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DETERMINING APPLE MASS ON THE BASIS OF REBOUND ENERGY DURING IMPACT

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Summary. The article presents a possibility of fruit mass estimation on the basis of response force measurement during impact. The applied method allows to determine the coefficient of restitution. It is calculated on the basis of the force course of two consecutive fruit bounces against a steel plate with a fastened force sensor. The theoretical substantiation of the method was given. For the experimental research Florina and Rajka apple varieties were used, characterized by high firmness and substantial mass dispersion of a single fruit. Before the experiment there was determined the maximum available drop height, at which plastic deformation did not yet occur during the impact. For both the tested varieties 15 mm drop height was assumed. A high correlation was stated between the actual apple mass value and the estimated apple mass value from the impact experiment. For Florina and Rajka varieties the coefficient of determination for the linear regression amounted to 0,994 and 0,998, respectively.

Key words: impact loading, apple, mass estimation, energy coefficient of restitution

INTRODUCTION

Analysis methods of response force during impact can generally be divided into three categories. The first method consists in recording impact force course in time domain and analysis of curve shape. From the shape of response force curve we can conclude the capacity of deformation and determine the parameters related to firmness and damage resistance [Delwiche & Sarig, 1991], [Lichtensteiger *at al*., 1988], [McGlone *at al*., 1997], [Rohrbach *at al*., 1982], [Zhang & Brusewitz, 1991]. The second method consists in determination of energy loss, described by coefficient of restitution. It is defined as the quotient of body velocity just after and before the impact [McGlone & Schaare, 1993]. In the third method impact force course in time domain is transformed into signal in frequency domain. The analysis of this signal allows to determine parameters related to fruit firmness [DeBaerdemaeker *at al*., 1982], [Delwiche, 1987]. From among the three above-presented analysis methods, the second approach was used in this article.

An apple's mass determines its bruise susceptibility because it has an influence both on bruise threshold value and on bruise resistance. It is also significant wherever an apple motion occurs – transport, sorting and packing line. The impact method is a commonly applied one to assess mechanical and qualitative features of an apple. It was also used to estimate kiwifruit mass [McGlone *at al*., 1997]. The strong effect of the apple mass on the value of most mechanical parameters determined in non-destructive conditions of fruit impact at rigid plane is an unfavourable phenomenon. It makes it rather difficult to design an integrated measure position in sorting lines, where it is hard to estimate bruise firmness and bruise susceptibility without considering the mass. On the other hand, an accurate apple mass estimation during twofold non-destructive impact might be realised simultaneously with the firmness estimation or the bruise susceptibility during the apple motion on the line. That creates some alternative for on-line measurement of the apple mass by means of weighing. The aim of this work was to check possibilities of apple mass determination in the impact test designed originally to obtain apple bruise susceptibility. The apple mass was determined from the coefficient of restitution calculated on the basis of surface area value occurring under impact response curve. Force courses in time were obtained during two successive fruit bounces against a steel plate attached to a force sensor.

METHOD OF FRUIT MASS ESTIMATION

As a result of collision of two bodies of specified masses the impulse of force is equal to the total momentum change of the system. If one of the two bodies is fixed (steel plate) and in addition its mass is much higher than that of the other one (fruit), the change of the system momentum is associated with the body of lower mass. For rectilinear motion with the change of impact direction turn, the impulse of the force I is equal to:

$$I = m \cdot (v_p + v_k) \tag{1}$$

m – fruit mass,
v_p – fruit velocity before impact,
v_k – fruit velocity after impact.

The coefficient of restitution e determines the amount of kinetic energy retained by the body during the impact and is defined as:

$$e = \frac{v_k}{v_p} \tag{2}$$

Considering two consecutive bounces of fruit against a steel plate we obtain:

$$I_1 = m \cdot (v_{p1} + v_{k1})$$

$$I_2 = m \cdot (v_{p2} + v_{k2}) \tag{3}$$

It was assumed that the coefficient of restitution is the same during each impact.
Then:

$$e_1 = e_2 = e, \qquad v_{1k} = v_{2p}, \qquad e = \frac{v_{1k}}{v_{1p}} = \frac{v_{2k}}{v_{2p}} \tag{4}$$

In that case, relationship of impulses of forces of consecutive impacts is equal to the coefficient of restitution:

$$\frac{I_2}{I_1} = \frac{v_{2p} + v_{2k}}{v_{1p} + v_{1k}} \tag{5}$$

dividing numerator and dominator by v_{1k} we receive:

$$\frac{I_2}{I_1} = \frac{1+e}{\frac{1}{e}+1} = e \tag{6}$$

The values of impulse force occurring during consecutive impacts can be determined over the integration of the surface area located under the impact force curve in time.
To determine an apple's mass we use the relationship:

$$I = \int_0^{t_1} f(t)dt = m \cdot (v_p + v_k), \qquad v_k = e \cdot v_p \tag{7}$$

t_1 – total impact time.
The final formula has the form:

$$m = \frac{I}{v_p \cdot (1+e)} \tag{8}$$

v_p value is calculated with the energy conservation law by dropping the fruit from a specified height h.

MEASURING STAND

The principle of pendulum action was used at measuring stand for impact tests and an apple was the striking element. The pendulum consisted of a pair of supported fishing line each 1m long to which a plastic plate with two tangs was fixed. An apple was fixed to the pendulum by the tangs. 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 suited the fruit bruise area. The sliding case and the clamp-joint made it possible to arrange the fruit (fixed to the pendulum) in a vertical position to the plate at the impact moment, thereby perpendicular direction of the impact force to the impact surface was obtained. The stand was also equipped with control screws, which allowed to arrange a girder (the pendulum rotation axis) into a position in which the impact force went through the center of the fruit mass. In that way the central collision conditions in the force sensor axis were met. An apple was placed on a requested drop height and remained there by means of suction pump. When the pump was turned off, the fruit was released. The drop height was determined by means of a scale with plotted quantities corresponding to specified free fall values. In order to precisely determine the moment of measurement start we applied a laser – detector gate. The force measurement during the impact was carried out by means of the piezoelectric force sensor, model 2311-10 with sensitivity 2,27 mV/N and the measurement range ± 2200 N [Product specification]. It measures electric charge produced by deformed piezoelectric elements. The force sensor has monolithic structure and is equipped with inner electric circuits, changing electric charge of piezoelement on voltage signal. The microprocessor recorder, which next transmitted data to a computer, cooperated with the force sensor. The sample frequency of the microprocessor recorder reached 38,4 kHz and the maximum amount of the measurement data was 128K.

MATERIAL AND RESEARCH METHOD

The subject of the studies were Florina and Rajka apple varieties characterized by high hardness and significant differences in individual fruit mass. The measurements were carried out in November 2006. After the harvest the fruit was stored in a cold room and carried to the room with temperature of 20°C a day before the research. For each variety the mass of the tested apples varied from 90g to 240g. The mass of the following tested apples differed from each other about 10g. The actual apple mass was determined by means of electronic scale WPT 5 with accuracy to 0,2g. An invariable value of the energy coefficient of restitution was assumed, which required using such experimental conditions, in which the quotient of the dissipation energy in the total impact energy will be identical in both collisions. In accordance with classical mechanics laws, the deformation of loaded material can be divided into elastic, viscous and plastic. During the deformation of tissue material the following phenomena take place: elastic strain cellular wall and gas compression in intercellular spaces, gas and fluid flows in intercellular spaces, tearing and cell rapture as well as tissue delamination. The extent of participation of different types of intracellular phenomena during the impact depend on mass and impact velocity.

The easiest way to guarantee the energy coefficient of restitution repeatability in the consecutive collisions would be the elimination of irreversible deformations, that is the plastic ones. Gas and fluid flows in intercellular spaces may be treated as viscous deformation. Lee and Radok [Lee & Radok, 1960] showed that if the deformation time is shorter than L' relaxation time occurring as a result of stress relaxation deformation, it is possible to describe viscoelastic body on the basis of elastic theory. In the planned experiment the time of the force increase does not exceed 3ms, and the time constant of the stress relaxation for the apple is the order of 200 second [Stropek, 2003]. Hence in the further part of the experiment, apple viscosity during the impact was not considered.

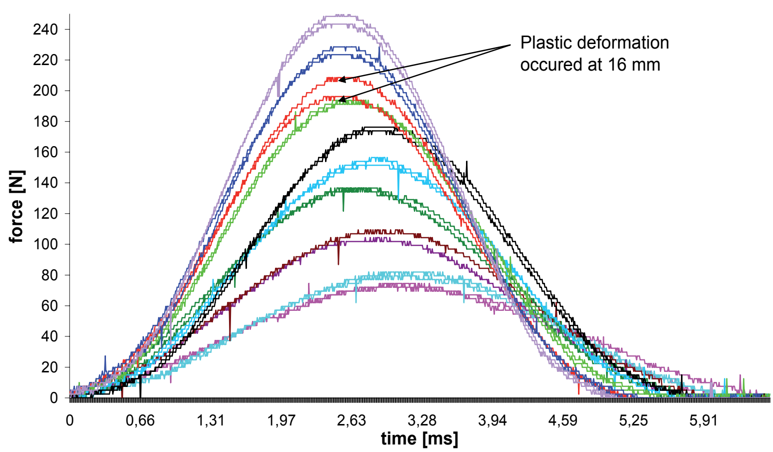

Fig. 1. Example of drop height limit determination procedure. Ten couples of force response profiles represent drop heights equal to 2,4,6,8,10, 12, 14, 16, 18, 20 mm.

In order to determine drop height, by which irreversible strain does not occur yet and strain can be treated as elastic, the method for determining bruise threshold was used [Bajema & Hyde 1998]. This technique involves dropping an apple twice on the same spot from an increasing height. Plastic deformation occurs when there is a discrepancy in force response profiles for two drops from the same height. The overlapping of these profiles testifies reversible deformation at the determined drop height.

Fig. 1. presents an example of „safety drop height" determination. At a drop height of 16 mm a significant difference between two force response profiles can be observed. It means that the safety drop height is situated underneath 16 mm.

The checking experiment was carried out for 20 apples each out of both the apple varieties. For 90% of the cases significant variance of reaction force curve was stated by height of 16 mm or more. Therefore, the height of 15mm was assumed as safe drop height.

RESULTS AND DISCUSSION

The relationship between the actual and the estimated apple mass is strongly linear with the coefficient of determination reaching 0,99 and with the slope near unity. For Florina variety the straight of linear regression had the form y=0,997x+5,404 at R^2=0,994, and for Rajka variety y=1,02x-1,008 at R^2=0,998. The following captions of the regression line coefficient: y = ax + b were assumed. Dash line means 95% confidence interval for regression line.

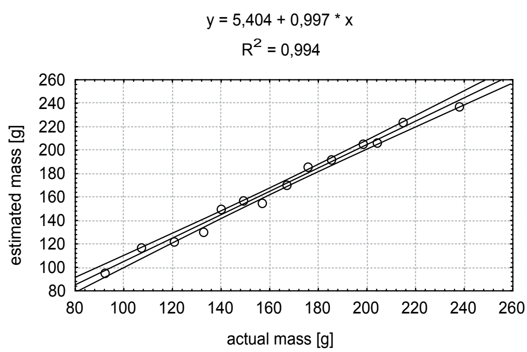

Fig. 2. Relationship between estimated and actual mass for variety of Florina apple.

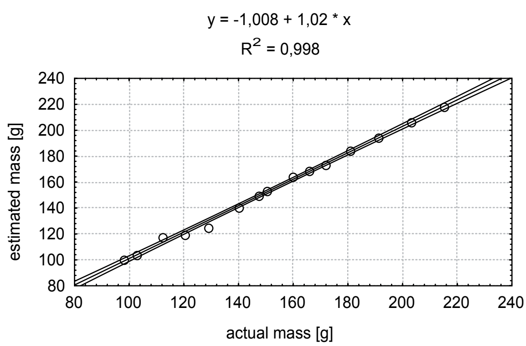

Fig. 3. Relationship between estimated and actual mass for variety of Rajka apple.

Parameters *a* and *b* in linear regression functions are loaded with errors, which were calculated by means of the least square method. For Florina variety they had Δa=0,034 and Δb=5,753 values, and for Rajka variety they reached Δa=0,016 and Δb=2,539.

The described method of mass estimation does not require the tested object to stop on the surface. That is why it can be used at fruits/vegetables sorting lines. There is a certain disadvantage of this method that a fruit has to bounce twice. It is related to specified duration of the measurement time depending on fruit elasticity and drop height. The use of this method in modern sorting lines would require a design of a suitable measure position in order to reduce the transport time of a single fruit.

However, the above method is useful while estimating fruit firmness by means of impact response force analysis.

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