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METHODS OF DESCRIPTION AND INTERPRETATION OF IMPACT TESTS RESULTS OF FRUIT AND VEGETABLES

Zbigniew Stropek

Department of Mechanical Engineering and Automatic Control, University of Life Sciences in Lublin, Poland, email: zbigniew.stropek@up.lublin.pl, ORCID 0000-0002-3293-7063

* *Corresponding author: e-mail: zbigniew.stropek@up.lublin.pl*

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ABSTRACT

The article presents determination methods of characteristic values of the reaction force course during the impact on fruit and vegetables to quickly assess their firmness or maturity. Moreover, various methods of modelling of the plant material behaviour during the impact that use differential equations, analytical equations, statistic models and numerical methods were discussed. Furthermore, dynamic methods that use fruit dropping on a rigid plate and measurement techniques that use a rigid element that hits a motionless fruit were reviewed and assessed. Advantages and disadvantages of these methods were presented. Statistical models are better for assessment of the bruise damage, but theoretical models are more useful for understanding the impact of various factors related to the impact damage. Various methods of application of rheological theories that describe a behaviour of the produce tissue treated as an elastic, elastic and plastic and visco-elastic were also described.

Introduction

Modelling of the impact course with various types of functions may be used for mathematical description of the fruit and vegetables behaviour during deformation and for description of their material properties during loading. It is of significance when investigating various processes where considerable velocities of fruit movement occur and for assessment of their quality, analysis of mechanical changes of fruit and vegetables properties and for ripening (Van linden et al., 2006; Rasli et al., 2019) and long-term storing (Yurtlu and Erdogan, 2005; Alamar et al., 2008). Determination of parameters of these functions is not easy due to a complex structure of the plant material and its different behaviour during deformation (Harker et al., 1997; Li et al., 2013). Reaction of fruit and vegetables during deformation at low stresses differs in quality from these at high stresses at which irreversible changes in the cell structure occur (Mitsuhashi-Gonzalez et al., 2010; Zarifneshat et al., 2010).

Determination of the impact speed and energy and measurement of the force during impact is not difficult. Modern apparatus and measurement methods will enable fast and precise determination of these values (Van Zeebroeck et al., 2003; Komarnicki et al., 2016; Stropek and Gołacki, 2020)

Many studies do not analyse the entire impact process, but only based on the force course in time, characteristic values are determined, which subsequently are correlated with the fruit firmness and may be used for sorting or classifying purposes (Ragni and Berardinelli, 2001; Jaren and Garcia-Pardo, 2002). They may also serve for determination of parameters that aim at fast assessment of maturity or the quality of agricultural produce (Delwiche and Sarig, 1991’ Brusewitz, 1994; Pang et al., 1996; Yen and Wan, 2003).

However, in comparison to the above mentioned methods, determination of the mathematical equation for the entire course of the impact force curve in time which could later be a basis for determination of new more precise parameters seems to be more useful (Surdilovic et al., 2018). Modelling of the impact processes and behaviour of fruit and vegetables in the conditions of fast-changing load and deformation values is related to many difficulties. Simplicity and easiness of physical interpretation of its parameters are required from the used models. Additionally, each model should have the widest range of utility and be universal through description of various types of material.

The aim of the paper was presentation of various methods of modelling of the reaction of plant materials during the impact, assessment of experimental methods used in various impact load conditions and showing the use of various rheological theories for description of the behaviour of fruit considered as an elastic, elastic and plastic and visco-elastic material.

Modelling with the use of various differential equations

The impact process of a visco-elastic fruit with a rigid round surface was modelled by Hunter (1960) using a differential equation of second order:

$$\frac{d^2z}{dt^2} + \eta\left(\frac{dz}{dt} - v_0\right) + D_1 \cdot z^{1,5} = 0 \tag{1}$$

where:
v_o – initial velocity of impact,
η – inverse of relaxation time,
z – movement
D_1 – rigidness parameter.

Hunter emphasised that the above equation of movement is precise only for the compression period, but for the extension period the equation should be modified. However, due to the simplicity of modelling procedures he used the same parameter values for the entire process of the impact duration. In his equations he also failed to mention the elastic wave energy that occurs in colliding bodies due to low values of the impact velocity in comparison to the velocities of distribution of the elastic wave in materials.

Gan-Mor and Galili (2000) developed a model of the visco-elastic body that collides with the elastic plate. They assumed that the visco-elastic body is significantly less rigid than the plate. Thus, the compressing strain of the plate near the contact zone are negligible in comparison with those in the visco-elastic body. Therefore, during the collision, a relative deformation of a fruit results from the compressive strain and plate deformation.

$$s = z - u \tag{2}$$

where:
s – relative shift,
z – shift of the centre of the mass of the colliding visco-elastic body
u – dislocation of the plate centre.

In the visco-elastic case, the impact force depends not only on the relative shift between a fruit and a plate but also on the element of distribution. Thus, the equation of the movement of the colliding body with the plate has the following form:

$$\frac{d^2z}{dt^2} + \eta\left(\frac{ds}{dt} - v_0\right) + D_1 \cdot s^{1,5} = 0 \tag{3}$$

where:
v_o – initial velocity,
η – inverse of relaxation time
D_1 – rigidness parameter.

Due to the fact that the fruit mass, which is in the contact zone, constitutes a significant part of the colliding body, its role in the equation of the movement may be omitted and the total impact of the sphere F_s is equal to the sphere acceleration multiplied by its total mass.

$$F_s = M \cdot \frac{d^2z}{dt^2} = -M \cdot \left[\eta\left(\frac{ds}{dt} - v_0\right) + D_1 \cdot s^{1,5}\right] \tag{4}$$

where:
F_s – force,
M – mass.

The above model was used for optimisation of separation of hard objects - stones from soft – potatoes at mechanical harvesting obtaining a considerable compliance with experimental results.

Bower and Rohrbach (1976) used Kelvin model for description of behaviour of blueberry in the sorting machine. They suggested determination of the spring constant and the coefficient of attenuation using a camera for fast images to determine the restitution coefficient and the impact time and expressions that originate in the movement equations. They assumed that the impact ends when the centre of the mass comes to its initial movement defined as a position of the beginning of the contact of both bodies. It suggested that the surface of the hit blueberry returns to its non-deformed state when the contact ends, which in reality occurs very early in case of attenuation is included.

Such a situation was included by Lichtensteiger et al., (1988) in his experiment where he took into consideration deformation of the body which takes place when there is no contact of both colliding objects. Moreover, consequences of the initial velocity of the impact on the value of the model coefficients were investigated. Kelvin model was used to describe the impact process of visco-elastic sphere that falls onto a rigid surface. It was assumed that the entire energy of impact is stored or changed into heat only in the contact zone when the rest of the sphere behaves like a rigid body during the entire event. Accumulation of the mechanical energy during the impact was presented by a single linear spring with a constant rigidness

K while transformation of the mechanical energy was determined with a single linear viscous attenuator with the attenuation coefficient B.

It was assumed that the deformation area in comparison to the surface of the sphere is relatively low and has no considerable effects of vibrations that were formed as result of impact. Thus, it may be assumed that the mass of the rigid body equals the mass of a sphere and is focused on the centre of gravity. A differential equation describing the sphere movement during the impact has the following form:

$$m\ddot{x} + B\dot{x} + Kx = 0 \tag{5}$$

where:
x – movement of the centre of the sphere mass measured from the moment of contact with a rigid plate,
K – spring rigidness,
B – attenuation coefficient

The force of gravity of the sphere was also neglected assuming that it is much lower than the impact force. This assumption is justified except for cases of low drops and soft objects. The above model was used for development of a determination method of its coefficients using the data from a single drop test and mathematical differential course of the force in time.

Another method of modelling of the impact course was shown by Franke and Rorbach (1981). They presented a movement of the centre of mass of the visco-elastic sphere which collides with a constant flat surface with a non-linear differential equation in the form of:

$$m\ddot{x} + c\frac{v_0}{v_t}\left(1 - e^{\frac{-t}{\tau}}\right)\dot{x} + k\left(x + \gamma\left(1 - e^{\frac{x}{\gamma}}\right)\right) = -mg \tag{6}$$

where:
x – movement,
t – time,
m – sphere mass,
k – spring constant,
c – attenuation constant,
v_o – initial velocity,
v_t – final velocity,
τ – time constant,
γ – relocation constant.

At the following initial conditions $x(0)=0$ and $v(0)=v_o$ the force acting on the flat stationary surface may be defined as:

$$F_s = -\left[c\frac{v_0}{v_t}\left(1 - e^{\frac{-t}{\tau}}\right)\dot{x} + k\left(x + \gamma\left(1 - e^{\frac{x}{\gamma}}\right)\right)\right] \tag{7}$$

where:
F_s – force

Moreover, methods of determination of parameters of the differential equation based on the contact force course in time. The first two methods use analytical formulas that enable determination of the coefficients of the power series that present the contact force course in time. The third method concerns a direct adjusting of the differential equation to the force course measured experimentally through the least squares' method.

Modelling of the impact course

Hamann (1970) described the impact of two identical fruit in the form of an ellipsoid. He assumed that both bodies are isotropic and homogeneous, and they behave linearly visco-elastically. Thus, the value of the uni-axial compression module and Poisson coefficient was constant. The model presented the course of stresses and deformation changes close to the contact zone of both fruit using Hertz equation. The contact surface of colliding bodies was assumed as small in comparison to its total dimensions as well as the course of deformation of the contact surface as monotonically increasing in time. Such a solution would enable determination of the value of the dimpling, surface pressure and internal stresses from the beginning of impact to the maximum deformation time.

Peląg (1984) developed a mathematical model of the mechanism of produce damage. The model assumed a spherical shape of fruit and considered typical cases: contact of two fruit, contact of a fruit with a rigid plate and contact of a fruit with a spherical dimpling. Fruit material properties were expressed by a non-linear relaxation model. The research result was determination of the maximum contact stress and deformation. Equations for the constant force, sinusoidally variable force and the force impulse were developed. It enables a comparison of the damage size caused by a static and dynamic load with the same size.

Equations describing the force course during the non-elastic impact of a body namely a peach with a hard surface were used by (Zhang and Brusewitz, 1991)

$$F = B\, sin(\pi t/T)\, exp(-\pi Rt/T) \tag{8}$$

$$F = Bt^p\, exp(-qt) \tag{9}$$

$$F = Bt^p \left(T-t\right)^q \tag{10}$$

where:
F – force,
t – time,
T – impact time,
B, R, p, q – model parameters

The above equations were compared to assess their precision of adjustment to the experimental course of the impact force in time. In case of peaches, the curve described with an equation (7) has an incorrect shape at the beginning and at the end of the impact process. A sinusoidal factor in equation (7) causes that the curve at the initial and final stage of impact is convex when in reality the reaction force of peaches during the impact is concave. Equation (8) also does not closely reflect the impact course due to the exponential element which causes that the reaction force value at the end of the impact is not zero but aims at the finite value. Whereas the equation (9) liquidates this imprecision.

Henry et al. (2000) developed a three-element model in the form of a polynomial which was an expansion into Taylor progression of the relation force-deformation. Each element described elastic, viscous, and destructing reactions of the material from the initial use of force to the final destruction. The model enables calculation of the elasticity module in any point of the curve, determination of the point of inflection and comparison of samples through suggestion of the theoretical destruction limit. The condition of the investigated material and assessment of the damage might be characterised by the symbol of the model coefficients.

Statistic models

The use of statistical models for assessment of the produce damage resulted from an attempt to characterize the susceptibility to the fruit and vegetables bruising with one parameter. Therefore, analysis of multiple regression was used to relate a mechanical damage (bruising, probability of impact damage, probability of piercing damage) to mechanical, geometrical parameters or cultivar properties. Siyami et al. (1988) used a step analysis of multiple regression using a diameter of a bruise as a dependent variable. Dependent variables were: diameter and mass of an apple, firmness, maximum acceleration, change of speed during the impact. Models were comparable with real bruising of apples “Ida Red” cultivar obtaining a high compliance. Menesatti and Paglia (2001) suggested an index of damage caused by dropping (DDI) which corresponded to the maximum dropping height expressed in mm for which the possibility of fruit damage is 5%. DDI presents a single numerical value which enables comparison of various models of multiple linear regression. Therefore, DDI may be used for determination of the sensitivity or resistance to impact damage of fruit. This index was used in other studies to obtain the most credible statistical model of linear and non-linear multiple regression. It enables more precise estimation of the susceptibility to bruising by including the cultivar specificity of fruit and impact conditions (Menesatti et al., 2002). Studies on the impact of factors related to fruit properties to damage caused by the impact served for development of statistical models that predict bruising of apples (Van Zeebroeck et al., 2007). Linear and non-linear model of multiple regression were used to relate the factors such as: maturity, acoustic rigidness, fruit temperature, curve radius and date of harvesting with bruising damage. The volume of bruising was assumed as the value describing the damage of an apple. The studies showed that the bruising volume decreased along with the rising temperature and harvesting date. While the curve radius of the fruit depended on the impact level.

Numerical methods

Presently, a very dynamic development of numerical methods in impact studies of fruit and vegetables is reported. A commonly used numerical method is the finite element method (FEM). It was used for description of internal stresses resulting from impact forces. This analysis is difficult due to the biological cell structure of fruit and fast deformation process during the impact which is a dynamical and non-linear phenomenon. Thus, this method is an alternative solution serving for forecasting the stresses and deformation distribution that occur in fruit in the conditions of the impact loads. This method replaces partial differential equations that describe a given phenomenon or the polynomial process which may be easily integrated or differentiated. Another problem is a product geometry since it basically affects deformation characteristics which causes that the analysis of the stresses and deformation state becomes more complex. Therefore, simplification of a non-regular fruit geometry to rectangular, spherical, conical, or elliptical shapes is used. Despite these adversities, this method is widely used in the research of fruit and vegetables. Ahmadi et al., (2016) stimulated behaviour of apples treated as a visco-elastic body in three various layers such as skin, flesh, and core. Celik (2017) focused on the issue of susceptibility to bruising through determination of stresses and deformation states of pears in dynamical cases of the impact with a non-linear stimulation of the finite elements method. Imprecision of analyses performed with the FEM results from the fact that the assessment of behaviour of the material in dynamic conditions is made based on the parameters that characterize the fruit of vegetable obtained in the conditions of quasi static conditions (Salarikia et al., 2017; Gao et al., 2018; Nikara et al., 2020).

Another commonly used numerical method is the discreet element method (DEM). The DEM method is used for modelling movement of particles that affect each other as a result of collisions. For example, one fruit may be considered as a particle. Particles may have an irregular shape or be simplified to the spherical shape. In the DEM method force of gravity and the contact acting on the particle are summed up. Then, the formed equations of movement of Newton and Euler are integrated to obtain a speed and location of a particle in the following time step. Particle movement in time and course of its impact are described in such a way. However, the use of this method for biological products has its limitations. Tijskens et al., (2003) paid attention to the fact that produce have irregular shapes which not necessarily are convex. Visco-elastic properties of fruit and vegetables differ significantly from ideal solid bodies and therefore are difficult for assessment. Another impediment is variability of mechanical properties not only between produce but also within the same cultivar. Dintwa et al., (2005) emphasised that the precision of simulation is mainly affected by the contact force model. The model should be possibly simple to limit the complexity of calculations and therefore precisely estimate the relation force-deformation.

Conclusion

The presented literature review shows that no satisfactory mechanical model describing plant tissues under the load has been developed so far, thus, it is difficult to conclude about the behaviour of a product during the impact based on the studies performed in the load conditions that differ from reality. The load is described as dynamic when its application causes distribution of stress in the material in the form of a wave. It takes place when a deforming element in a given moment causes a considerable deformation of one end of a sample while the other end stays non-deformed since the stress wave had not reached it yet. A considerable majority of mechanical damage of fruit and vegetables is caused by impacts. Thus, it may be responsibly concluded that the majority of strength tests of plant tissues performed in quasi-static conditions of load is useful from the practical point of view.

The review showed that the applied measuring methods have their limitations. An inherent problem of the drop methods is the fact that the impact force depends on the mass and radius of the fruit curve thus the big variability of these parameters unfavourably affects the precision of its assessment. An additional impediment is a varied height of fruit dump at the determined settings of the measurement stand resulting from absence of fruit with ideally identical shapes. Therefore, in some experiments, an impacting element with an accelerator is used. On the other hand, in comparison to the fruit drop, methods that use an impacting element have one drawback, namely distribution of energy of impact in more than one spot and no possibility of determination of its percentage participation in particular places of contact. In case when the plant material is dropped onto a stiff surface, the impact energy is absorbed in one place. Additionally, a falling fruit is more precise in real character of the impact. On the other hand, there is a need to weight the dumped fruit due to the relation of the impact energy to their mass. Moreover, there is a problem of obtaining a suitable impact energy in a case when the impacting element mass is considerably lower than the impacted fruit mass. It enforces the need of drop from a height which results in high velocities of the impact load which are inadequate to the real impact on the plant material. This circumstance is significant taking into consideration the fact that fruit and vegetables behave visco-elastically, and their mechanical properties change along with the load velocity.

In case of dynamic loads, we deal with two aspects of these loads with a physical and chemical nature. The physical aspect is a mechanical damage to tissues. The chemical aspect is browning and dark spots resulting from the mechanical impact sufficient for mixing of the substrate and enzyme. If these substances are not freed, a sufficient amount will not be discoloured. For the research on the plant material sensitivity to damage, we need objective indices the values of which will depend on the physiological changes in the damaged tissues while they will be determined based on the material resistance. Among them, we may differentiate the threshold of bruising and resistance to bruising and the maximum dynamic pressure transferred by the tissues without causing further damage. The bruising threshold is a drop height when a sample with a determined mass, shape and the impact surface gets bruised. Resistance to bruising is a ratio of the bruising energy to the bruising volume. It is an inverse of the bruising volume at the determined fall height for a sample with a given mass.

The presented methods seem to be relevant for the majority of produce since these materials have a rather low Poisson coefficient and thus during the impact we do not have to expect their vibrations but rather destruction of tissues around the impact surface. Besides, these materials are destroyed rather as a result of compressing forces and not the shearing ones.

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METODY OPISU I INTERPRETACJI WYNIKÓW TESTÓW UDAROWYCH OWOCÓW I WARZYW

Streszczenie. W artykule przedstawiono sposoby wyznaczania charakterystycznych wielkości przebiegu siły reakcji podczas uderzenia owoców i warzyw mających na celu szybką ocenę ich jędrności lub dojrzałości. Omówiono także różne metody modelowania zachowania się materiałów roślinnych podczas udaru wykorzystujące równania różniczkowe, równania analityczne, modele statystyczne oraz metody numeryczne. Dokonano również przeglądu i oceny metod dynamicznych stosujących zrzut owocu na sztywną płytę oraz technik pomiarowych wykorzystujących sztywny element uderzający w nieruchomy owoc. Przedstawiono wady i zalety tych metod. Modele statystyczne są lepsze do oceny uszkodzenia obicia, ale teoretyczne modele są bardziej przydatne do zrozumienia wpływu różnych czynników powiązanych z uszkodzeniem udarowym. Pokazano również różne próby zastosowania teorii reologicznych opisujących zachowanie się tkanki produktów rolniczych traktowanych jako sprężysty, sprężysto-plastyczny i lepko sprężysty materiał.

Słowa kluczowe: obciążenie udarowe, modelowanie, oszacowanie obicia