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COMPARISON OF PUNCTURE TEST, ACOUSTIC EMISSION AND SPATIAL-TEMPORAL SPECKLE CORRELATION TECHNIQUE AS METHODS FOR APPLE QUALITY EVALUATION*

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A b s t r a c t. A major quality problem for producers and consumers of apples is their softening during storage. This paper presents comparison of three methods for monitoring quality changes of apples during shelf-life storage: puncture test with acoustic emission and spatial-temporal speckle correlation technique. Firmness, acoustic emission counts and cross-correlation coefficient difference obtained by these methods, respectively, were analysed. The parameters show different correlation coefficients with time of storage. The highest correlation coefficient was obtained by the non-destructive spatial-temporal correlation technique. Puncture test with acoustic emission shows also significant changes with time and these methods provide information about mechanical properties and especially about the fracture properties of the material. Higher correlation coefficient between firmness and acoustic emission counts was obtained than between firmness and cross-correlation coefficient difference. The experiment has shown that for testing the quality of apples there is no difference related to the side of apples.
K e y w o r d s : nondestructive method, biospeckle, acoustic emission, puncture

INTRODUCTION

The apple industry is one of the largest producers and exporters of fresh produce in Poland. A major quality problem is apple softening during storage. This

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undesirable ripening process results in decrease of apple crispness, crunchiness, juiciness and increase of apple mealiness (Abbott *et al.* 1984, Harker *et al.* 2002). These texture attributes have origin in the sensory analysis of food stuff. Szcześniak (2002) gives a description of texture as sensory and functional manifestation of structural, mechanical and surface properties of foods detected through the senses of vision, hearing and kinesthetics. Although the sensory evaluation is a widely accepted method for quality decision making, instrumental methods for food texture evaluation are also looked for. Since eating is a highly destructive process, the most popular instrumental methods base on high deformation mechanical testing. Puncturing, compression, tension and bending are examples of many different tests used. The parameters obtained relate to elastic properties and to fracture properties of the material. Puncturing is one of the tests which is the simplest and the most popular for apples. The maximum force of puncturing is the apple firmness. Many works were done showing decrease of the firmness during apple storage (Dobrzański *et al*. 2000, Konopacka and Płocharski 2002 and 2004). Apple softening during storage is considered as related to changes in pectins during ripening (Johnston *et al.* 2002, Lin *et al.* 1999). Enzymatic degradation of pectins decreases mainly cell-cell adhesion, which leads to decrease of firmness of the tissue. The second important process from the point of view of tissue firmness is turgor decrease during storage (Tong *et al.* 1999). Tissue under high turgor fails by cell wall rupture, whereas tissue under low turgor fails by cell separation (Lin and Pitt 1986, Niklas 1992). High turgor increases tissue firmness due to high preliminary tension of the cell walls and due to higher intracellular pressure which increases contact forces between cells as well. Deformation of highly turgid tissue causes fast increase of the response force, however cell wall rupturing starts at lower deformation compared to tissue under low turgor. The cracking processes can be analysed using acoustic emission (AE) method. The method has been applied for potato and apple tissue (Zdunek and Konstankiewicz 2004, Zdunek and Bednarczyk 2006, Zdunek and Ranachowski 2006). The AE can detect cell wall rupturing, thus the failure mode through cell wall rupturing can be analysed. It has been shown that the number of acoustic events or counts in compressed potato tissue decreases with turgor decrease or when degradation of pectins in middle lamellas has occurred after temperature treatment. Similarly, apple tissue tends to decrease the number of acoustic events when turgor decreases (Zdunek and Bednarczyk 2006). Zdunek and Ranachowski (2006) showed that the number of acoustic events also decreases during shelf-life storage of apples when pectin degradation and water evaporation occur. These results are interpreted such that AE events or AE counts relate to sudden rupturing of cell walls during deformation, not to the cell-cell separation process.

On-line quality evaluation of fruits requires using non-destructive methods. Among many of them, optical techniques are used (Butz *et al.* 2005), like laser scattering (Tu *et al.* 2006), Doppler spectroscopy (Ul'yanov 1995), microscopy (Rogers 1991) and simple surface inspections (Tao and Wen 2002). The non-destructive techniques are used for the assessment or inspection of quality parameters of fruits including internal disorders, but also taste, sugar content, and so forth. Lately, a new non-destructive method, so called spatial-temporal speckle correlation was introduced for evaluation of changes of apple quality during shelf-life (Zdunek *et al*. 2007).

In the spatial-temporal speckle correlation method a laser illuminates an object. When laser light impinges on the surface of biological material, it will pass through one or more layers (air space, skin, cell walls) and 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”. The measurement technique bases on correlation analysis of a reference speckle pattern of the specimen in its initial state with sequential speckle patterns while the surface or subsurface of the specimen changes. Usually a set of images are taken, with an appropriate interval in time. The recorded patterns are entered into a 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.

In the case of living material, such as fruits and vegetables, speckles change in time, so they can be called biospeckles. To obtain the temporal dependencies of biospeckle pattern movement speed, each pattern is separated on *M* by *N* subimages and each *m, n*th subimage is correlated with the respective subimage belonging to any other pattern of the same studied area. As a result, cross-correlation coefficients can be calculated using the formula (Zdunek *et al.* 2007):

$$C_{m,n}^{k\tau} = \left| \frac{\left\langle \left(S_{i,j}^{t_0} - \left\langle S_{i,j}^{t_0} \right\rangle \right) \left(S_{i,j}^{t_0+k\tau} - \left\langle S_{i,j}^{t_0+k\tau} \right\rangle \right) \right\rangle}{\sigma_{i,j}^{t_0} \cdot \sigma_{i,j}^{t_0+k\tau}} \right|, \tag{1}$$

where: i, j is the pixel number in the m, n^{th} subimage of the digital biospeckle pattern, $i = 1,\ldots, I$, $j = 1,\ldots, J$, $m = 1,\ldots, M$, $n = 1,\ldots, N$, $S_{i,j}$ 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.

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 whose 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 change similarly. In this case, the peak grating can be changed by one peak, the intensity of which is calculated as a mean value of intensities of all peaks and the cross-correlation coefficient can be expressed as:

$$C^{k\tau} = \left| \frac{\left\langle \left(S_{im,jn}^{t_0} - \left\langle S_{im,jn}^{t_0} \right\rangle\right)\left(S_{im,jn}^{t_0+k\tau} - \left\langle S_{im,jn}^{t_0+k\tau} \right\rangle\right) \right\rangle}{\sigma_{im,jn}^{t_0} \cdot \sigma_{im,jn}^{t_0+k\tau}} \right|, \qquad (2)$$

where: $im = 1,\ldots I,\ldots, 2I,\ldots, MI$ and $jn = 1,\ldots, J,\ldots, 2J,\ldots, NJ$.

The spatial-temporal speckle correlation method was applied for apples during 12 days of shelf-life (Zdunek *et al.* 2007). In the experiment the cross-coefficient (Eq. 2) was analysed for the same places on apples. It was observed that the cross-correlation coefficient decreased faster if apples were more fresh. For observing changes during storage the cross-correlation coefficient difference $\Delta C^{k\tau}$ between the value of the cross-correlation coefficient equal to 1 and for point t equal to 15 s were chosen. The $\Delta C^{k\tau}$ decreases exponentially with time of apple storage.

Previous experiments have shown that the acoustic emission method and spatial-temporal speckle correlation method allow for quality evaluation of apples (Zdunek and Ranachowski 2006, Zdunek *et al.* 2007). However, the AE counts and cross-correlation coefficient $\Delta C^{k\tau}$ at this moment are not yet as well researched in the food domain as the firmness is. The first of them is a destructive method, however it provides important data about the fracture properties of apples. The AE method gives higher determination coefficients with storage time than firmness from puncture test. The second one is a non-destructive method and also can be used for quality evaluation of apples. However, the spatial-temporal speckle correlation method has never been compared with firmness yet. Since firmness is the most used parameter for softening evaluation of apple, other methods should be referred to the puncture test. The goal of this research is to compare the acoustic emission method and the spatial-temporal speckle correlation method with the puncture method for the evaluation of apple quality.

MATERIALS AND METHODS

For the experiment 72 apples (*Malus Domestica*, *cv* Jamba) were bought as one batch at a local grower just after harvest. Apples were only roughly selected according to size and shape. After 5 days of cold storage the apples were divided into 6 groups. The first group were tested on the second day after removing apples from cold storage to room conditions. The remaining groups were left in room conditions in order to simulate shelf-life for 13 days. The tests were performed after 4, 6, 8, 11 and 13 days of the shelf-life. On both blush and shaded side of each apple the investigation areas where marked. For each of the investigation areas the spatial-temporal speckle correlation method was used first, and next the puncturing with acoustic emission method was performed on the same places. The method of measurements of acoustic emission during the puncture test has been described by Zdunek and Ranachowski (2006).

The experimental setup for the spatial-temporal speckle correlation method is schematically shown in Figure 1. Quasi-monochromatic light of wavelength λ from a laser source (He-Ne laser, 5 mW, λ = 632.8 nm) was filtered and expanded so that the object under investigation was illuminated by a collimated beam under an angle $\Theta = 30°$. The scattered light was collected by a lens and imaged onto the target of a digital camera with a high resolution charge-coupled-device (CCD). Yet, the specimen surface and the camera target are assumed to be in conjugate planes,

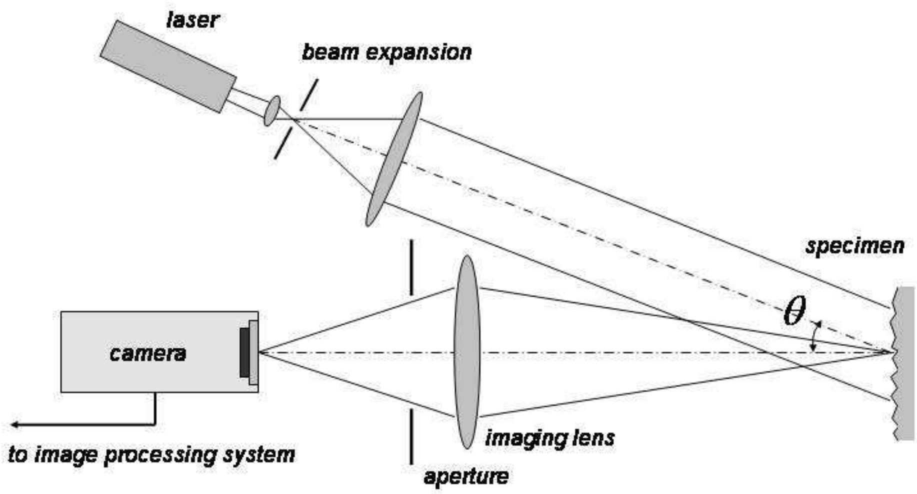


Fig. 1. Configuration of the system for spatial-temporal speckle correlation method

i.e., the image of the apple was focused onto the target. The whole system was placed on an anti-vibration plate. When the apple was illuminated by the laser, a 24-second movie was taken with 15 fps rate. Next, the movie was converted into frames with resolution of 640×480 pixels and cross-correlation coefficient $C^{k\tau}$ according to equation 2 was calculated for each frame. The average speckle size was adjusted to make it much larger than the pixel size of the camera which was 4.65 μm per pixel. For given experiments, the studied area size equal to 30 mm^2 was chosen. Such area dimensions allow neglecting the curvature of apple surfaces.

The puncturing tests were performed using a universal testing machine Lloyd LRX with 500 N load cell and the program Nexygen (Lloyd Instruments Ltd, Hampshire, UK) provided with the apparatus. A crosshead speed of 20 mm min^{-1} was used in both mechanical tests.

Acoustic emission (AE) during the puncture test was recorded using an AE head with an acoustic emission sensor. The AE head and the sensor position were described by Zdunek and Ranachowski (2006). In this research the 4381V sensor (Bruel&Kjear, Narum, Denmark) was used working in audible range of 1-16 kHz. The sensor was connected by a 2 m cable to AE Signal Monitor (EA System S.C., Warsaw, Poland). The AE Signal Monitor was set to a discrimination level above the noise level of the Lloyd LRX and it counted peaks of the AE signal and stored them in internal memory at every 100 ms. This descriptor is called the AE count rate. The sum of the AE counts in the whole puncturing is called AE counts. To the AE head, the puncture probe of 11.1 mm of diameter with spherical ending, made of the same material as the AE head, was screwed making solid contact between punctured apple and the sensor. Before puncturing the skin the apples were sliced (2 mm thickness). The puncturing was performed using 20 mm min^{-1} speed and depth of 8 mm. Maximum force was read as the firmness of the apple.

RESULTS AND DISSCUSION

Calculation of the cross-correlation coefficients $C^{k\tau}$ for each frame of the movie of the apple speckles allows obtaining its changes in time as it is shown as an example in Figure 2. The example is shown for a fresh apple (1 day of shelf-life) and for a soft one (13 days of shelf-life). The difference between these two periods of storage is in the rate of changes of $C^{k\tau}$ in time. For fresh apples the rate of cross-correlation coefficient decrease in time is much higher than for very soft apples. As the indicator of the rate of decreasing of cross-correlation coefficient the difference $\Delta C^{k\tau}$ between the $C^{k\tau}$ at the first second and the 15th second was chosen for evaluation of apple quality in storage time.

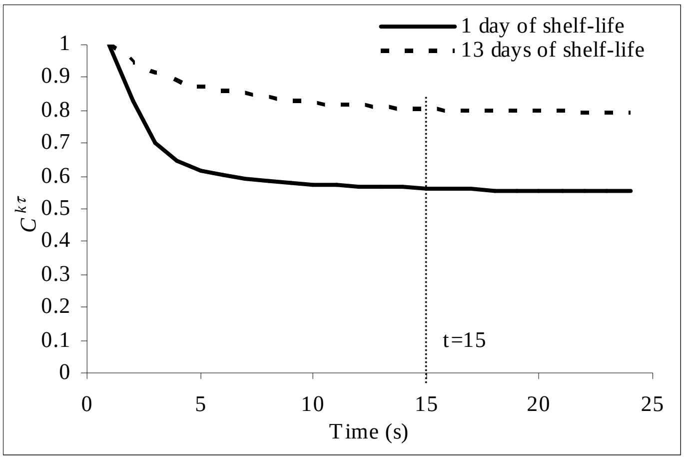


Fig. 2. Changes of the cross-correlation coefficient $C^{k\tau}$ in time for fresh apple (1 day of shelf-life) and for soft apple (13 days of shelf-life). $\Delta C^{k\tau}$ is difference between the $C^{k\tau}$ at the first second and after 15 seconds

All parameters: firmness, AE counts and the cross-correlation coefficient difference of apple speckle were obtained on the blush and shaded sides of apples in order to check differences in the parameters analysed. In Figures 3-5 the parameters analysed are shown for both sides of apples separately. In general, it cannot be stated that there is any significant difference between the sides of apples. Only for the freshest apples the firmness and the number of AE counts are slightly higher for the blush side than for the shaded one. On average, the blush side has firmness only 1.7N higher than the shaded side, and the number of AE counts recorded during puncturing was only 140 000 higher than for the shaded side and for $\Delta C^{k\tau}$ there was no difference. No differences between both sides were observed also for the character of changes during the shelf-life storage. The empirical equations which describe the relationships are almost the same for both sides of apples. Concluding, the differences in the parameters analysed are not significant relative to the side of apple.

Figure 3 shows the firmness changes during shelf-life storage. Similarly to many other experiments, the firmness of apples decreases in time. Since the firmness is the reaction force of the tissue to deformation, the exponential curve would be used as the empirical model of tissue softening. Just after harvest the tissue has some finite firmness and it decays to a very low value after very long time of storage, never reaching zero value. In this experiment the apples just after harvest had firmness around 50 N and it decreased till 20 N after 13 days of shelf-life, so the firmness decreased during storage to 40% of the initial value. It is necessary to notice that the apples of the cultivar used showed very different firmness at the same storage conditions and it decreased to unusually small firmness during shelf-life, differently to what was observed in another experiment (Zdunek and Ranachowski 2006).

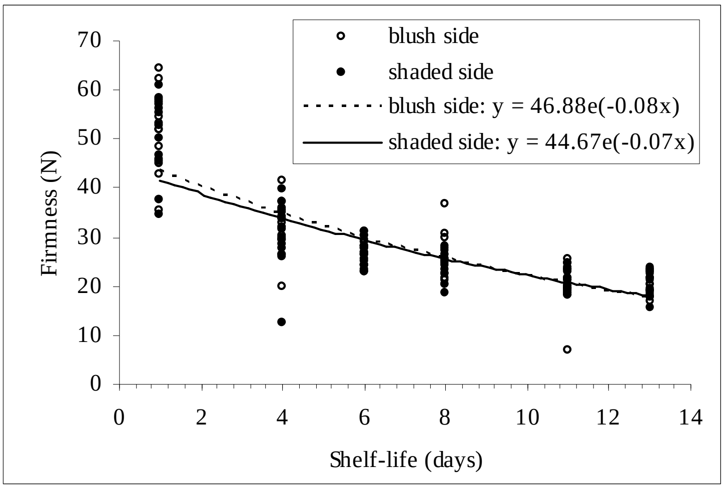


Fig. 3. Changes of the firmness of apples during shelf-life for the blush and the shaded side

Figure 4 shows changes of the number of AE counts recorded during the puncturing in the function of shelf-life storage time. The change has a similar exponential character to the one obtained for firmness. Such curve character was also observed in the previous experiment using another descriptor – AE events (Zdunek and Ranachowski 2006). The number of AE counts decreased from 20 000 000 counts for the fresh apple to less than 550 000 for the softest apples, thus the number of AE counts decreased during shelf-life storage to 3% of the initial value. The AE Signal Monitor allows measuring the number of AE counts, where a single crack within material, due to sensor response characteristic, generates a single AE event. The AE event consists of a group of counts (Zdunek and Ranachowski, 2006), therefore the real number of cracks is much lower than the number of AE counts recorded in the experiment. Comparing changes of the firmness and the AE counts, a significant difference was observed for changes between the first and the fourth day, where the AE counts decreased to 20% of the initial value while the firmness decreased to 60% of the initial value only.

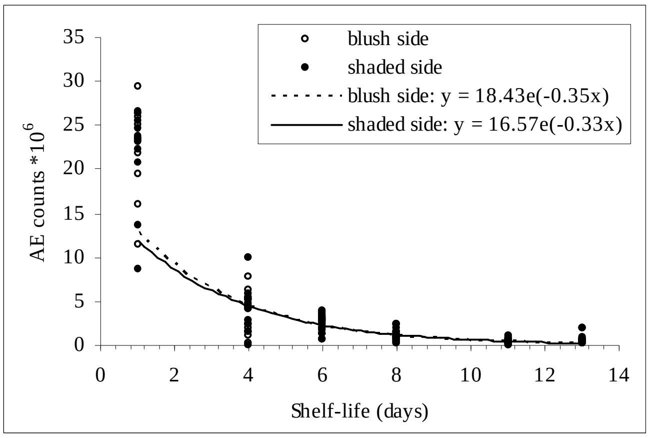


Fig. 4. Changes of the AE counts during shelf-life obtained during puncturing on the blush and the shaded side of apples

The cross-correlation difference $\Delta C^{k\tau}$ obtained using the spatial-temporal correlation technique changes similarly to the two previous parameters analysed. The change shown in Figure 5 has exponential character. Similar relationship was observed in the previous work with the use of this method for apples (Zdunek *et al.* 2007). The cross-correlation coefficient in Fig. 5 decreases from 0.44 to 0.20, thus more than by 50% of the initial value. The changes are more similar to firmness changes than to changes of AE counts. Similarly as it was for previous parameters, the most significant change is observed between the first and the forth day of shelf-life storage – decrease up to 70% of the initial value.

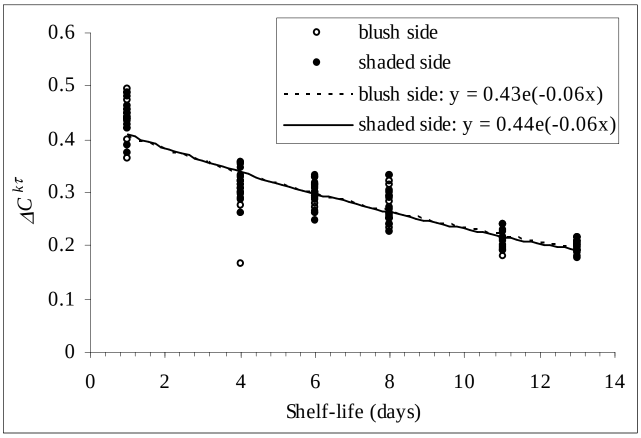


Fig. 5. Changes of the cross-correlation coefficient difference $\Delta C^{k\tau}$ of apples during shelf-life for the blush and the shaded side

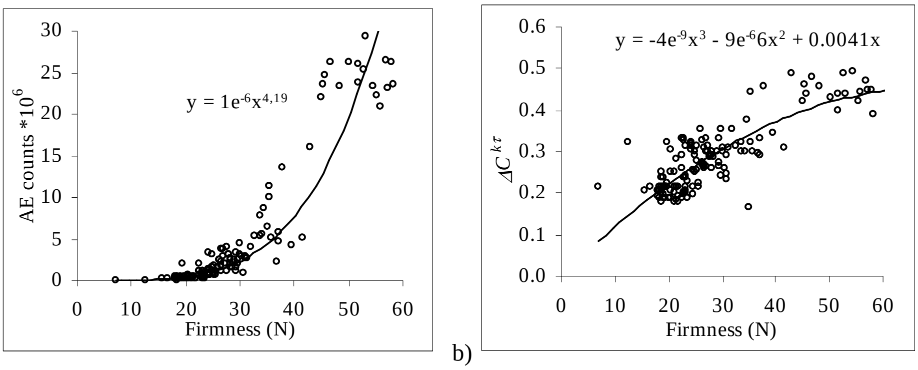
To fit a model curve to changes of parameters analysed in figures 4 and 5 in time of storage, the exponential curves were used because of even after long term storage a small value of them is expected, while simultaneously at initial state of the material the parameters have a finite value. Since the parameters analysed change exponentially with time of storage, the correlation coefficients of linear regression were calculated for their logarithmic values and they are presented in the Table 1. For all parameters analysed there are significant at $p < 0.01$ correlations with the storage days. However, the correlation coefficient for firmness is the lowest (R = –0.82). Slightly better correlation was obtained in the case of the AE counts (R = –0.85). For these two parameters there exists high positive correlation as well (R = 0.93), presented in Table 1. The highest correlation coefficient for changes in time of storage was found for the $\Delta C^{k\tau}$ obtained by the spatial-temporal correlation technique (R = –0.91).

Table 1. Correlation coefficients *R* of linear regression between logarithmic values of firmness, AE counts and $\Delta C^{k\tau}$ with days of shelf-life storage, and correlation coefficients *R* for the relationship between firmness and the AE counts and the $\Delta C^{k\tau}$. ** correlations significant at $p < 0.01$

	Ln(Firmness)	Ln(AE counts)	Ln($\Delta C^{k\tau}$)
Days	–0.82**	–0.85**	–0.91**

	AE count	$\Delta C^{k\tau}$
Firmness	0.93**	0.82**

Firmness is one of the most common parameters describing softening of apples during storage. In figure 6 comparisons of the number of AE counts (Fig. 6a) with the firmness and the cross-correlation coefficient difference $\Delta C^{k\tau}$ (Fig. 6b) with the firmness are shown. The first relationship has the power character while the second one has the third-order polynomial character, however close to a linear function. Both parameters - AE counts and cross-correlation coefficient difference – correlate well with firmness, however higher determination coefficient was obtained for AE counts, which is 0.93, than for $\Delta C^{k\tau}$ which is 0.82 (Tab. 1).



a) b)

Fig. 6. Relationship between firmness and AE counts (a), and between firmness and the cross-correlation coefficient difference $\Delta C^{k\tau}$

CONCLUSIONS

The comparison of the puncture test with the acoustic emission and the spatial-temporal correlation technique has shown that:

1. All three methods: firmness, AE counts and cross-correlation coefficient can be used for quality evaluation of apples.

2. Analysis of values obtained by these methods for apples in shelf-life conditions shows different correlation coefficients with time of storage. In this case the most accurate results were obtained by the spatial-temporal correlation technique. The advantage of this method is that it is also a non-destructive way of quality monitoring. Since the biospeckle movements are related to movement of particles in a living tissue and also to water content, the method can be used for evaluation of the biological state of the material.

3. Puncture test with acoustic emission shows also significant changes with time of storage and these tests can be used for quality monitoring during storage as well. However, these methods provide information about the mechanical properties and especially about the fracture properties of the material. Therefore one can suggest that they should be used for monitoring of texture properties like hardness, crispness, crunchiness, juiciness and mealiness.

4. High correlation between firmness and number of AE counts is observed. The acoustic emission provides direct information about sound emitted by crushed material while firmness is the mechanical parameter. Thus, both of them should be used in the future to describe texture of apples. Higher correlation coefficient between firmness and acoustic emission counts was obtained than between firmness and cross-correlation coefficient difference.

5. The experiment has shown that for testing the quality of apples there is no difference relative to the side of apples.

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PORÓWNANIE TESTU PRZEBICIA, EMISJI AKUSTYCZNEJ I PRZESTRZENNO-CZASOWEJ KORELACJI PLAMKOWEJ JAKO METOD OCENY JAKOŚCI JABŁEK PODCZAS SYMULOWANYCH WARUNKÓW OBROTU HANDLOWEGO

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Streszczenie. Głównym problemem producentów i konsumentów jabłek jest utrata jędrności podczas przechowywania. Praca ta prezentuje porównanie metod oceny zmian jakości jabłek podczas przechowywania w symulowanych warunkach obrotu handlowego: testu przebicia z emisją akustyczną i przestrzenno-czasowej korelacji plamkowej. W pracy analizowane były jędrność, zliczenia emisji akustycznej i różnica współczynnika korelacji wzajemnej uzyskane odpowiednio przy pomocy tych metod. Parametry te w różny sposób korelują z czasem przechowywania. Najwyższy współczynnik korelacji zanotowano dla różnicy współczynnika korelacji wzajemnej uzyskanego przy pomocy przestrzenno-czasowej korelacji plamkowej. Test przebicia z emisją akustyczną również wykazuje znaczące zmiany w czasie. Metody te dostarczają informacji o właściwościach mechanicznych a szczególnie o procesach pękania materiału. Zaobserwowano wyższe współczynniki korelacji pomiędzy jędrnością i liczbą zliczeń emisji akustycznej niż pomiędzy jędrnością i różnicą współczynnika korelacji wzajemnej. Badania pokazały, że dla oceny jakości jabłek nie istotna jest badana strona jabłka.

Słowa kluczowe: metoda niedestrukcyjna, korelacja plamkowa (biospeckle), emisja akustyczna, przebicie