Postharvest Biology and Technology 120 (2016) 157–166

Contents lists available at ScienceDirect

Postharvest Biology and Technology

journal homepage: www.elsevier.com/locate/postharvbio

Development of a visco-elastoplastic contact force model and its parameter determination for apples

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ARTICLE INFO

Article history:
Received 20 January 2016
Received in revised form 3 June 2016
Accepted 6 June 2016
Available online 23 June 2016

Keywords:
Apple
Discrete Element Method
Normal contact force model
Mechanical properties

ABSTRACT

A contact force model was developed to model the visco-elastoplastic (VEP) behaviour of apples. The model is based on the elastoplastic Thornton model and has been written in a pressure-based formulation to extend the application of the model to Discrete Element Method (DEM) simulations with arbitrary rounded shapes. The parameters of the new developed VEP contact force model were determined by fitting the experimental data acquired from Jonagold, Joly Red and Kanzi apples impacted by a pendulum. With only one parameter set per cultivar and for a large impact range (impact velocity range: 0.3–1.5 m/s), the VEP-model ($R^2 = 0.90 \pm 0.13$) provides a better description of the force-deformation profiles than the viscoelastic Kono and Kuwabara (KK) model ($R^2 = 0.71 \pm 0.20$). The equivalent Young's modulus (E^*) was also determined under quasi-static conditions, which resulted in measured E^*-values for Jonagold, Joly Red and Kanzi apples of respectively 4.24 ± 0.96 MPa, 5.09 ± 1.27 MPa and 7.82 ± 0.41 MPa. The novel VEP-model has the potential to help predict and understand bruise damage in apples as well as other horticultural products.

1. Introduction

For apples, bruising is the major postharvest mechanical damage problem (Knee and Miller, 2002; Van Zeebroeck et al., 2006). In apples, bruising may occur in several ways. On the tree, apples can bruise by colliding with branches or other apples. At harvest, pickers can damage the apple by applying too high force with the fingers or by dropping the apple into the picking baskets. On their way to the consumer, apples bruise due to the vibrations that occur during the various forms of transport (e.g. fork-lift tractor) and due to impact against other apples or hard surfaces during grading and container transfers. Furthermore, bruise damage may also result from consumer handling in store (rifling) or compression inflicted by the neighbouring apples during transport and storage (Knee and Miller, 2002). Dynamic forces during transport and handling are the main causes of bruise damage (Mohsenin, 1986; Van Zeebroeck et al., 2006). Simulations that can model both the kinematics, dynamics and the resulting bruise damage of apples during transport and handling could help to optimise sorting lines and packaging materials to reduce the likelihood of bruise damage. The Discrete Element Method (DEM) is a suitable numerical technique to perform such simulations (Tijskens et al., 2003). Recently, a new method for modelling arbitrary shapes in DEM has been developed (Smeets et al., 2014), which makes DEM more suitable for modelling fruit by taking into account their non-perfectly-spherical shape. Here, interaction forces are not computed directly, but obtained by numerically integrating the pressure over the contact area between two particles. The latter is important for modelling damage, since bruise damage is related to local pressure levels.

However, a normal contact force model (i.e. a model that relates the normal component of the deformation vector to the normal component of the contact force) that adequately describes both viscoelastic and plastic deformations is still lacking. Apple tissue behaves visco-elastoplastically when the contact pressure exceeds a critical value (Van Zeebroeck, 2005). As yet, the viscoelastic Kuwabara and Kono (KK) model (Brilliantov et al., 1996a,b; Kuwabara and Kono, 1987; Van Zeebroeck, 2005) has been

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http://dx.doi.org/10.1016/j.postharvbio.2016.06.003
0925-5214/

commonly used to describe contact behaviour of fruit and vegetables (Van Zeebroeck, 2005; Ahmadi et al., 2012). This viscoelastic KK-model generalizes Hertz' law to include viscous damping forces that occur during contact between viscoelastic bodies. The KK-model states the following relation for the contact force between particles with radius of curvature R_i (i = 1, 2):

$$F^{KK} = \frac{4}{3}E^*\sqrt{R^*}\left(\delta^{\frac{3}{2}} + A^*\,\delta\,\sqrt{\delta}\right) \tag{1}$$

where δ is the deformation (i.e. the apparent overlap), $\dot{\delta}$ is the relative normal velocity between the two contacting particles, A^* is the equivalent dissipative parameter combining the viscous properties of the two colliding bodies, R^* is the effective radius of curvature and E^* is the equivalent Young's modulus which are defined as:

$$A^* = \frac{A_1 + A_2}{2}, R^* = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1} \text{and } \frac{1}{E^*} = \frac{1-{\nu_1}^2}{E_1} + \frac{1-{\nu_2}^2}{E_2} \tag{2}$$

with E_i and ν_i respectively the Young's modulus and the Poisson's ratio of one of the impacting objects.

The total Hertz pressure that includes the elastic Hertzian pressure (p_e) and the dissipative pressure (p_v) associated with the damping, can be written as (Brilliantov et al., 1996a):

$$p^{KK}(r) = p_v(r) + p_e(r), \text{ with } p_v(r) = \frac{E^*}{\pi}\sqrt{R^*\delta - r^2}\frac{3A^*\dot{\delta}}{R^*\delta} \text{ and } p_e(r) = \frac{2E^*}{R^*\pi}\sqrt{R^*\delta - r^2} \tag{3}$$

The contact parameters of the KK-model have been determined for apples, potatoes, tomatoes and peaches, using a non-linear least square fitting technique on loading data obtained by a pendulum device (Van Zeebroeck, 2005; Ahmadi et al., 2012). Van Zeebroeck (2005) argued that this model can also describe an impact where plastic energy dissipation occurs if the contact force model parameters are allowed to depend on the degree of impact. His justification is that the net effect of both viscous and plastic energy dissipation is captured by the damping term.

Several elastoplastic models have been developed (Kruggel-Emden et al., 2009; Rathbone et al., 2015; Thornton and Ning, 1998; Vu-Quoc et al., 2000; Zhang and Vu-Quoc, 2002). The elastoplastic Thornton contact force model consists of a Hertzian unloading phase and a loading phase comprising a Hertzian elastic part followed by a linear plastic part. The Thornton pressure during loading (p^T_{load}) is depicted in Fig. 1 and is expressed as (Thornton and Ning, 1998):

$$p^T_{load}(r) = \begin{cases} p_e(r) & \delta < \delta_y,\ \dot{\delta} > 0 \\ p_y & \delta \geq \delta_y,\ \dot{\delta} > 0 \end{cases} \tag{4}$$

where p_y is the yield pressure and δ_y is the deformation above which plastic deformation starts to occur. Since, according to this model, the pressure is purely elastic until plastic deformation takes place, δ_y is defined as:

$$\delta_y = \frac{p_y^2\pi^2R^*}{4E^*} \tag{5}$$

In the work of Thornton and Ning (1998), the Thornton force (F^T) during loading was derived via integration of p^T_{load} (Eq. (4)). The net Thornton force during unloading follows from the assumption of a Hertzian unloading phase with a reduced curvature corresponding to the point of maximum compression. For a detailed derivation thereof the Thornton force we refer to the work of Thornton and Ning (1998). The force-deformation relationship of the Thornton model is expressed as:

$$F^T = \left\{\begin{array}{ll} \frac{4}{3}E^*\sqrt{R^*}\delta^{\frac{3}{2}} & \delta < \delta_y, \dot{\delta} > 0 \\ 2E^*\sqrt{R^*\delta_y}(\delta - \delta_y) + \frac{4}{3}E^*\sqrt{R^*}\delta_y^{\frac{3}{2}} & \delta > \delta_y, \dot{\delta} > 0 \\ \frac{4}{3}E^*\sqrt{R_p^*}\left(\delta + R^*\frac{\delta_{max}}{R_p^*} - \delta_{max}\right)^{3/2} & \dot{\delta} < 0 \end{array}\right\} \tag{6}$$

where R_p^* is the corrected effective radius of curvature expressed as:

$$R_p^* = \frac{4E^*}{3F_{\max}}\left(\frac{2F_{\max} + F_y}{2\pi p_y}\right)^{3/2} \tag{7}$$

with $F_{\max}$ the maximum force that occurs at a maximum deformation $\delta_{\max}$ at the end of the loading phase.

The main objective of this study was to enable realistic DEM-simulations with apples, wherein bruise damage can be predicted, hypothesizing that bruising occurs above a certain pressure (yield pressure) threshold. Support for this hypothesis comes from the fact that bruise damage is characterised by the failure of cells on which the stress exceeds a critical value (Baritelle and Hyde, 2001). Modelling bruises based on more simple mechanical measures such as force, impact energy, etc. will lead to less successful predictions since such models neglect the importance of the geometry (i.e. contact area, curvature, etc.) in the problem. To clarify the latter, although the peak force and/or impact energy might be the same in case of an impact in a standardised test and an impact in the apple handling chain, the pressure distribution in both cases may vary significantly from each other since the shape and material properties of the object(s) that come into contact with the apple can differ. Since apple tissue behaves visco-elastoplastically and bruising is related to pressure, an important step towards realistic simulations is the development of a visco-elastoplastic (VEP) model with which the pressure evolution in apple tissue can be computed and which can be used to determine the yield pressure of apples. In this study a VEP model was elaborated that is based on both the KK-model and the Thornton model.

First, the visco-elastoplastic contact force model is introduced and the proposed pressure formulation is related to its force-based equivalent. Next, the experimental set-up and data-processing of the quasi-static and dynamic measurements are described and the model performance is evaluated on experimental data obtained on

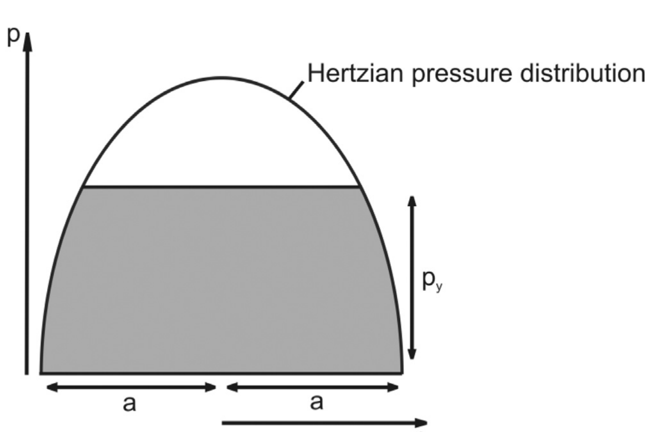

Fig. 1. The pressure distribution assumed by the Thornton model over the contact area with radius a during the loading phase in which plastic deformation occurs (indicated in grey).