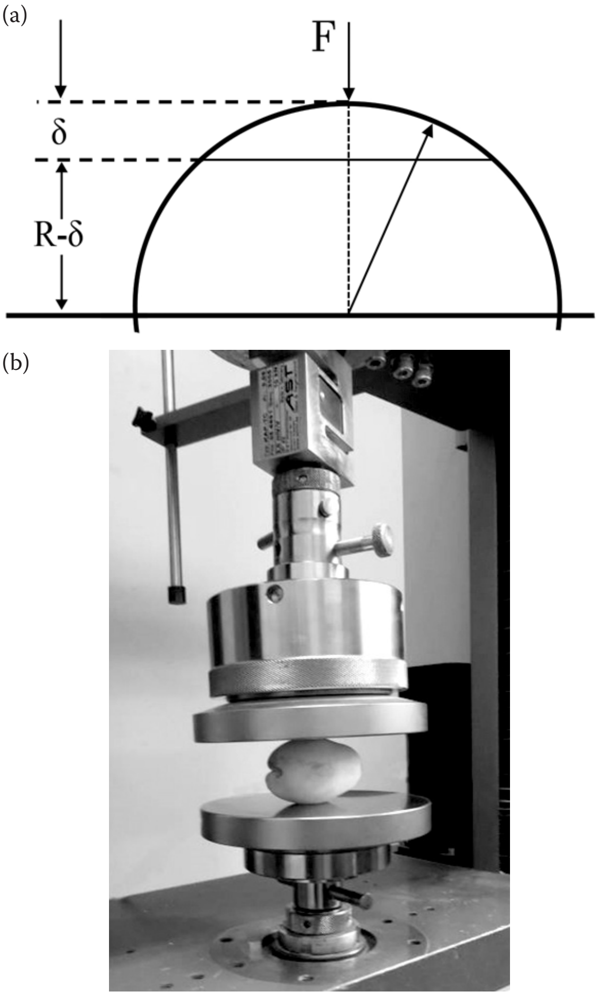

Fig. 1. (a) Forming of the deformation in measuring the elastic module and (b) measuring the elasticity modulus of the apricot using a universal testing machine

Properties of the apricot packages. All the experiments in the present study were conducted using two different types of reusable plastic containers (RPCs). These two packages were chosen among the various packages that are used in the local fruit market for the packaging of fruits like apricots, type A and B (Fig. 2). The type A package dimensions were 360 × 240 × 80 mm and could hold two layers of apricots giving a total number of 60 apricots, and weighing approximately 3 kg with the apricots. The type B package dimensions were 350 × 230 × 130 mm, weighing approximately 4.5 kg with the apricots, which could hold three layers of apricots giving a total number of 90 apricots. In addition, both packages were filled with apricots without any special order and no caps were used to close the packages.

(a) (b)

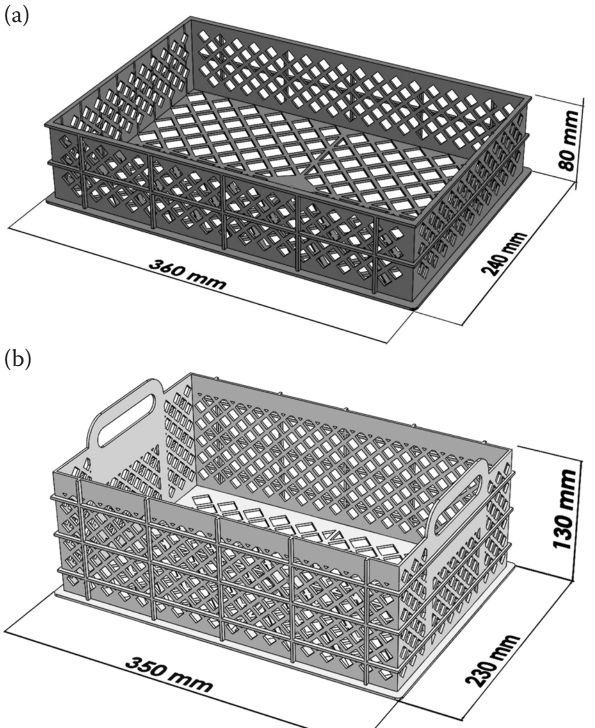

Fig. 2. The two different types of the packages used in the vibration tests: (a) the box with a 3 kg apricot capacity and (b) the box with a 4.5 kg apricot capacity

Vibration tests' procedure. Prior to the vibrating tests, the fruit packages were taken out of the refrigerator and stored at the laboratory temperature (24°C) for at least 4 hours. An electro-dynamic vibration simulator driven by a power amplifier was used. A large framework was fastened on top of the simulator and the apricot packages were placed inside the framework so that packages could move freely in three dimensions inside the framework. A four-channel data acquisition system (PULSE system, model 3564, Brüel & Kjær, Denmark) with a signal conditioning amplifier (NEXUS, Brüel & Kjær, Denmark) was used to amplify the signals, then the signals were processed using a PULSE® program (version 12) and Fast Fourier Transform (FFT) was performed to obtain the frequency spectrum of the signals. Fig. 3. shows the schematic plan of the system used for the vibration tests. Two piezoelectric accelerometers (Bruel & Kjær) were

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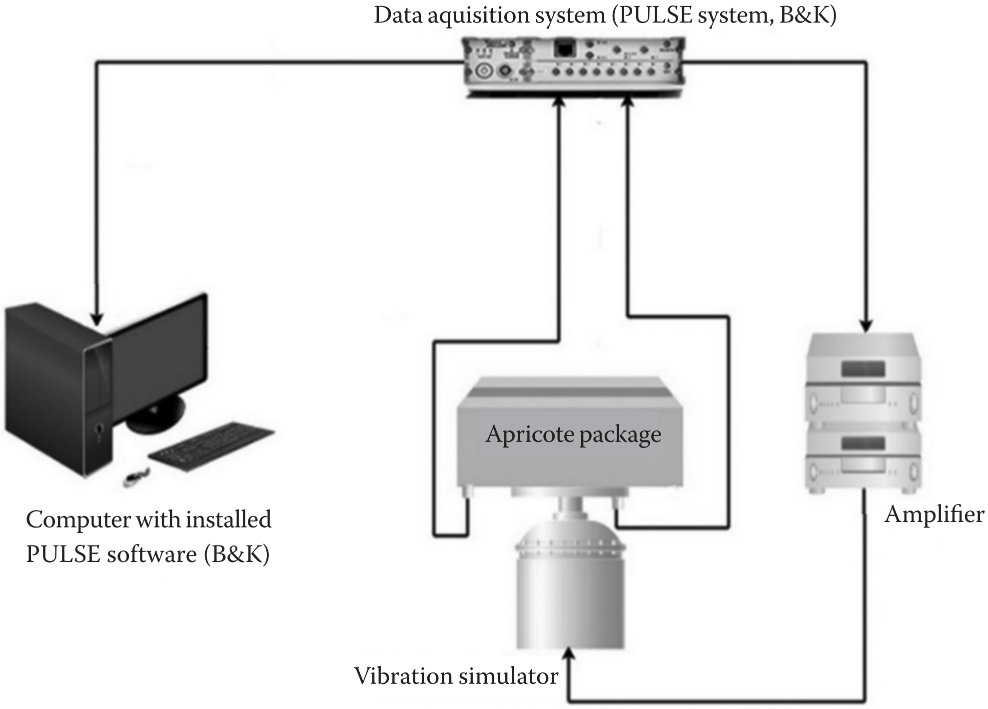

Fig. 3. The schematic plan of the system used for the vibration tests

used which could only detect the vertical accelerations. One of the accelerometers was fixed to the framework as a reference and the other one was embedded in the middle of an apricot. To do this, the fruit was carefully cut through the middle with sharp razor and the stone was replaced with the accelerometer (Fig. 4). The accelerometer was firmly ground inside the apricot to create a good connection between the accelerometer and the fruit. In addition, to ensure that the accelerometer was kept vertically during the tests, it was bound by invisible threads (not shown in the Fig. 4) and the surrounding fruit inside the package.

As mentioned earlier, most fruit damage occurs at the resonance frequencies, therefore, firstly, a simple sinusoidal sweep mode test (with at least

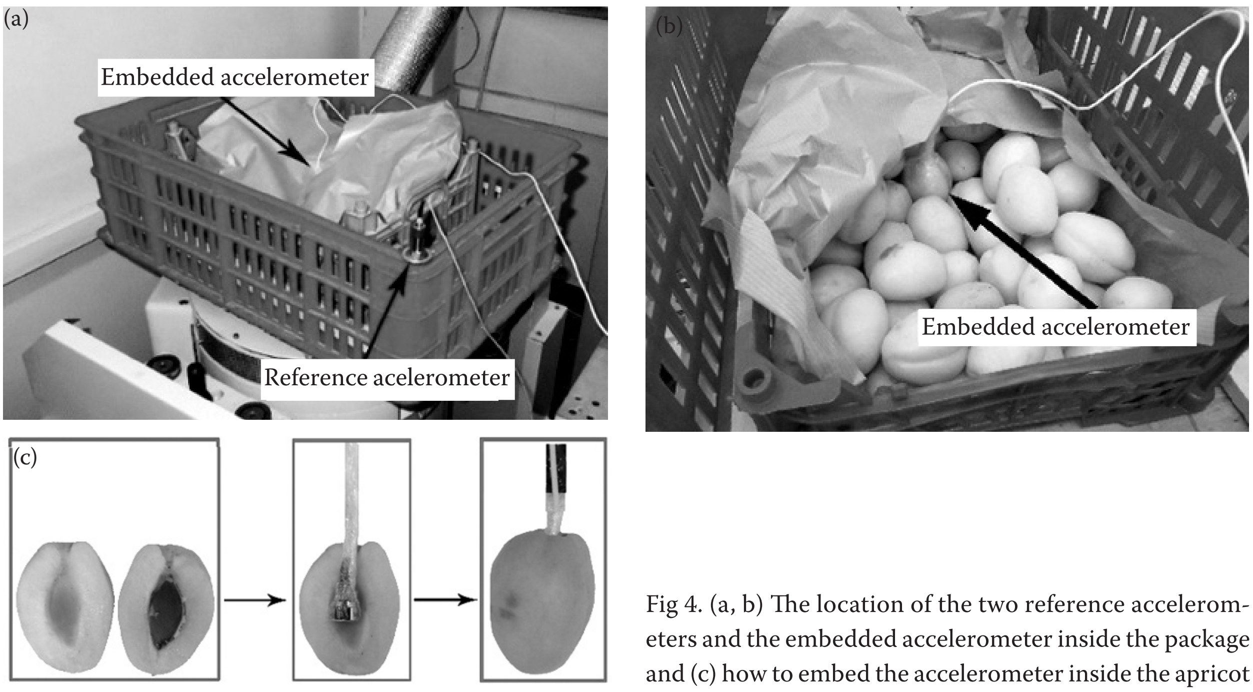

Fig 4. (a, b) The location of the two reference accelerometers and the embedded accelerometer inside the package and (c) how to embed the accelerometer inside the apricot

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3 replications) was undertaken to determine the first and second natural frequency on both packages. The ASTM D999 (ASTM 2015) standard was adopted for the vibration tests and the frequency ranges of 5 to100 Hz which is normally encountered during road transportation was selected for the sweeping (Chonhenchob et al 2010; Chonhenchob et al 2008). Based on the data gained from the sweep tests, the first and second natural frequency of the Shahroudi cultivar were 17 and 20 Hz, and were 17 and 19 Hz for the Urdoobad cultivar, respectively. Therefore, the 17 and 20 Hz frequencies were used in all of the vibration tests to investigate their effect on the apricot damage. Also, the pre-tests indicated that there were no significant changes in the accelerations at the different areas and the different depths of the packages, which is similar to the result that was reported previously by O'Brien and Guillou (1969) about apricot fruit (Blenheim cultivar). Therefore, the accelerometer was only placed in the middle of the packages during all of the tests. Two different vibrational periods including 15 and 30 minutes were investigated in this study, where the duration of 15 minutes and 30 min was considered as the equivalent of transportation distances less than 1,000 km and greater than 1,000 km (Shahbazi et al. 2010), respectively. A constant acceleration value of 0.7 g (the average acceleration of a truck's bed on asphalt roads) was used in all the vibration tests. Also, the packaging transmissibility was calculated using Eq. (2) at the frequencies between 5 to 23 Hz at intervals of 3 Hz (Idah et al. 2012):

$$P_T = \frac{a_b}{a_t} \times 100 \quad (2)$$

where: P_T – the packaging transmissibility (percentage); a_b – the measured acceleration on the package (g); a_t – the applied acceleration from the simulator (g)

According to Eq. (2), P_T is a dimensionless parameter and it indicates that how much the simulator acceleration has been transmitted to the package at a certain frequency. This parameter is useful to determine the frequencies at which the vibrating system are sensitive to it and generally, the maximum transmissibility occurs at the resonant frequencies of the vibrating system.

Apricot damage measurement and analysis. After a run of 48 vibration tests, the apricots were kept at room temperature for 24 to 48 hours in order for the full development of the fruit bruises and for the bruises to become apparent. Then, all the apricots visually were evaluated for bruises and each fruit was categorised according to the severity of its bruises in a 5–level scale, including sound (1), slight damage (2), moderate damage (3), severe damage (4) and fruits with cuts (5). Eq. (3) was used to compute the fruit damage index (FDI) for each experiment. According to Eq. (3), FDI is a dimensionless parameter (Jiménez-Jiménez et al. 2013).

Bruise index by visual estimation (Eq. 3.):

$$\text{FDI} = \frac{0 \times X_0 + 1 \times X_1 + 2 \times X_2 + 3 \times X_3 + 4 \times X_4}{X_0 + X_1 + X_2 + X_3 + X_4} \quad (3)$$

where: X – the number of fruits; 0 – without bruising (sound); 1 – slight damage; 2 moderate damage; 3 severe damage; 4 fruits with cracks

The data on the bruises were analysed statistically using a randomised complete block design basis on a factorial experiment to study the effects of four independent factors including the apricot cultivar (Shahroudi and Urdoobad), the package type (2 types), the vibration frequency (17 and 20 Hz), and the vibration duration (15 and 30 min) on the FDI. Each experiment was conducted in 3 replications and SPSS software (version 24.0) was used for the statistical analyses.

RESULTS AND DISCUSSION

Performing the analysis of variance on the collected data indicated that the independent variables, including the fruit cultivar, vibration frequency, and vibration duration have a significant effect ($P < 0.01$) on the calculated FDI, except for the package type (Table 1). The evaluation of the interaction effects indicated that only the interaction effect of the fruit cultivar by the vibration frequency was significant ($P < 0.01$).

The effect of the package type and vibration frequency on the packaging transmissibility

Fig. 5 indicates the transmissibility value (%) of the packages versus the vibration frequency chang-

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Table 1. The ANOVA summary of the apricot Fruit Damage Index (FDI) affected by the independent variables

Source of the variation	*df*	Sum of the squares	MSE	*F* – value
FC	1	10.572	10.572	114.041 **
B	1	0.329	0.329	3.544 ns
FC × B	1	0.017	0.017	0.184 ns
F	1	6.263	6.263	67.557 **
FC × F	1	0.888	0.888	9.578 **
B × F	1	0.043	0.043	0.466 ns
FC × B × F	1	0	0	0.002 ns
D	1	4.492	4.492	48.455 **
FC × D	1	0.342	0.342	3.685 ns
B × D	1	0.011	0.011	0.115 ns
FC × B × D	1	0.014	0.014	0.150 ns
F × D	1	0.176	0.176	1.896 ns
FC × F × D	1	0.159	0.159	1.714 ns
B × F × D	1	0.013	0.013	0.142 ns
FC × B × F × D	1	0.067	0.067	0.723 ns
Error	30	2.967	0.093	

FC – fruit cultivar; B – package type; F – vibration frequency; D – vibration duration; *df* – degrees of freedom; MSE – mean square

**Significant at a 1% probability level; ns: not significant

es. The chart of transmissibility depicts that at which frequencies the apricot package vibrates at higher levels than the simulator (P_T > 100 %) and at which frequencies the apricot package vibrates at lower levels than the simulator (P_T < 100 %). As shown in Fig. 5, when increasing the vibration frequency, the transmissibility curve of both packages increases gradually, and after reaching its maximum value on certain frequencies (the natural frequency of the package), it begins to decline. According to Eq. (2), this could be explained with the escalation of the package acceleration (a_b) at the natural frequency with the constant input of the acceleration on the simulator (a_t). When the resonance frequency of the fruit package coincides with the excitation frequency, the acceleration of the product could be significantly amplified and severe damage to the fruit can result (Shahbazi et al. 2010). For package type A, the highest (180%) packaging transmissibility was observed at the frequency of 20 Hz, While, for package type B the highest (217%) packaging transmissibility value was observed at the frequency of 17 Hz. The difference between the weights of the containers tends to be in the variability observed in the transmissibility between both packages. Because, the weight of the package creates resistance to speeding up the package and stores energy, which must be spent to accelerate the package (Fadiji, 2016). As indicated in Fig. 5, for package type B with the weight of 4.5 kg, the highest packaging transmissibility occurred at the lower frequency (higher period) of 17 Hz. While, the highest packaging transmissibility for the package type A design occurred at the higher frequency (lower period) of 20 Hz. As shown in Figure 5, when the vibration frequency reaches the system resonant frequencies (17 and 20 Hz in the present study), the acceleration of the system (fruit-package) could be sharply amplified and severe fruit damage could occur (Shahbazi et al. 2010; Jarimopas et al. 2005). Slaughter et al. (1993) conducted a study on the vibration behaviour of Bartlett pear pallets and reported that by reaching the packaging transmissibility on levels greater than or equal to 400 %, the acceleration levels on the top boxes would be greater than or equal to 1 g. It means that the packages broke free from the packages below them in the pallet and became air borne at certain frequencies. Based on their report, frequencies between 2 and 40 Hz are the most critical frequencies in the fruit distribution system. From the perspective of packaging transmissibility, it could be concluded that package type A might make fruits to bear lower damage compared to

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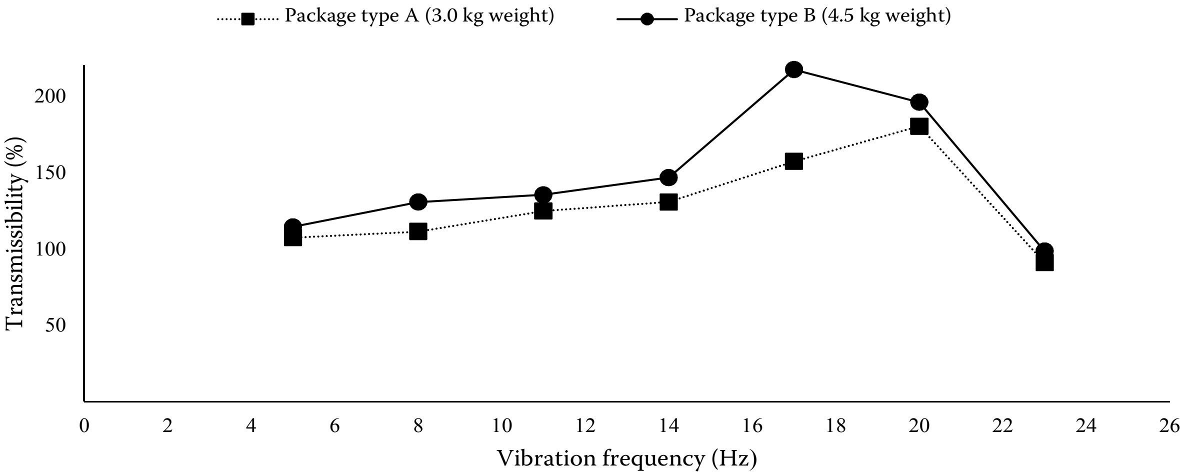

Fig. 5. The calculated packaging transmissibility of the type A and type B packages

package type B, because this package has a lower weight (lower packaging transmissibility at both 17 and 20 Hz of vibration) and transmit a lower portion of the implied vibration to the apricots and, therefore, creates less bruises.

The effect of the vibration frequency and apricot cultivar on the FDI

Fig. 6 indicates the interaction effect of the fruit cultivar by the vibration frequency on the FDI value. For both apricot cultivars, an increase in the vibration frequency from 17 to 20 Hz decreases the FDI value significantly ($P < 0.01$). In the Shahroudi cultivar, increasing the vibration frequency decreased the FDI value from 2.511 to 1.517 (40 %), and in the Urdoobad cultivar, this reduction was from 1.300 to 0.851 (35 %). This result could be explained with the higher packaging transmissibility that could occur at frequency of 17 Hz compared to 20 Hz. In other words, a larger portion of the implied vibration forces transferred at a frequency of 17 Hz from the simulator to the apricot package and was absorbed by the fruits that causes more bruise damage (Vursavus, Őzguven 2004). To support this result, Shabazi et al. (2010) stated that at constant acceleration, increasing the vibration frequency from 7.5 to 13 Hz had a significant effect on the reduction of the elasticity modulus of a watermelon's flesh. It could be noted that increasing the vibration frequency at constant acceleration decreases the displacements of each fruit during transportation and consequently reduces the impact numbers between the fruits which tends to reduce the damage.

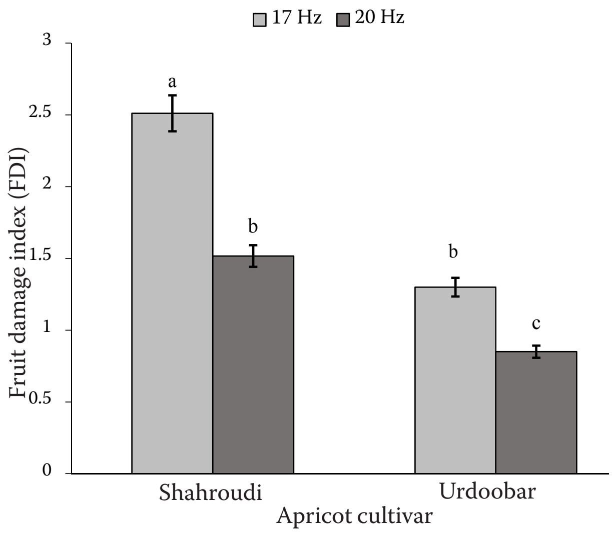

Fig. 6. The effect of the apricot cultivar and vibration frequency interaction on the FDI value

Pretorius and Steyn (2012) compared the resonance vibration frequencies for different types of fresh produce that they derived from various literature with vibrations experienced on the fresh fruit containers during transportation (Fig. 7). As shown Fig. 7, the coloured area depicts the overlap of the dominant frequencies during the transportation with the frequencies that create damage in many types of fruits. Therefore, this overlap area is a critical zone during the transportation and should be avoided by proper strategies. In addition, based on the study of Jarimopas et al. (2005), the frequency range between 5 to 20 Hz represents the axle hop re-

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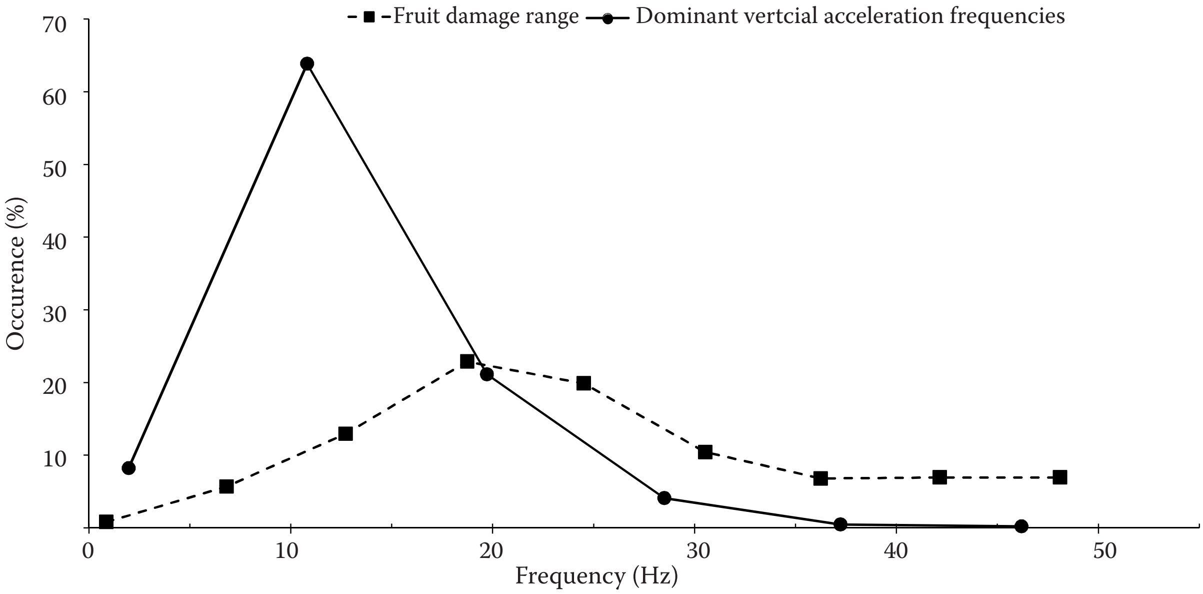

Fig. 7. The comparison among the dominant frequencies encountered by the fruit load and the vibration range that results in the fruit load damage (Pretorius, Steyn 2012)

sponse and these frequencies are usually transferred to the fruit load inside of the packaging, especially in the case of a bad truck suspension. Besides, according to results of this study, the natural frequencies of both apricot cultivars were among this critical zone. Therefore, to reduce the damage, the system vibration must be shifted out of the critical range and the resonance frequencies must be avoided as well. The best recommendations to fulfil these goals are to use other types of packages, the use of protective materials inside the packages, and the use of a tight filling method to increase the package's natural frequency.

According to Fig. 6, the apricot cultivar has a significant effect on the FDI too, so that, at a constant frequency, changing the apricot cultivar from the Shahroudi to Urdoobad significantly reduced the FDI value. The total FDI value for the Shahroudi and Urdoobad cultivars at the frequency of 17 Hz was 2.51 and 1.30, respectively, which represents a 48 % decline in the FDI value, while this reduction in the FDI value at the frequency of 20 Hz was about 44 %. The significant difference between the apricot cultivars could be attributed to the larger longitudinal dimension of the Shahroudi variety and its softer content (due to its lower firmness) (Table 2) versus the Urdoobad's longitudinal dimension. Table 2 presents the mean values of the main characteristics for both apricot cultivars. According to Table 2, the Shahroudi cultivar has a bigger mean length value and lower width and thickness values compared to the

Table 2. The mean values of the main characteristics of the apricot cultivars

Parameters	Shahroudi	Urdoobad
Length (mm)	53.26	46.66
Width (mm)	39.92	45.51
Thickness (mm)	39.26	42.57
Mass (g)	47.92	52.94
Sphericity (%)	82	96
Moisture content (%)	84.5	69.6
Elasticity Modulus (MPa)	0.186	0.243

Urdoobad cultivar that led the Shahroudi cultivar to have an oval shape (Fig. 8.). Therefore, the calyx and peduncular sections of the Shahroudi cultivar have a smaller radius of curvature and the probability of bruising is higher at those sections. This result is in agreement with study of Van Zeebroeck et al. (2005) which reported that apples with a low radius of curvature bear more bruise damage compared to apples with a larger radius of curvature, because, a lower radius of curvature leads to a higher peak stress at the contact point. In addition, the authors stated that fruits like tomatoes with a small radius of curvature absorb more energy (which leads to more bruising) than fruits with a higher radius. In support of this result, Tabatabaekoloor et al. (2013) stated that kiwifruits with a bigger size have more freedom during the transport and the damaged fruit could increase. Also, Berardinelli et al. (2005) studied the

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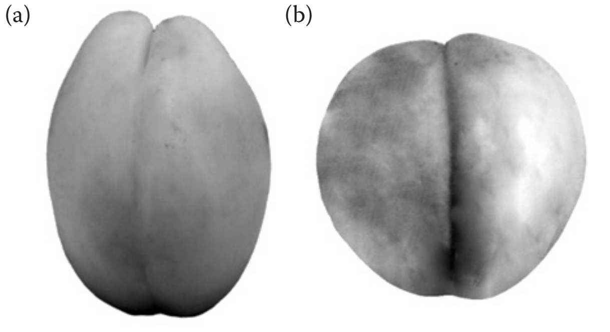

Fig. 8. The comparison of appearance of the Shahroudi and Urdoobad cultivars, the Shahroudi cultivar with an oval shape (a), the Urdoobad cultivar with a circular shape (b)

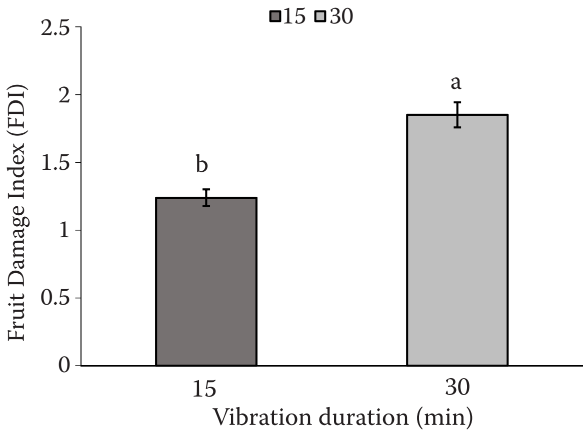

Fig. 9. The effect of the vibration duration on the FDI value

vibration damage to three pear cultivars (the Abate, Conference and Decana) caused by the simulated transportation and reported that the pear cultivar had a significant effect on the vibration damage. The authors reported that the samples of the Abate pears (with a higher mean value of the mass and length) had the maximum average dimensions of damage compared to the Conference and Decana cultivars.

To evaluate this result from another aspect, the impact of the fruit's firmness could be considered. According to Table 2, the firmness (modulus of elasticity) of the Shahroudi cultivar was 30% lower than the firmness of the Urdoobad cultivar. Garcia et al. (1995) stated that a decrease in the apple's firmness led to more damage. In addition, Arpaia et al. (1987) studied the bruising susceptibility of three cultivars of the avocado fruit and stated that fruit bruising had a negative relationship to the fruit firmness and avocados with a lower firmness showed higher degrees of bruising. Also, this result agrees with the results of Shahbazi et al. (2010) who studied the effect of the road vibrations on watermelon damage. They used the modulus of elasticity changes as their damage criteria and reported that at constant accelerations, fruits with soft materials (lower modulus of elasticity) were more sensitive to lower frequencies. Consequently, in terms of the physical properties, the Urdoobad variety can suffer less damage because of its higher radius of curvature and firmness and is more suitable to transport over a long distance.

The effect of the vibration time on the FDI

As shown in Fig. 9, increasing the vibration duration from 15 to 30 minutes significantly increased the FDI value from 1.24 to 1.85 (49%). Therefore, doubling the vibration duration increases the FDI value by 1.49 times. This result has good agreement with the results of Shahbazi (2017) who investigated the effect of the package position (in the fruit stack), the vibration frequency, and the vibration duration on the weight loss of the apricot fruit. The author reported that doubling the vibration duration has a significant effect on the weight loss of the apricot fruit and it increased the weight loss in the apricot fruit by 1.4 times. Other researchers such as Laurenti et al. (2002) and Mohsenin et al. (1978) have reported similar results as well. This result could be explained by increasing the number of fruit-fruit and fruit-package wall impacts by increasing the vibration duration. Increasing the number of impacts leads to an increase in the risk of plastic deformation and, consequently, irreversible damage.

CONCLUSION

The results of the present study indicated that the vibration properties including the vibration frequency, the vibration duration, and the apricot cultivar have a significant effect on the damage to the apricot fruits during transportation at a 1% probability level.

Based on the results, the Urdoobad cultivar was more resistant to the vibration damages and could be used for export purposes to transport over distances of more than 1,000 km, while the Shahroudi cultivar was more susceptible to the vibration

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damages during transportation and should not be transported over long distances without using protective materials and suitable vehicles.

The frequencies of 17 and 20 Hz were determined as being the first and second natural frequencies (the most critical frequencies) in both the Shahroudi and Urdoobad cultivars that tend to cause most damage.

Among the investigated frequencies, both of the evaluated cultivars were more vulnerable at 17 Hz than 20 Hz.

It is not recommended to ship apricot fruits when using conventional trucks and the current packaging systems over long distances.

It is suggested that one should investigate the effect of other factors such as fruit protective materials, the arrangement of the fruit, and the package cap, as well as the effect of lower and higher frequencies than the resonance frequency on the amount of the apricot vibrational damage.

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