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Evaluation of impact effect and fruit properties on apple dynamic behavior

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Abstract

Apple fruit can be damaged because of some impact forces which are the main sources of apple degradation during the contact. To reduce the damage, it is necessary to investigate normal contact forces. The normal contact force models depend on dynamical parameters such as spring and damping. The spring and damping parameters of Kuwabara and Kano normal contact force model are obtained in different levels of impact velocity (0.1; 0.2; 0.27; 0.34; 0.5; and 0.7 m s^{-1}) for apple fruit by using the nonlinear least squares method. Significant effects of impact velocity, contact time, fruit properties (effective radius of curvature and acoustic stiffness) and some interaction effects on spring and damping parameters were obtained at probability level of 5% with determination coefficient (R^2) of 0.98 and 0.94 for "k" and "c" models of Golden delicious and also 0.98 and 0.98 for Golden delicious, respectively. However, there was no significant acoustic stiffness effect on the "k" and "c" parameters. The results showed that lowering the impact velocity and increasing the effective radius of curvature and contact time will enhance the parameters "k" and "c" of the apple fruit.

Keywords: dynamical properties; damping parameters; regression models; normal contact.
Abbreviations: k: Spring parameter, [N $m^{-3/2}$], c: Damping parameter, [kg $m^{-1/2}$ s^{-1}], R: Radius of curvature, [mm], t: Contact time [s], v: Impact velocity [m s^{-1}], S: Acoustic stiffness, [s^{-2} $kg^{2/3}$], F: Normal contact force, [N], δ : Displacement, [m], $\dot{\delta}$: Displacement rate, [m s^{-1}], m : Mass of fruit, [kg], f: First resonance frequency, [s^{-1}].

Introduction

Mechanical damage is extremely common during fruit handling and transportation, and is defined as plastic deformation, superficial rupture and destruction of tissue due to external forces (Sanches et al., 2008). Physical impacts are transitory movements, caused by sudden acceleration or deceleration bringing about great dissipation of energy and consequent damage to the fruit. The fruit properties and impact velocity determine the fruit reaction model for the impact and influence its susceptibility to impact damage. Understanding bio-particle collisions is important for numerous applications, covering wide fields of interest, such as handling, transportation, and processing of agricultural, horticultural, and food products. A computer simulation technique was applied to get insight into the mechanical damage problem. The response of bio-materials and structures under impact loading is quite complex. In order to improve the mechanical process control of fruit handling with respect to bruising, efforts have been made to develop a generic computer model for these processes based on discrete element modeling (DEM). Such models rely on the basic laws of classical mechanics (Newton's law of motion) and a contact force model to simulate the trajectory and the impact history of each fruit, throughout the process (Van Zeebroeck et al., 2004). In order to do so, models of the forces, acting between particles (like fruits) in contact, need to be specified. Forces acting between the two particles are decomposed into normal and tangential components (Ahmadi et al., 2012). Selecting the most adequate contact force model plays a key role to properly design and analyze these mechanical system types. The inter-particle contact law was pioneered by Hertz (Hertz 1881) for normal contact, which has been validated by experiments and numerical studies for elastic spheres. Yet, Hertzian theory is not sufficient to determine the contact for the energy dissipation in the collisions of particles. In general, two mechanisms of energy dissipation are considered, i.e. plasticity and viscoelasticity, which give rise to normal force-deformation. Agricultural and food materials tend to behave as viscoelastic materials, when they are subjected to various conditions of stress and strain (Mohsenin 1986; Tsuji et al., 1992; Rong et al., 1993, 1995a, b; Sakaguchi et al., 2001; Raji and Favier 2004a). Food can be regarded as a kind of complex polymer. The different food matrix shows different mechanical properties in different viscoelastic regions: the glass-like region, where the material shows a rigid and brittle character and the modulus is relatively high , the glass-transition region, where the storage modulus of the material decreases remarkably , the rubber-like region, where the material shows a high-elastic property; and the terminal region, where the material flows like liquid (Le Mast et al., 2002). In viscoelastic contact models, elastic term can be determined by the Hertzian theory for the normal force while the damping term is in proportion to the relative velocity between two colliding particles. Damping often plays an important role in the prediction of the dynamical response of materials. Damping is defined by various terms such as energy loss percycle, logarithmic decrement, complex modulus, and rise time (Assie et al., 2010a). Schäfer et al. (1999) presented a comprehensive review of the various contact force models that have been suggested or implemented in various granular matter simulations. The models vary in simplicity from linear elements to a variety of complex non-linear ones. Kuwabara and Kono (1987) and Brilliantov et al. (1996a, b) proposed analytical models for the normal contact force of viscoelastic material, respectively. The contact - impact is often used to stress the dynamic effects in contact phenomena (Assie et al., 2010b). In order to evaluate the contact-impact forces resulting from collisions in handling and transportation efficiently, special attention must be paid to the physical and mechanical properties of biomaterial product. Information on the impact velocity, material properties of the colliding bodies and geometric characteristics of the contact surface must be included in the dynamic behavior. Within the recent years of fruit impact damage researches, different test equipment was developed to assess the dynamic stresses in fruits. Among the dynamic apparatuses, there are two main types of design: drop and pendulum design. Currently, experimental methods such as pendulum experiments are used to study the impact behavior of fruit and to determine the contact parameters to be used with the DEM models (Pang et al., 1992; Bajema and Hyde, 1998; Van Zeebroeck et al., 2003; Ahmadi et al., 2012). Because of the precise stiffness and lack of fruit damping determination (viscoelastic material), dynamic analysis research of bio-material is rare. The dynamic analysis of viscoelastic materials (fruit) is treated numerically based on DEM method by Van Zeebroeck et al. (2006a, b) and Ahmadi et al. (2012). The objective of the present paper was to investigate the collision processes in fruit handling to simulate normal contact force model, which is necessary for DEM. This research aims to develop the parameters of spring "k" and damping "c" prediction models for "apple" using impact properties together with the fruit properties.

Result and discussion

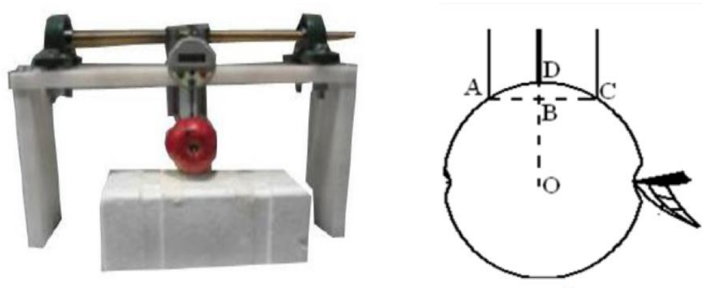
In the literature, there are no data available about the dynamic behavior for Golden delicious and Red delicious apples. The stiffness "k" and damping "c" parameters of Kuwabara and Kono model are estimated for any experiment. The results of the parameter estimation are depicted in Table 2. Van Zeebroeck et al. (2003) and Ahmadi et al. (2012) using Kuwabara and Kono model, calculated the dynamical properties of Gonagold apple, potato and peach. Main effects (impact velocity, contact time and the effective radius of curvature) and some interactions were significant at the 5% probability level. Table 3 shows the final models having all of the independent variables. For these models, the predicted values of the spring and the damping parameter versus experimental values of the contact force model parameters are presented in Figs. 4 and 5, respectively. Figures 6-9 show the combined effect of the impact velocity, contact time and the effective radius of curvature on the contact force model parameters.

Impact velocity effect on the contact force model parameters

The most general and predominant type of collision is the oblique eccentric collision, which involves both relative normal velocity and relative tangential velocity (Maw et al., 1975; Zukas et al., 1982). In this study the normal velocity was evaluated. Increasing the impact velocity will increase impact energy and as a result this causes an increase of the impact force. The analysis of backward multiple regression results showed that impact velocity affected the spring and damping parameters significantly. The data indicated that the parameters "k" and "c" decrease when the impact velocity is increased (Table 3 and Figs. 6-9). The significant interaction ($P < 0.05$) between impact velocity and radius of curvature indicated that the effect of impact velocity on the parameters "k" and "c" was higher at the small radius of curvature. Spring parameter for Golden delicious apples was up to 59 % higher in the impact velocity of 0.1 m s^{-1} for low effective radius of curvature (0.031 m), while it was about 37 % higher for a high effective radius of curvature (0.07 m). Also, the damping parameter of this impact velocity was up to 51 % higher for low effective radius of curvature (0.031 m), while 90 % higher for a high effective radius of curvature (0.07 m). For red delicious apples, it was up 43 % to higher in the impact velocity of 0.1 m s^{-1}, for a low effective radius of curvature (0.025 m) while it was about 41% higher for a high effective radius of curvature (0.07 m). Also, the damping parameter of this impact velocity was up to 69% higher for low effective radius of curvature (0.025 m) while it is 95 % higher for a high effective radius of curvature (0.07 m). The interaction effect of the acoustic stiffness with the impact velocity was not significant. The spring and damper parameter describes the elasticity of the contacting bodies and the loss of kinetic energy during the impact, respectively. Studied theoretically and experimentally the impact between bodies demonstrated that at low impact velocities, the hysteresis damping is the prime factor for energy dissipation (Flores et al., 2005). The negative effect of the impact velocity on the spring parameter may be justified on the basis that increasing impact velocity increases the impact energy level, which causes the increment in the amount of deformation. Therefore, the low impact velocity causes shallow deformation, but high impact velocity causes deep deformation in internal tissue of fruit. Regarding the fact that the fruits are grouped as viscoelastic materials, the external tissue of an apple treats as elastic behavior. The dependence on the elastic properties is in the fact that they control both the duration time of the collision and the speed of the waves through the body (Dintwa et al., 2008). Several researchers (Hunter, 1957; Hayakawa and Kuninaka, 2002; Gerl and Zippelius, 1999) report that, with all factors being equal, the coefficients of restitution (i.e. ratio of the rebound velocity to impact velocity of the colliding object) decrease with increasing impact velocity. Because of relatively stiffness, crust, and internal tissue of apple show viscous behavior mostly. Therefore on low energy level the lower deformation occurs and an elastic nonlinear behavior is obtained from deformation–force curve and in high energy level more deformation occurs and a non-Newtonian behavior is observed from forces-deformation curve, which explains the decrease in stiffness. Dintwa et al. (2005) showed that the viscosity of most materials negatively correlates with the shear rate. Decreasing the amount of dissipative material parameter causes impact velocity to increase and damping parameter to decrease. Amount of energy loss is dependent on the elastic properties of the material, the geometrical size of the colliding objects as well as the collision velocity (Dintwa et al., 2008). From a macroscopic view, the energy loss is due to the force-deformation hysteresis of the impact procedure. It is known that the viscoelastic effect and the plastic deformation play import roles in energy loss during low-velocity impact and high velocity impact, respectively (Kim et al., 2007; Wall et al., 1990). The inherent viscoelasticity of solid materials leads to the damping force that increases with the increasing relative velocity of two colliding bodies. On the other hand, when the incident velocity exceeds the yield limit, the plastic deformation

Table 1. Acoustic stiffness of apples obtained through acoustical stimulus and response.

Sample	Acoustic stiffness ($HZ^2 Kg^{2/3}$)
Golden delicious	25.6
Red delicious	29.7

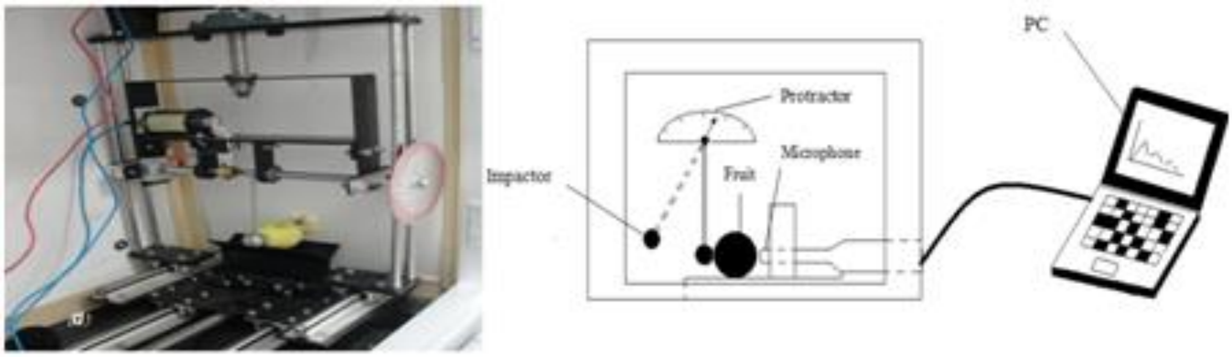


a b

Fig 1. (a) General view of the radius of curvature meter and (b) schematic representation of geometry to calculate the radius of the apple fruit.

Table 2. Kuwabara–kono contact force model parameter estimation of apples based on displacement, displacement rate and contact force.

Sample	Spring parameter	Damping parameter	Standard deviation as percent of the average	
			k	c
Golden delicious	899166.2	2550	26	12
Red delicious	1011961	2959	6	14



a b

Fig 2. (a) General view of the acoustic device and (b) schematic representation of the acoustic response technique for determination of stiffness.

occurs in the softer body around the local contact area (Wall et al., 1990; Kogut et al., 2003; Kim et al., 2007).

Lankarani and Nikravesh (1990, 1994) also described the relation of damping with impact velocity and the restitution coefficient of the model, which predicted a lower damping parameter with the increase of impact velocity.

Effect of contact time on the contact force model parameters

The data indicated that the parameters “k” and “c” for Golden delicious apples increased with the increase of contact time (Table 3 and Figs. 6 and 7). The difference in the parameters “k” and “c”, between two extreme values of contact time (0.004 and 0.008 s), were not similar at low and high impact velocity. When the contact time increased from 0.004 to 0.008 s in impact velocity of 0.1 m s^{-1}, the spring parameter increased 27% and in impact velocity of 0.7 m s^{-1}, this parameter increased 8%. Also, with the increase of contact time from 0.004 to 0.008 s in impact velocity of 0.1 m s^{-1}, the damping parameters increased 15% and in impact velocity of 0.7 m s^{-1}, this parameter increased 5%. The effect of contact time on the parameters of applying contact force model on Red delicious apple was positive (Table 3 and Figs. 6 and 7). The difference in the parameters “k” and “c” between two extreme values of contact time (0.004 and 0.008 s) was not similar at low and high impact velocity. When the contact time increased from 0.004 to 0.008 s in impact velocity of 0.1 m s^{-1}, the spring parameter increased 7% and in impact velocity of 0.7 m s^{-1}, this parameter increased 9%. Also, after contact time increased from 0.004 to 0.008 s in impact velocity of 0.1 m s^{-1}, the damping parameters increased 14% and in impact velocity of 0.7 m s^{-1}, this parameter increased 24%. The Positive effect of the contact time on the contact force model parameters may be justified as expected from the one-dimensional wave theory. The contact time is independent of the impactor velocity, whereas the contact force is dependent on it. At higher impact velocities, the contact force increases with high rate, as compared to low impact velocities. Then, the impact process is followed by a small increasing rate of the contact force and then decreased with small rate until it reaches zero. The collision time is

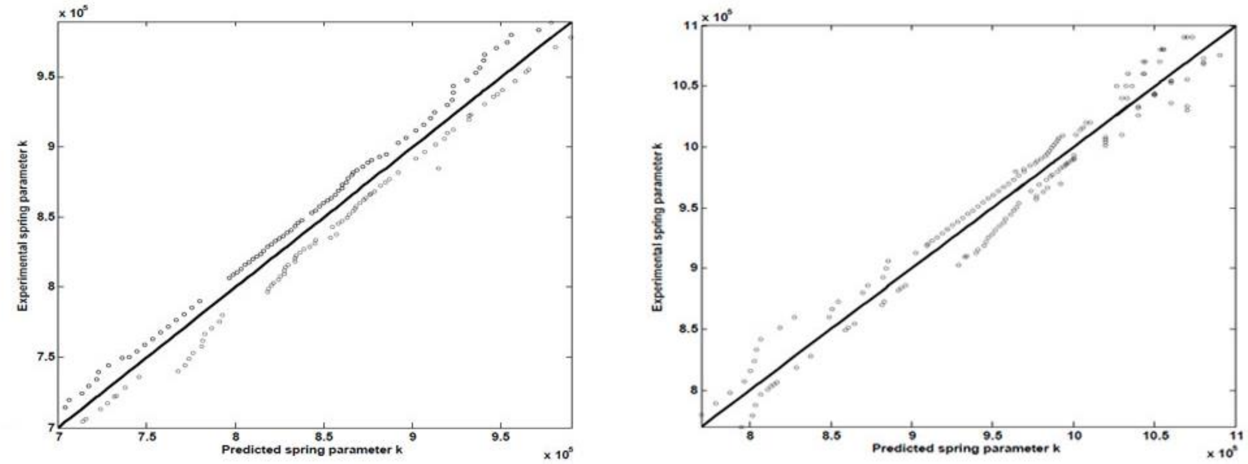
Table 3. Multiple regression equation of the contact force (spring parameter, "k" and damping parameter, "c") of the "Golden delicious" and "Red delicious" apple relation to impact velocity (V), contact time (t) and the effective radius of curvature (R) as independent variables.

Sample	Models*	
Golden delicious	k = 662728.094 - 328492.591*V + 216226.530*R + 4.058E7*t + 434154.296*V*R	0.98
	c = 1176.304 + 9292.689*R + 183433.133*t - 33556.643*V*R	0.94
Red delicious	k = 914530.920 - 393893.060*V + 1.335E6*R + 2.479E7*t - 1.194E6*V*R	0.98
	c = 2891.098 + 7860.022*R - 3417.168*V - 16991.535*V*R + 422075.266*V*t	0.98

*: Minimum probability threshold P≤ 0.05

(a) (b)

Fig 3. General view of the pendulum device for measuring impact force, impact displacement and impact velocity of the apple fruit (b) the anvil and rod of the pendulum at beneath the frame.



(a) (b)

Fig 4. The predicted values of the spring parameter, "k"(N $m^{-3/2}$) versus spring parameter experimental :(a) "Golden delicious" and (b) "Red delicious".

decreasing with the increasing collision velocity. The higher coefficient of restitution, the larger maximum deformation and the longer contact time lead to the maximum deformation. The reason is that the damping force during the contact process is smaller for the higher coefficient of restitution. If the coefficient of restitution is higher, the recovery procedure is shorter, so the contact duration time is shorter. The relationship of force-deformation shows the hysteresis damping characteristic and reflects the energy dissipation during contact process (Bai and Zaho.,2012). Several investigators have shown that for relatively small bodies, as is the case with many agricultural products, the collision period is much longer and depends primarily on the deformation occurring at the region of contact (Sarig 1991). Fluck and Ahmed (1972) have recorded values of impact duration that ranged from 9 to 26 ms for various fruits and vegetables such as: peaches, cucumbers, lemons and tomatoes. The time from the beginning of contact for separation of the two bodies is known as the contact time. The contact time can be divided into three main periods. The first period is known as the bounding period, which begins from zero time of contact to the maximum contact force time. During this period, the contact force increases with a high rate until it reaches the maximum value. This period is followed by a period of compacting the two bodies. During this period the contact force is approximately constant. After compaction, the rebounding period starts where the contact force decreases gradually until separation. Also, it is noted that the contact force in viscoelastic bodies is smaller than that in the elastic bodies and the contact time is longer. The contact force reduction and the increase of contact time mean that the viscoelastic bodies are softer and have ability to

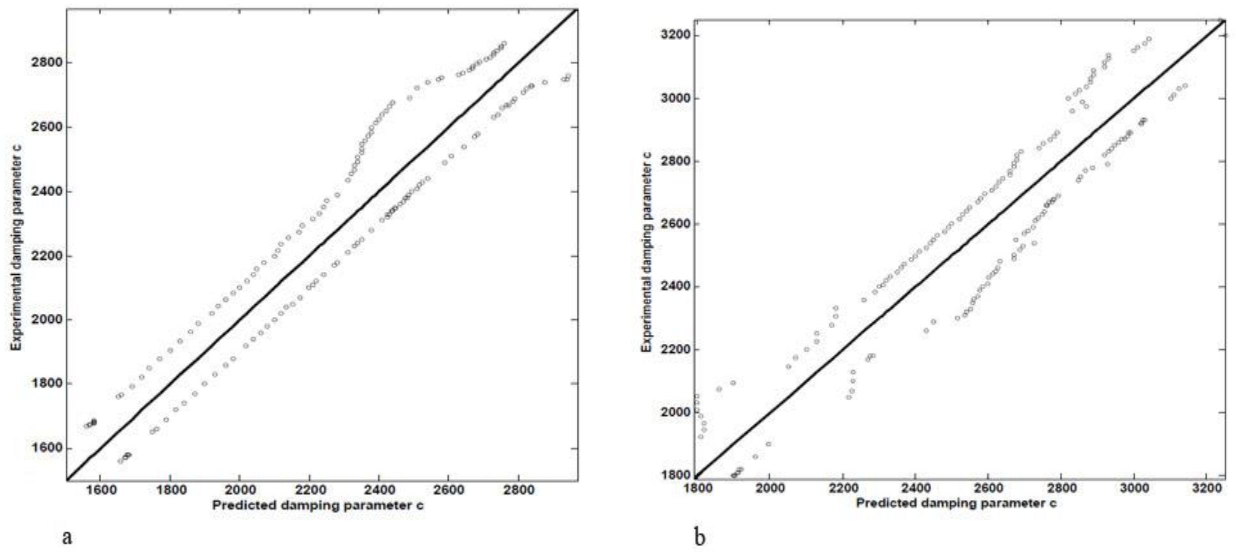


Fig 5. The predicted values of the damping parameter, “c” (Kg $m^{-1/2}$ s^{-1}) versus damping parameter experimental: (a) “Golden delicious” and (b) “Red delicious”.

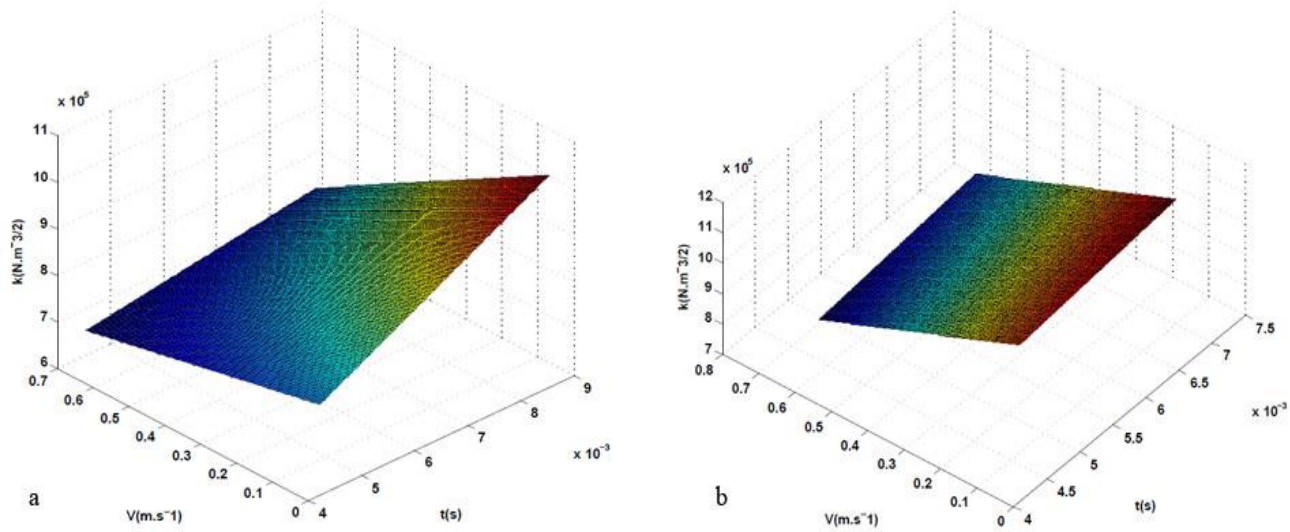


Fig 6. Effect of impact velocity, “V” (m s^{-1}) and contact time, “t” (s) on the spring parameter, “k”(N $m^{-3/2}$): (a) “Golden delicious” and (b) “Red delicious”.

absorb the impact energy more than the other case.The long contact time, relative for example to that of metal spheres striking at the same speed, may be attributed to the relatively low modulus of agricultural products and the existence of air-filled inter-cellular spaces (Sarig 1991). Hence, during the deformation process there is sufficient time for elastic waves to travel back and forth several times before they are dissipated throughout the colliding bodies. Thus, in this event only the local contact phenomenon may be considered, the bodies may be considered to be in a state of quasi-equilibrium, and the effect of wave propagation may be ignored without loss of accuracy. When the contact velocity decreases, the contact time increases and less impact energy is applied to fruit in contact area. In this case, the fruit does not enter plastic phase and consequently the stiffness and damping parameters increases. For this reason, the stiffness and damping parameters increase at higher contact time. Higher elasticity leads to shorter impact time and higher viscosity leads to longer impact time (Van Zeebroeck 2005).

The effect of effective radius of curvature on the contact force model parameters

The spring parameter is dependent on the material properties and the shape of the contact, surfaces. For two spheres in contact the generalized stiffness coefficient is the function of the radius of the spheres and the material properties (Bai and Zaho., 2012). The contact force model parameters are dependent on the effective radius of curvature, according the Hertz theory for the spring parameter and according to Kuwabara and Kono (1987) for the damping parameter. The contact force parameters are also dependent on the impact velocity. Golden delicious apples with a high effective radius of curvature showed more contact force parameters (spring

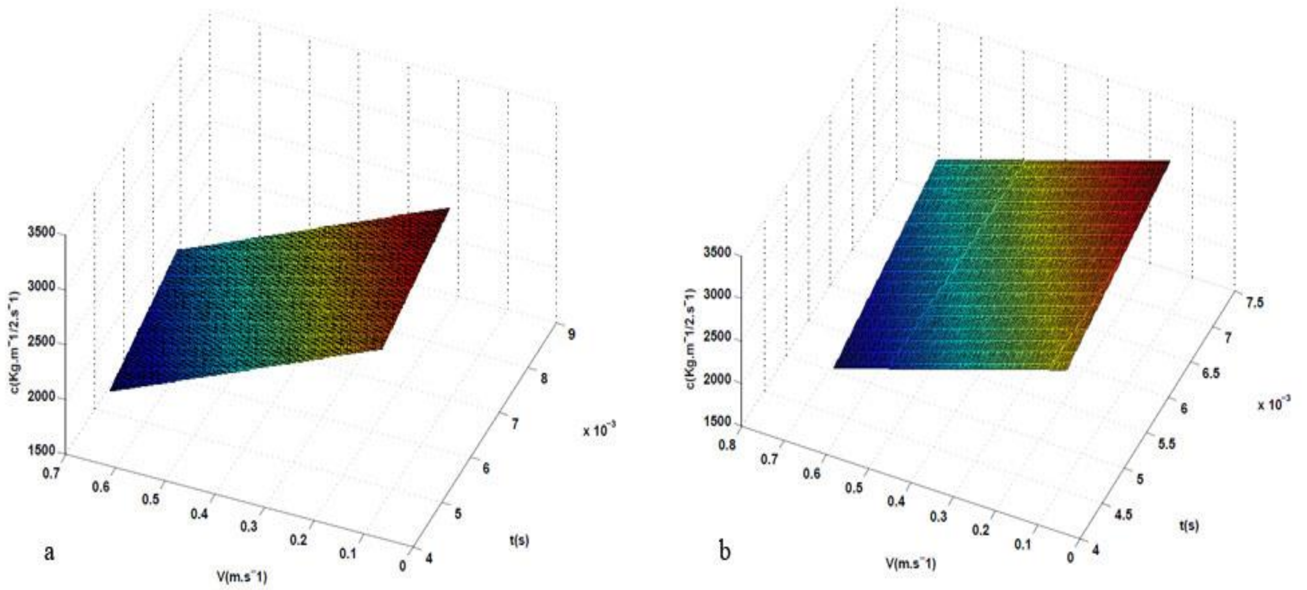


Fig 7. Effect of impact velocity, “V” (ms^{-1}) and contact time, “t” (s) on the damping parameter, “c” (Kg m$^{-1/2}$ s^{-1}): (a) “Golden delicious” and (b) “Red delicious”.

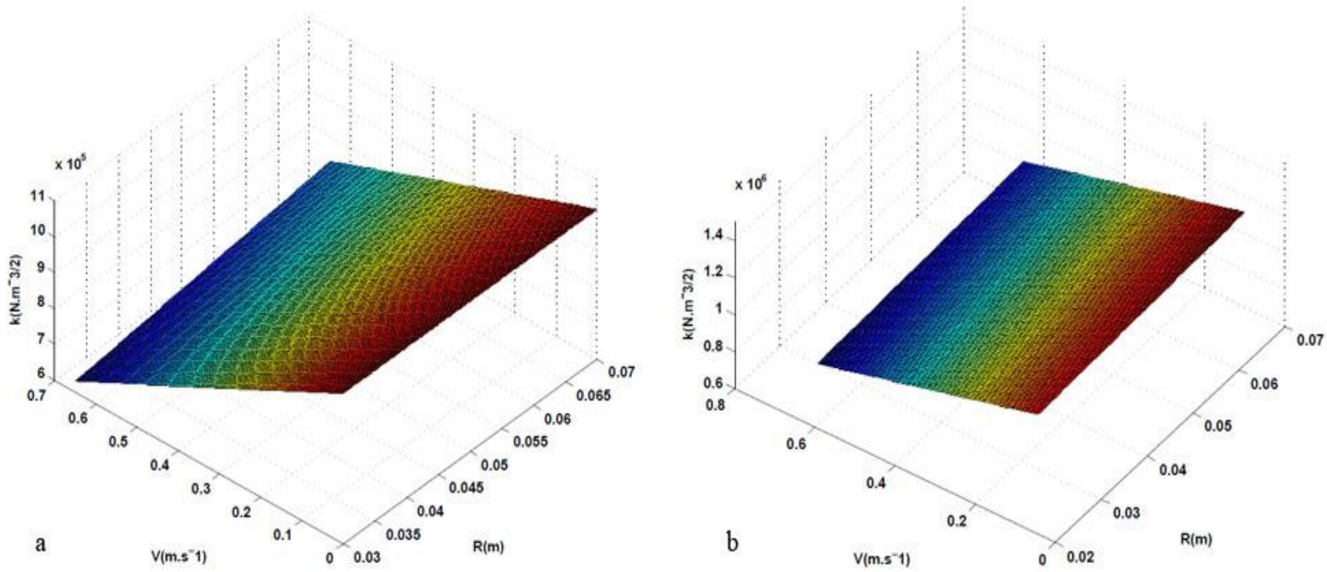


Fig 8. Effect of impact velocity, “V” (m s^{-1}) and the effective radius of curvature, “R” (m) on the spring parameter, “k” (N m$^{-3/2}$): (a) “Golden delicious” and (b) “Red delicious”.

and damping), compared with small Golden delicious apples in each impact velocity (Table 3 and Figs. 8 and 9). The difference in the parameters “k” and “c”, between two extreme values of effective radius of curvature (0.03 and 0.07 m), was not similar at low and high impact velocity. With the increase of the effective radius curvature from 0.03 to 0.07 m in impact velocity of 0.1 m s^{-1}, the spring parameter increased 2% and in impact velocity of 0.7 m s^{-1}, this parameter increased 17%. Also ,with the increase of effective radius of curvature from 0.03 to 0.07 m in impact velocity of 0.1m s^{-1}, the damping parameters increased 10%. For impact velocity of 0.7 m s$^{-1,}$ the effective radius curvature effect on damping parameter had the opposite result which could not be explained. The data indicated that the parameters “k” and “c” for Red delicious apples increase if the radius of curvature is increased (Table 3 and Figs. 8 and 9). The difference in the parameters “k” between two extreme values of radius of curvature (0.025 and 0.07 m) was not similar at low and high impact velocity. When the radius of curvature was increased from 0.025 to 0.07 m in impact velocity of 0.1 m s^{-1}, the spring parameter increased 4% and in impact velocity of 0.7 m s^{-1}, this parameter increased 5%. Also, with the increase of effective radius of curvature from 0.025 to 0.07 m in impact velocity of 0.1 m s^{-1}, the damping parameters increased 2%. For high impact velocity of 0.7 m s^{-1}, the effective radius curvature effect on damping parameter had the opposite result which could not be explained. When the radius of curvature in contact area increased, the curvature decreased and consequently the concentration of spring and damper elements in this area increased. This indicates that the

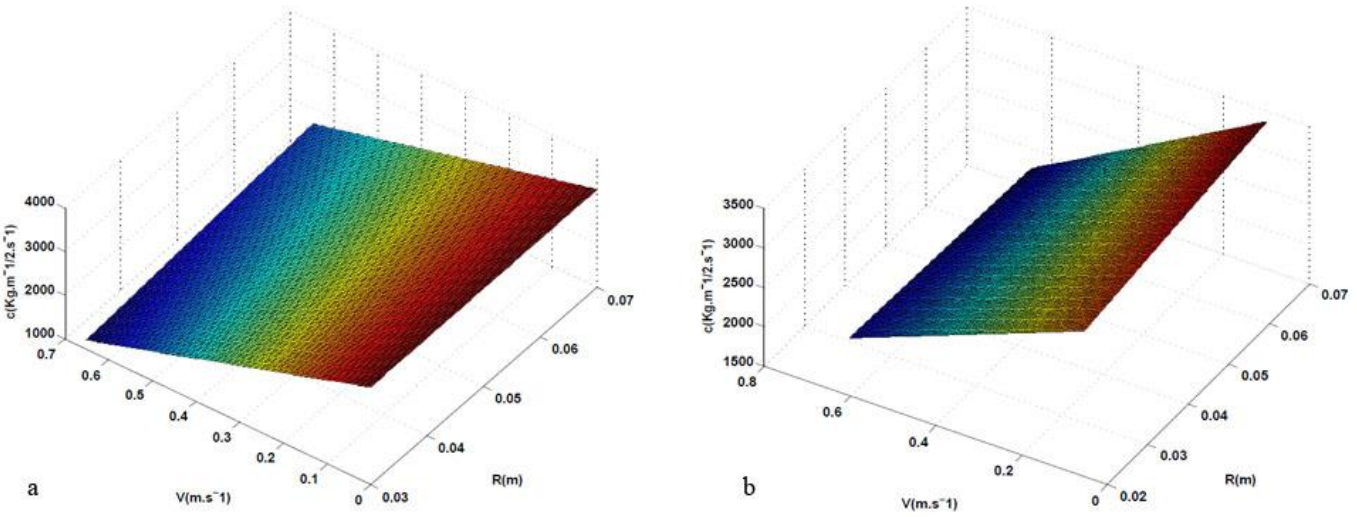


Fig 9. Effect of impact velocity, "V" (m s^{-1}) and effective radius of curvature, "R" (m) on the damping parameter, "c" (Kg $m^{-1/2}$ s^{-1}): (a)"Golden delicious" and (b) "Red delicious".

stiffness and damping parameters are higher in the fruits that have more radius of curvature in contact area. An explanation of the effect of radius of curvature on absorbed energy could be that the higher peak contact stress for fruit with smaller radius of curvature dominates the lower contact area during impact (based on the Hertz theory for elastic bodies) (Van Zeebroeck et al., 2007a). It can be seen that a large radius of curvature results in a lower peak stress and thus leads to less bruise damage.

Material and method

Apple sample

The "Golden Delicious" and "Red Delicious" apple varieties were used in the experiments. The apples were hand-harvested in 2011 from "Abbas Abad" district, Hamedan, Iran. Apples were hand-picked at an educational- research orchard to insure their freshness and avoid damage during harvesting and transporting. Fruits were conditioned at the desired temperature in a cool room at 3˚C, 85% RH for a week, and held at room temperature (about 20–22˚C) within 8 hours before being tested. The radius of curvature was measured locally at the location of impact by a radius of curvature meter (Fig. 1a). The curvature radius was determined using the following equation (Mohsenin, 1986) (Fig. 1b):

$$RADIUS = \frac{(AC)^2}{8(BD)} + \frac{(BD)}{2} \quad (1)$$

Fruit stiffness is a suitable indicator of fruit quality. The apple acoustic stiffness was determined on preconditioned fruit based on the acoustical impulse response method (Diezma et al., 2006; Wang et al., 2006; Van Zeebroeck et al., 2007 a, b; Ahmadi et al., 2010). A constructed apparatus was used to measure acoustic stiffness (Fig. 2). The acoustic response of each fruit was measured by collision of the fruit with an impactor and the generated sound was detected by a microphone (Standard, 8851/8852, Resolution: 0.1dB) on the opposite side and saved in a data file for processing. A fast Fourier transform (FFT) of the signal was performed to determine the frequency spectrum, and subsequently, the first resonance frequency of the apple was specified. The acoustic stiffness was calculated as (Table 1):

$$S \cong f^2 m^{2/3} \quad (2)$$

Experimental setup

Apples were subjected to dynamic loading by means of a pendulum. The pendulum consisted of a 0.577 m long rod with an aluminum chap, having an impactor (D = 12.7 mm). With the help of force sensor and the acceleration sensor attached to the impactor, the required data (force, displacement and displacement rate), were obtained for an estimate of the parameters (Fig. 3). The force sensor (PCB 208c02, PCB piezotronics, USA, sensitivity: 10.97mV/N) was mounted on a impactor. At the same location, an accelerometer was attached (PCB 320c33, PCB piezotronics, USA, sensitivity: 105.2mV/g). At the hinge of the pendulum rod, an incremental optical encoder (Autonic E 5058, resolution 0.018, Korea) was mounted. A Data logger and analyzer (ECON, AVANT Lite, model: MI-6004) was used to analyze data. The fruit was placed on the anvil port of the pendulum, and became fixed by adjustable jaws. The jaw was designed, built and installed for inhibition of trembling and dislocating fruit in the impact time. The first contact time of the impactor with the sample was detected by the force sensor. The displacement at the point of first contact of the impactor with the sample was equated to 0. Using the triggering point significantly decreased the calculation time of signal (Fig. 3). Regarding the fact that the force, displacement and displacement rate must be measured during the mentioned period (impact time), a proper voltage level (force at the start of the contact) was considered by a data acquisition system, equivalent to a unit of the contact force (~1N). The contact force was measured by the force sensor. Displacement and displacement rate were measured by the optical incremental encoder, which in fact measures the angular position of the impactor.

Experimental procedure

The contact parameters, k (stiffness) and c (damping), of the Kuwabara and Kono model were estimated from the experimental data by minimizing an error function that indicated the difference between the experimental data and predictions based on the Kuwabara and Kono contact force model. The parameter estimation was carried out using a nonlinear least squares technique. This experimental technique is outlined in detail in Ahmadi et al (2012). The Kuwbara and Kono contact force model (Kuwabara and Kono, 1987; Brilliantov et al., 1996a, 1996b) is defined as:

$$F = k\delta^{\frac{3}{2}} + c\delta^{\frac{1}{2}}\dot{\delta} \qquad (3)$$

The impact energy levels in the experiment were chosen below and above the critical impact level of apple. The constant height multiple impact (CHMI) method was used to estimate the critical impact of energy level. The dependence of the contact parameters (k and c) on the effective radius of curvature (R), acoustic stiffness (S), contact time (t) and impact velocity (V) was investigated. Six velocity levels were applied in the experiment: 0.1; 0.2; 0.27; 0.34; 0.5; and 0.7 m s^{-1}. Forty apples ("Golden delicious" and "Red delicious") were used for each variety to determine the contact parameters of the normal contact force model. Twenty apples were used for the velocity level of 0.1 - 0.34 m s^{-1} and the rest for the velocity level of 0.5 and 0.7 m s^{-1}. Apples were repeatedly impacted for the velocity level of 0.1 - 0.34 m s^{-1} (on one spot), starting with 0.1 m s^{-1}, subsequently 0.2, 0.27 and 0.34 m s^{-1}. As a consequence, for each impact velocity (0.1; 0.2; 0.27; 0.34 m s^{-1}), the impact was measured on twenty apples. To avoid the influence of damaged tissue on the contact force parameters, the impact levels of 0.5 and 0.7 m s^{-1} were not measured in the same apples. Ten apples were measured at 0.5 ms^{-1} and ten at 0.7 ms^{-1}.For each impact, the contact parameters were determined by performing a nonlinear least squares method minimizing the error between the experimental variables (contact force, displacement, and displacement rate) and the predictions by the Kuwabara and Kono (1987) contact force model. After the spring and damping parameters were distinguished for every impact, a backward multiple regression procedure was conducted to select the relevant independent variables influencing the dependent variable using 5% significance level. Furthermore, in order to verify the accuracy of multiple regression models, a chi-square test was carried out using the predicted and experimental data and SPSS software (version 19) was used for data analysis.

Conclusions

Towards the analysis of viscoelastic impact of the bodies, a normal impact model is developed. The proposed model, capable of analyzing the nonlinear dynamic viscoelastic contact-impact problems for apples is presented. The effect of fruit properties (the effective radius of curvature at the location of impact) and impact properties (impact of velocity and contact time) on the response of the impact of viscoelastic bodies were determined. Significant main effects and also significant interactions between fruit properties and the impact properties were observed. The main features of the proposed model can be summarized as follows:

- ❖ The impact velocity had a negative effect on the spring and damping parameters.
- ❖ The effective radius of curvature had a positive effect on the spring and damping parameters.
- ❖ The impact time had a positive effect on the spring and damping parameters.

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