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New nondestructive method based on spatial-temporal speckle correlation technique for evaluation of apples quality during shelf-life**

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A b s t r a c t. This paper presents a new spatial-temporal speckle correlation technique applied for quality evaluation of apples. Evaluations were performed using a nondestructive and noninvasive method based on the interpretation of an optical phenomenon that occurs when the fruit is illuminated with coherent light, referred as biospeckle. The temporal and spatial changes of speckle patterns created by laser light scattered in fruit have been measured through their correlation functions. The cross-correlation coefficient of biospeckle patterns decrease or increase in fruits with different speeds subject to conditions of their freshness, moisture and preservation. Significant exponential changes of the cross-correlation coefficient value difference $C_{t=15}$ were observed during apple shelf life. This shows that the method can be utilized for quality evaluation of apples.

K e y w o r d s: nondestructive method, speckle phenomena, apple, shelf-life, cross-correlation coefficient

INTRODUCTION

Texture, appearance, flavour and nutrition are main quality factors in foods (Bourne, 2002). Szcześniak (2002) gives a description of the texture as the sensory and functional manifestation of structural, mechanical and surface properties of foods detected through the senses of vision, hearing and kinesthetics. The texture as the quality parameter is also important for apples (Dobrzański *et al.* 2000; Konopacka and Płocharski, 2002, 2004). Quality of apples changes in time because it is a living organism where many chemical and physics processes occur constantly. For example, fruit softening which occurs during ripening results from the loss of cell cohesion (Van Buren, 1991). Pectolytic enzymes and changes in pectin composition are responsible for the decreased adhesion between cells and have been the focus of numerous studies of fruit ripening (Johnston *et al.* 2002). The cold temperature slows ripening process, but does not stop it. Usually, during long term cold storage or during shelf-life apples lose firmness significantly due to water evaporation, chemical processes of pectines within intercellular lamellas and within cell walls (Lin *et al*., 1999).

For nondestructive testing of fruits and vegetables many optical techniques are used (Butz *et al*., 2005), like laser scattering (Tu *et al.,* 2006), Doppler spectroscopy (Briers, 2001; Ul'yanov, 1995), microscopy (Rogers, 1991) and simple surface inspections (Tao and Wen, 2002). The nondestructive techniques are used for the assessment or inspection of quality parameters of fruits including internal disorders but also taste, sugar content, and so forth.

A state of a fruit is related to living processes within cells, therefore a detection of particles movement can be used for quality monitoring of the tissue. When a laser illuminates a rough surface, a diffused reflected laser light exhibits mutual interference and forms random bright and dark spots, called laser speckle in space. Since the surface height variation for the diffuse object is usually random, the properties of the speckle, such as the intensity and the average size, can only be analysed statistically. The spatial appearance of the speckle pattern is determined by the

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characteristics of the rough surface, the property of the laser beam and parameters of an optical-digital system generating and recording the speckle pattern.When laser light impinges on the surface of biological material, it will pass through one or more layers (air space, skin, cell walls), each of them will act as a stationary diffuser (Junior *et al*., 2006). Particles within the material are thus illuminated by a laser speckle field and will scatter the laser light back out through the air space. Hence the laser light is diffused many times before finally a speckle field is formed in space. If the particles within the biological material are in motion, the speckle field exhibits temporal fluctuations and is said to 'boil' or 'twinkle' (Rabal *et al*., 1996). This phenomenon had been referred to as 'biospeckle'.

This biospeckle phenomenon has been used for measuring motion of particles within botanical samples, for sensing the age of a botanical sample (Zheng *et al.*, 1994), which would be an indicator of shelf life, for study blood flow monitoring in the retina and other tissues (Asakura and Takai, 1981; Briers *et al.*, 1999).

The goal of this paper is presentation of the new method for nondestructive quality evaluation of fruits and vegetables based on spatial-temporal speckle correlation technique and evaluation of changes of apple quality during shelf-life by this method.

MATHERIALS AND METHODS

Definition of speckle size

In Fig. 1, a structure of an optical system for creation of subjective speckle pattern (the speckle pattern is called subjective, if a lens is used to image the reflecting surface onto a screen) is shown. In this case, the structure of the optical system is very important element for applying the digital speckle correlation (DSC) technique, because an average speckle size should be much larger than a pixel size of a digital camera. The average speckle size contains two parts: parallel and ortogonal.

In coherent optical system the orthogonal average speckle size is defined as (Sjödahl and Benckert, 1994):

$$\varepsilon\perp = 1.22\frac{\lambda z}{D}, \tag{1}$$

where: λ is the wavelength of a monochromatic light, D is the dimension of a lens aperture and z is the distance from the aperture to an image plan. If a speckle is recorded by a matrix sensor, the Nyquist criterion must be taking in account for definition of the average speckle size. Because the power spectral density of a speckle pattern has the restricted spectrum with limiting spatial frequency $\alpha_{\max} = D/\lambda f$, the maximum pitch between two adjacent pixels is connected with a speckle size by next equation (Sjödahl and Benckert, 1993):

$$\max\left|\delta_x, \delta_y\right| \le \frac{\lambda z}{2D}. \tag{2}$$

Taking in account Eq. (1), Eq. (2) can be rewritten as (Sjodahl and Benckert, 1993):

$$\max\left|\delta_x, \delta_y\right| \le 0.41\,\varepsilon\perp.$$

Spatial-temporal speckle correlation technique

In the digital speckle correlation (DSC) technique a measuring process is based on correlation analysis of a reference speckle pattern of the specimen in its initial state with sequential speckle patterns while changing the surface or subsurface of the specimen (Sjödahl, 1998). Usually a set of images with an appropriate interval is taken in time. As all data are stored in the image processing system, any two images (patterns) can be compared to analyze the changes between the associated object states. The recorded patterns are entered into computer where they are divided into two matrixes of isometric fragments. Further, cross-correlation of each pair of respective fragments (fragments with identical indexing) occurs. As a result of cross-correlation of all respective fragment pairs, the rectangular grid of correlation peaks is generated. The location of each peak can be considered as the end of a displacement vector of a fragment in a digital speckle pattern 2 concerning the location of a respective initial fragment in a digital speckle pattern 1.

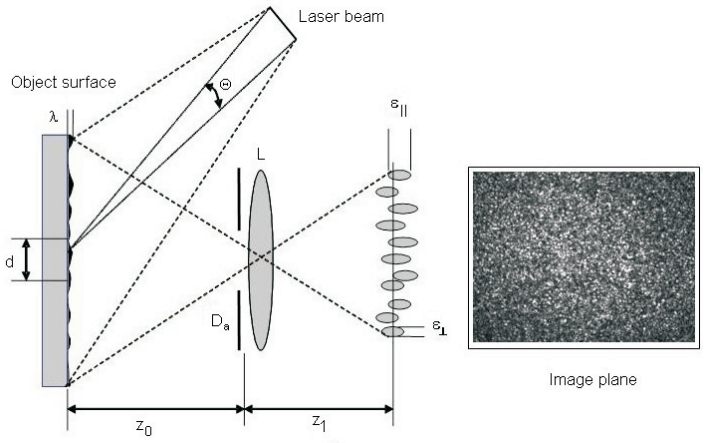

Fig. 1. Creation of the subjective speckle pattern.

If one uses the DSC techniques and divides two digital patterns 1 and 2 into two matrixes of $M \times N$ rectangular isometric fragments, the cross-correlation function of respective fragment pairs with identical indexing can be expressed as:

$$C_{m,n}(k,l) = \frac{1}{IJ} \sum_{i}^{I} \sum_{j}^{J} r_{m,n}(i,j) s_{m,n}(i+k, j+l), \quad (3)$$

where: $r_{m,n}$ is the m, nth fragment of the pattern 1, $s_{m,n}$ is the m, nth fragment of the pattern 2, m=1, ..., M and n=1, ..., N are the numbers of fragments, i=1,..., I and j=1,..., J are the numbers of fragment pixels, k=1,..., K and l=1,..., L are the discrete samples of the cross-correlation function. Displacement of the cross-correlation function's maximum *ie* the cross-correlation peak, concerning the centre of a fragment $r_{m,n}$ or the peak maximum of an autocorrelation function defines a displacement value and direction of a fragment $s_{m,n}$ after a specimen changes.

Because the use of a frequency domain in a digital image processing greatly reduces an amount of calculations, the most frequently applicable algorithm for a cross-correlation function calculation can be is expressed by:

$$C_{m,n}(k,l) = F^{-1}\left[R_{m,n} S^*_{m,n}\right], \quad (4)$$

where:

$R_{m,n}(p,q) = F\left[r_{m,n}(i,j)\right]$, $S_{m,n}(p,q) = F\left[s_{m,n}(i,j)\right]$,

F is the FFT operator, F^{-1} is the inverse FFT operator, * is the symbol of a complex conjugated function, p=1,..., P and q=1,..., Q are the discrete spatial frequencies.

In order to raise a peak-to-noise ratio (PNR) *ie* a ratio of a peak maximum intensity to dispersion of noise samples surrounding a peak, and also to raise peak sharpness and to narrow a peak width, a spectrum $R_{m,n} S^*_{m,n}$ is filtered by a fractional power filter. Using such filter, the cross-correlation of two fragments $r_{m,n}$ and $s_{m,n}$ is expressed as:

$$\tilde{C}(k,l) = F^{-1}\left[\frac{R_{m,n} S^*_{m,n}}{\left|R_{m,n} S^*_{m,n}\right|^{v/2}}\right], \quad (5)$$

where: the filter parameter v accepts only real values.

In the case of living material as fruits and vegetables speckles changes in time, thus a spatial-temporal digital speckle correlation technique should be used and due to heterogeneity of the object surface imaging field should cover few square centimetres. In the present study, an optical system is set up allowing surface pattern analysing of a few square centimetres by calculating the temporal fluctuations of biospeckle patterns. These patterns were created by coherent light illumination of the selected area and its multifold recording by digital camera. To obtain the temporal dependencies of biospeckle pattern movement speed, each pattern was separated on M by N subimages and each m,nth subimage was correlated with respective subimage belonging to any other pattern of the same studied area. As a result, cross-correlation coefficients were obtained using the equation:

$$C^{k\tau}_{m,n} = \left| \frac{\left\langle \left(S^{t0}_{i,j} - \left\langle S^{t0}_{i,j} \right\rangle \right) \left(S^{t0+k\tau}_{i,j} - \left\langle S^{t0+k\tau}_{i,j} \right\rangle \right) \right\rangle}{\sigma^{t0}_{i,j}\, \sigma^{t0+k\tau}_{i,j}} \right|, \quad (6)$$

where: i, j is the pixel number in the m, n^{th} subimage of the digital biospeckle pattern, i=1,…, I, j=1,…, J, m=1,…, M, n=1,…, N, $S_{i,j}$ is the i, j^{th} pixel intensity, k is the number of a biospeckle pattern, τ is the interval between two adjacent frames containing recorded biospeckle patterns,

$\sigma_{i,j} = \sqrt{\left\langle \left(S_{i,j} - \left\langle S_{i,j} \right\rangle \right)^2 \right\rangle}$ is the variance.

Calculation of the cross-correlation coefficients for series of speckle pattern's subimages recorded in the given temporal order allows receiving the temporal dependencies of these coefficients as functions of the biospeckle pattern movement speed. Each such dependency is equivalent to temporal degradation of correlation peak. The matrix of calculated coefficients can be considered as the rectangular grating of correlation peaks. The difference of the biospeckle movement speed in different parts of the studied area leads to nonequivalent degradation of correlation peaks belonging to this grating. In this case, the varied degradation of each peak, which considers the biospeckle fluctuation speed of a respective part of the area, can be studied.

If the biospeckle properties of each surface subimage are homogeneous, the biospeckle pattern movement speed is equal for every part of the studied surface area. Therefore, the correlation peaks, which locations correspond to locations of selected subimages, become degraded with equal speed. Due to homogeneity of biospeckle properties of each surface fragment, the intensities of all correlation peaks belonging to rectangular peak grating have changed similarly. In this case, the peak grating can be changed by one peak, which intensity is calculated as a mean value of intensities of all peaks and the correlation coefficient can be expressed as:

$$C^{k\tau} = \left| \frac{\left\langle \left(S^{t0}_{im,jn} - \left\langle S^{t0}_{im,jn} \right\rangle \right) \left(S^{t0+k\tau}_{im,jn} - \left\langle S^{t0+k\tau}_{im,jn} \right\rangle \right) \right\rangle}{\sigma^{t0}_{im,jn}\, \sigma^{t0+k\tau}_{im,jn}} \right|, \quad (7)$$

where: im=1,…I,…,2I,…, MI and jn=1,…,J,…, 2J,…, NJ.

Experimental setup

The experimental setup of a Digital Speckle Correlation system is schematically shown in Fig. 2. The quasi-monochromatic light of wavelength λ from a laser source is filtered and expanded so that the object under investigation

is illuminated by a collimated beam under an angle θ. The scattered light is collected by a lens and imaged onto the target of a digital camera with a high resolution charge-coupled-device (CCD). Instead of a single lens, a more complex imaging system, for example a standard photographic lens, can be used. Yet, the specimen's surface and the camera target are assumed to be in conjugate planes *ie* the image of the specimen is focused onto the target. The images taken by the camera are transferred to a PC based image processing system where they can be displayed and analyzed.

In order to study the biospeckle temporal properties of apples the experimental setup was mounted. This setup is shown in Fig. 3 and contains a He-Ne laser (5 mW) with λ=632.8 nm, a photographic objective for expanded laser beam, a specimen, which was placed on a coordinate table, a digital camera with special objective and transition rings, camera was connected to PC with developed software. The optical part of the setup was disposed on the special table for decreasing the influence of vibrations.

The angle of incidence of the laser beam on the botanical specimen was equal to 30 grades. The average speckle size was adjusted to make it much larger than the pixel size of the camera, which is 4.65×4.65 μm. For given experiments, the studied area sizes equal to 30 mm^2 was chosen. This corresponds to resolution of 640×480 pixels. Such area's dimensions allow neglecting the curvature of botanical specimen surfaces. For experiment, the recording time equals to 15s with the frame rate equals to 15fps were chosen.

Materials

For the experiment 24 apples (*Malus Domestica,* cv Jonagored) were bought as one batch at local grower. Apples were stored in controlled atmosphere for 5 months prior to experiment. Next, the material was stored in room conditions with temperature 20°C for 12 days in laboratory without humidity control for shelf-life simulation. The investigation area on apple was their blush side. The apples were numbered and the observation area was marked on each of them. At every second day measurements were performed on the same place of apples.

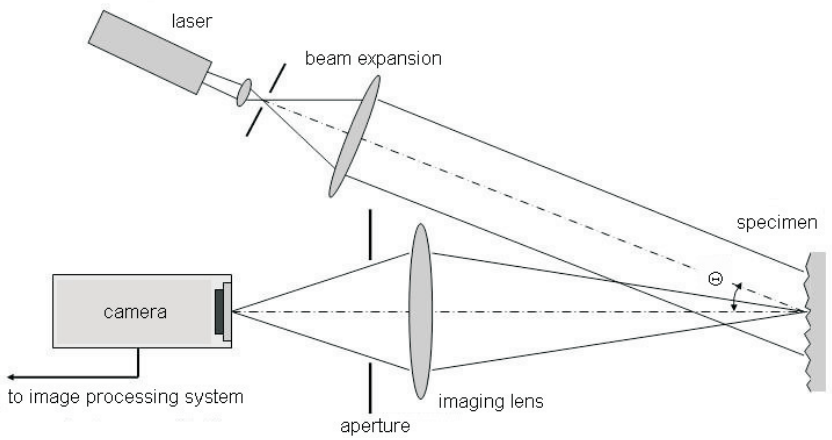

Fig. 2. Experimental setup for Digital Speckle Correlation system.

Fig. 3. Experimental setup for studying of apple specimen biospeckle temporal properties.

RESULTS AND DISSCUSION

The images of speckles were obtained as a movie. Form the movie following would be noticed:

- Biospeckles fluctuate with time while speckles of material surfaces practically do not change in stationary conditions.
- Biospeckles are created not only by light scattering on a surface but also by scattering inside a botanical specimen in the thin layer under the surface. It was visible that there were immobilized speckle probably from the apple skin and moving speckle probably from deeper parts of apple.

The movies were next recorded as speckle pattern series (series of images) and they were processed in PC by special software developed. The software calculated the correlation coefficients $C^{k\tau}$ according to Eq. (7). These data were used to plot the temporal dependencies of these coefficients (Fig. 4).

The similar graphical dependencies of the cross-correlation coefficient versus time of ageing were obtained for all 24 apples. Temporal changes of the cross-correlation coefficients for apple surface number 9 are presented in Fig. 4 as an example. As it is seen, the cross-correlation coefficient decreases faster when apple is fresher. The cross-correlation coefficient $C^{k\tau}$ of the one day-old apple drops from 1 to 0.59 in 15 s, whereas in the same time the cross-correlation coefficient $C^{k\tau}$ of the twelve day-old apple drops from 1 to 0.8. This phenomenon can be explained by mobility of particles inside the cells. Xu *et al.* (1995) stated that the higher water content in the cells of the specimen provides higher mobility to the moving particles in the cells while the particles inside the deteriorating cells have less mobility due to decreasing of living activity. Shelf life storage causes both decreasing water content and decreasing particles movement (slowing down living processes). Therefore, also the cross-correlation coefficient decreases slower for less fresh tissue.

Then, for all 24 graphical dependencies, the cross-correlation coefficient difference $\Delta C^{k\tau}$ between the value of the cross-correlation coefficient $C^{k\tau}$ equal to 1 and $C^{k\tau}$ value for point t equal 15s was chosen.

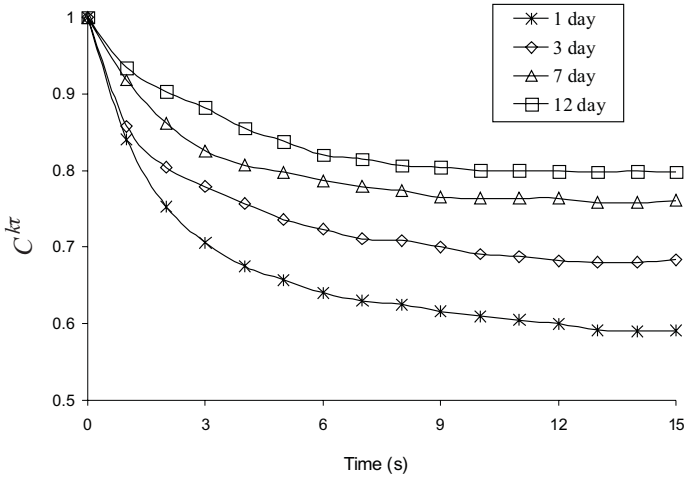

Fig. 4. Temporal changes of cross-correlation coefficients for apple surface during shelf-life storage (12 days).

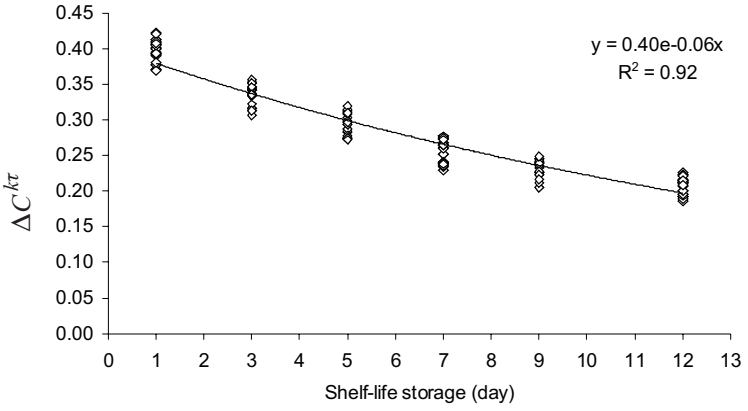

Fig. 5. The cross-correlation coefficient value difference $\Delta C^{k\tau}$ in a function of storage day (shelf-life).

These dependences of the cross-correlation coefficient value difference $\Delta C^{k\tau}$ for all apples of 12 days storage are shown in Fig. 5. From this figure, it is easy to see, that the $\Delta C^{k\tau}$ decreases with increase of the shelf-life storage time. The change has an exponential character similar to observed in previous research using puncture test (Zdunek and Ranachowski, 2006). For the material used in the experiment at the first day (freshest apples) $\Delta C^{k\tau}$ has value 0.4 and decreases approaching 0 for long term shelf life storage (softening of apple flesh) when living processes in apples completely stop. In Fig. 5, all experimental points are shown and it is visible that there are significant differences between groups of points obtained with the time interval equals 2 days. The correlation coefficient R^2 is 0.92. The maximum scattering of points obtained for 24 apples at the same day is not higher than 0.06 and confidence interval (α=0.05) to the mean value ratio is equal to 1.6% for the freshest apples and 2.6% for lowest quality apples. It shows that proposed method is accurate and very sensitive for quality changes of the apples during shelf-life.

CONCLUSIONS

1. The cross-correlation coefficient of biospeckle patterns decreases faster when apple is fresher.

2. Significant exponential changes of the cross-correlation coefficient value difference $\Delta C^{k\tau}$ were observed during apple shelf life. This shows that the method can be utilized for quality evaluation of apples.

3. Due to nondestructive way of testing there is possibility also to use the spatial-temporal digital speckle correlation technique on line. However, the most important problem to be solved will be preventing the system from vibration.

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