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# A new method for measuring impact related bruises in fruits

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ABSTRACT

This paper presents a new method for the direct determination of apple deformation under impact loading conditions that uses a high speed camera. The separately mounted camera was not susceptible to impact oscillations, which allowed for more accurate measurements of displacement. The application of two independent measuring systems, a high speed camera and a force sensor, enabled the quantitative assessment of phenomena occurring during and after the impact of apples against a rigid, flat plate. For the apples with a mass between 170 and 180 g, bruising started at impact velocities of 0.5 m s$^{-1}$. Permanent deformation and maximum stress were the best parameters determining the damage under impact loading conditions. The experiment confirmed the importance of the critical stress criterion as regards the whole fruit under impact loading conditions.

## 1. Introduction

An increasing demand for fresh fruit and vegetables requires mechanical handling, which results in mechanical damage during harvest, transport, sorting, packing and grading. Mechanical damage causes product quality deterioration which results in economic losses. To minimize these losses, some research has been carried out to evaluate the effect of impact and quasi-static loading conditions during harvest and postharvest handling of fruit, vegetables and other materials of biological origin on mechanical damage (Shirvani et al., 2014; Stropek et al., 2014; Li and Thomas, 2014). The most common impact methods are drop tests (Ragni and Berardinelli, 2001; Menesatti and Paglia, 2001; Lewis et al., 2007; Celik et al., 2011; Ozbek et al., 2014; Shafie et al., 2015) and pendulum tests (Yen and Wan, 2003; Opara et al., 2007; Ahmadi et al., 2010; Polat et al., 2012; Stropek and Gołacki, 2013; Abedi and Ahmadi, 2014). The research was focused on detection of different kinds of damages: bruise, puncture, rupture, cracking and abrasion. Bruise is the most frequent symptom of mechanical damage (Opara and Pathare, 2014). It is due to the action of excessive external force on fruit surface during the impact against a rigid plate or fruit against fruit. Impacts have been measured and the bruise size was quantitatively assessed by several authors (Bollen et al., 1999; Kabas, 2010). Another aspect of the research was the determination of bruise size dependence on mechanical parameters such as peak force, impact energy, absorbed energy, impact velocity, drop height (Brusewitz and Bartsch, 1989; Kitthawee et al., 2011; Boydas et al., 2014). Moreover, the factors influencing the bruise damage were determined. The bruise incidence and its size depend on numerous factors, including ripeness, harvest date, temperature, irrigation, weather (Van Zeebroeck et al., 2007). Bruise susceptibility is also affected by macroscopic factors such as size and shape (mass, curvature radius), firmness and turgor (Opara, 2007) as well as microscopic ones which are cell wall strength, elasticity and cell shape (Devaux et al., 2005; Vanstreels et al., 2005; Alamar et al., 2008). The most frequent results of fruit impact measurements are force-time and displacement-time curves. The determination of the force-time curve during impact is not a difficult task, whereas that of the displacement-time curve gives some difficulty. The traditional method consists in measuring acceleration in time and double integration while calculating the initial velocity from the energy conservation law (Fluck and Ahmed, 1973; Lichtensteiger et al., 1988; Jaren and Garcia-Pardo, 2002). However, the double integration results in significant errors that are a result of inaccurate assumptions about integration constants and integration time (Fluck and Ahmed, 1973; Musiol and Harty, 1991). Van Zeebroeck et al. (2003) found that the largest errors occurred at the end of the impact and the final values of velocity and displacement were lower compared to the experimentally determined ones.

To avoid this an attempt was made to determine displacement-time courses by direct measurements. Jarimopas et al. (1990) used an electro-optical displacement follower to determine deformation of whole apples under impact loading conditions. Bajema et al. (1998) installed an angular displacement transducer on the pendulum shaft to measure the hammer position during the impact in the cylindrical apple samples. A similar solution was proposed by Van Zeebroeck et al. (2003) who used a pendulum

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impact device with the incremental optical encoder fixed to the axis to measure displacement in time. Tijskens et al. (2003) determined displacement-time courses by means of computer simulations using the DEM technique.

The above mentioned measuring systems were permanently fixed to a measuring device in a mechanical way. As a consequence, mechanical oscillations may occur during the impact originating from the measuring system. The authors applied a high speed camera to eliminate the effect of mechanical oscillations on the measurement of displacement-time courses during the impact and thus to determine them more precisely. The use of two independent measuring systems, a high speed camera and a piezoelectric force sensor, enabled precise recording of three characteristics—the time shift between the peak force response and peak deformation, the elastic deformation at relaxation, and the third one permanent deformation.

The aim of this research was the determination of force response-time and displacement-time curves as well as of parameters describing the course and effects of such impacts, such as permanent deformation, elastic relaxation after the impact and time difference between the peak force response and peak deformation during the impact. The maximum stress value during the impacts was also calculated. Subsequently, the mechanical parameters were related to the bruise appearance.

## 2. Materials and methods

### 2.1. Research material

The research was carried out on ‘Rubin’, ‘Florina’ and ‘Freedom’ apple cultivars. Fresh apples stored no longer than two weeks after picking up were used in the examination. To eliminate the influence of mass and shape (curvature radius) on bruise size, all fruit were selected to have a mass between 170–180 g and a maximum diameter of 75–80 mm. One of the criteria of fruit selection was their almost spherical shape. This eliminated a large distribution of bruise surface area size. The second important criterion of apple cultivars selection was their firmness. The ‘Florina’ cultivar is considered to be hard, ‘Rubin’ firm and ‘Freedom’ soft. The apples were dropped from six different heights to obtain impact velocities equal to 0.25, 0.5, 0.75, 1, 1.25, 1.5 m $s^{-1}$, which corresponded to drop heights of 3, 13, 29, 50, 80, 115 mm respectively. For each drop height 10 repetitions were made, resulting in testing 60 apples of each cultivar. In total 180 fruit were subjected to measurements.

### 2.2. Apple flesh firmness measurements

To make an appropriate choice of apple cultivars, preliminary research was carried out to determine firmness by means of the manual Magness-Taylor penetrometer. The firmness measurement consisted in determining the maximum force required for punching apple flesh with a bar of 11.1 mm diameter 8 mm deep at constant velocity. Apple skin and a thin flesh layer were removed using a special knife at half the distance between the stem and the calyx perpendicular to the largest apple diameter. The removed skin area had a shape of a circle with a 15–20 mm diameter. To ensure linearity of displacement and constant slope angle of the head, the penetrometer was mounted on a universal stand for drills. To eliminate temperature effects, apples were kept at room temperature for 12 h before examination. Measurements were made on 30 apples from each cultivar of the same mass and size as in the case of impact tests. To account for differences in flesh firmness within a single fruit (blush and non-blush sides), 5 replicate measurements were made for each apple. The accuracy of firmness measurements was 1 N. Based on this, ‘Florina’, ‘Rubin’ and ‘Freedom’ apple cultivars were selected for impact studies. The firmness differed between cultivars in a statistically significant way (Table 1).

### 2.3. Measuring device

The pendulum principle was used in this measuring stand and an apple was the striking object. The pendulum consisted of a pair of supported fishing lines each 1 m long to which a plastic plate with two tangs was fixed. An apple was fixed to the pendulum. The force sensor was screwed into a sliding case clamped to a thick steel plate fixed permanently to a concrete wall. Moreover, a light titanium plate was screwed to the force sensor. Its diameter was a little larger than the fruit bruise area (Fig. 1). The sliding case and clamp-joint made it possible to place the fruit (fixed to the pendulum) into a position vertical to the plate at the impact moment. In this way a perpendicular direction of the impact force to the impact surface was attained. The device was also equipped with control screws, which allowed positioning of a girder (pendulum rotation axis) so that the impact force direction could pass the fruit mass centre. The drop height was determined by means of a scale with the plotted quantities corresponding to the specified free fall values. The force during the impact was measured by means of a piezoelectric force sensor, model 2311-10 with a sensitivity of 2.27 mV/N and a measurement range of ± 2200 N (Technical Manual, 2013). The sensor incorporated a small piezoelectric crystal that was deformed to a very small extent during the impact. Therefore the influence of both the inertia force and of voltage signal delay generated by the deformed piezoelectric crystal on the measurement results could be neglected. At any time the voltage value generated by the piezoelectric crystal was proportional to the applied force. Hence, the error resulting from a dynamic character of apple force response measurement was insignificant and was treated as random.

### 2.4. Measuring apparatus

Two systems were used for measuring impact. To determine the force response course in time, an LMS SCADAS recorder of Siemens company integrated with the LMS Test.Xpress software for data acquisition and analysiswas used. The force response recording frequency was 10 kHz and the measurement was released by means of the trigger after exceeding 0.5 N. The apple impact against a rigid plate was analysed by means of Phanton Miro M320S digital high speed camera of Vision Research company and a lens with the constant focal length of 50 mm. The impact course was recorded by means of the Phantom Camera Control (PCC-2) software at the resolution of 1024 × 768 pixels and velocity of 3300 frames/s.

The measurement errors during image recording with a high speed camera may result from a deviation from perpendicularity of the optical axis of the camera towards the apple motion plane, inappropriate image focus of the observed object, conversion of the apple image dimensions from pixels into length unit (in this case the scale factor amounted to 0.125 mm/pixel).

The camera was placed on a special head enabling regulation along three planes with an accuracy of 1°. The large contrast of the

**Table 1**
Firmness of the tested apple cultivars.

| Cultivar | Firmness (N) | Standard deviation | Standard error |
|---|---|---|---|
| Freedom | 52 | 3.2 | 0.7 |
| Rubin | 64 | 3.5 | 0.7 |
| Florina | 75 | 5.8 | 1.2 |