Dynamic laser speckle for non-destructive quality evaluation of bread

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ABSTRACT

Coherent illumination of a diffuse object yields a randomly varying interference pattern, which changes over time at any modification of the object. This phenomenon can be used for detection and visualization of physical or biological activity in various objects (e.g. fruits, seeds, coatings) through statistical description of laser speckle dynamics. The present report aims at non-destructive full-field evaluation of bread by spatial-temporal characterization of laser speckle. The main purpose of the conducted experiments was to prove the ability of the dynamic speckle method to indicate activity within the studied bread samples. In the set-up for acquisition and storage of dynamic speckle patterns an expanded beam from a DPSS laser (532 nm and 100mW) illuminated the sample through a ground glass diffuser. A CCD camera, adjusted to focus the sample, recorded regularly a sequence of images (8 bits and 780 x 582 squared pixels, sized 8.1 × 8.1 μm) at sampling frequency 0.25 Hz. A temporal structure function was calculated to evaluate activity of the bread samples in time using the full images in the sequence. In total, 7 samples of two types of bread were monitored during a chemical and physical process of bread's staling. Segmentation of images into matrixes of isometric fragments was also utilized. The results proved the potential of dynamic speckle as effective means for monitoring the process of bread staling and ability of this approach to differentiate between different types of bread.

Keywords: dynamic speckle, biospeckle, structure function, bread staling

1. INTRODUCTION

Coherent illumination of a diffuse object yields a randomly varying speckle pattern, which changes over time at any object modification[1]. Variations of the speckle pattern may be caused by a mass transfer throughout the sample, e.g. blood flow[2], or by random movement of scatterers and random time fluctuations of refractive index that lead to fluctuations of optical paths of the interfering light beams in the image plane. As the interference pattern associated with a changing in time rough object visually resembles that of a boiling liquid, it is addressed in the literature as "boiling speckle", "biospeckle" in case of biological samples or dynamic speckle in general[1]. The phenomenon of dynamic speckle can be used for non-invasive whole-field detection and visualization of physical or biological activity in various objects through statistical description of laser speckle dynamics[3]. Typical examples of such activity are the processes in biological samples or the processes as vibration, corrosion, drying of paints or coatings etc. Speckle fluctuations can be easily seen with a bare eye but a comprehensive statistical analysis is required to retrieve relevant information[3].

Usage of modern 2D optical sensors to register Fresnel speckle formed at free space propagation provides large amount of data for accurate estimation of both first and second statistical moments[1,3]. Over the years, a variety of approaches has been developed to characterize activity of samples by statistical processing of time sequences of speckle patterns. Depending on the size of the processed area of the speckle pattern, they can be characterized as pointwise, 1D and 2D

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approaches. Accuracy of pointwise approaches, which are fast and have high time resolution, is too low[4]. Storage of a single column from consecutive 2D images of speckle patterns recorded at equal time intervals forms a 2D image called a time history of a speckle pattern (THSP)[5]. It contains valuable information about the short-period activities inside the object. In the THSP image each row shows variation of the intensity at a single point on the object surface in time whereas each column gives spatial distribution of intensities along a line at a given moment of time. Different useful characteristics as e.g. inertia moment of co-occurrence matrix are derived from the acquired THSPs[3]. Statistical processing of whole-field images provides means to differentiate between the regions of high and low activity in the sample[6]. Popular methods are: i) laser speckle contrast analysis[7] which calculates spatial distribution of the speckle contrast from the recorded speckle pattern by averaging in a small spatial window; ii) Fujii's method[8] and the method of generalized differences[6] which both emphasize the variations by summation of differences between selected pairs of images in the recorded time sequence of speckle patterns.

Dynamic laser speckle has been applied in medicine for the study of perfusion of blood flow in human tissues[9,10], in biology for the study of bacterial response[11], in agriculture for the study of plant development processes[12,13], seeds viability[14,15], quality assessment of fruits, animal reproduction. The aim of the present report is to check the potential of dynamic speckle approach for non-destructive evaluation of bread staling. Staling leads to huge economic losses both for baking industry and consumers. To the best of our knowledge, spatial-temporal characterization of laser speckle has not been yet applied for monitoring of this process. There are only few reports concerning application of speckle techniques for control of pasty products. Using of biospeckle phenomenon for monitoring the expansion of the dough during the leavening process is reported in Ref.16. The effect of appearance of small hairline cracks in biscuits and crackers, known under the name 'checking', has been thoroughly studied using speckle interferometry[17]. The present study has two goals: i) to prove the potential of dynamic speckle as effective means for monitoring the process of bread staling; ii) to check the ability of speckle approach to differentiate between different types of bread.

2. DESCRIPTION OF EXPERIMENTS AND PROCESSING METHODS

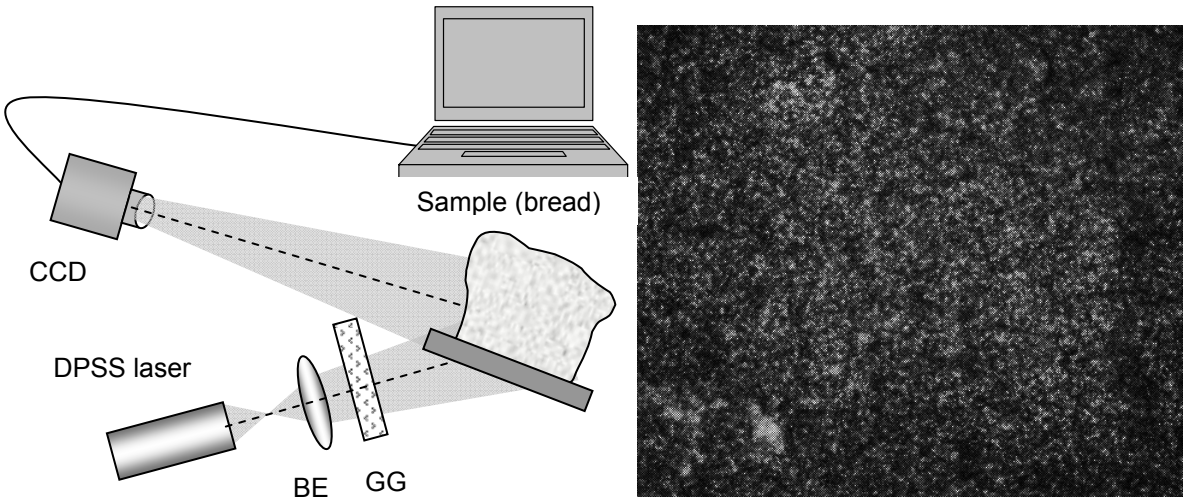

Fig.1 Illumination and capture set-up for monitoring of dynamic speckle for non-destructive quality evaluation of bread (left); speckle pattern of light scattered from a bread surface (right); BE – beam expander, GG – ground glass diffuser.

In the set-up for acquisition and storage of dynamic speckle patterns (Fig.1 left) an expanded beam from a DPSS laser (532 nm and 100 mW) illuminated the sample through a ground glass diffuser. The set-up was positioned on a vibration insulated table. An optical axis of a CCD camera, adjusted to focus the sample (bread), is normal to its surface. It recorded regularly a sequence of images (8 bits and 780 x 582 squared pixels, sized 8.1 × 8.1 μm) at sampling frequency 0.25 Hz. The sample bread has been baked with a Moulinex Breadmaker using two of the included recipes which are given in Table 1 under the names Bread 1 and Bread 2. The temperature in the laboratory was regularly measured and it was kept equal to 18°C ± 1°C. The records for each sample were made several times per day. To ensure that the

registered speckle change is due to some activity within the sample and not to noise and vibration, we recorded time sequences of speckle patterns for a diffuse screen immediately after the acquisition of the time sequences for the sample. It should be noted that only statistical processing of the acquired images could reveal the difference between speckle patterns of a still screen and a sample with processes running within. This is clearly seen in Fig.2, which compares two histograms of intensities (given as grey levels from 0 to 255) that are built from single images of speckle patterns of the sample and the screen respectively. Both histograms are practically the same. However, the THSPs of the sample and the screen that have been composed from 100 images exhibit different behavior (Fig.3). The THSP of the sample resembles a random pattern whereas the THSP of the screen consists practically of straight lines.

Table 1

Bread 1 recipe (Milk loaf – 1000 g)		Bread 2 recipe (French style white bread – 1000 g)	
Butter	70 g	Water	365ml
Salt	1.5 tsp*	Salt	2tsp
Sugar	3 tbsp	White bread Flour	620g
Liquid Milk	350 ml	Yeast	1.5tsp
White bread flour	530g		
Yeast	1.5 tbsp		
*tbsp – table spoon			

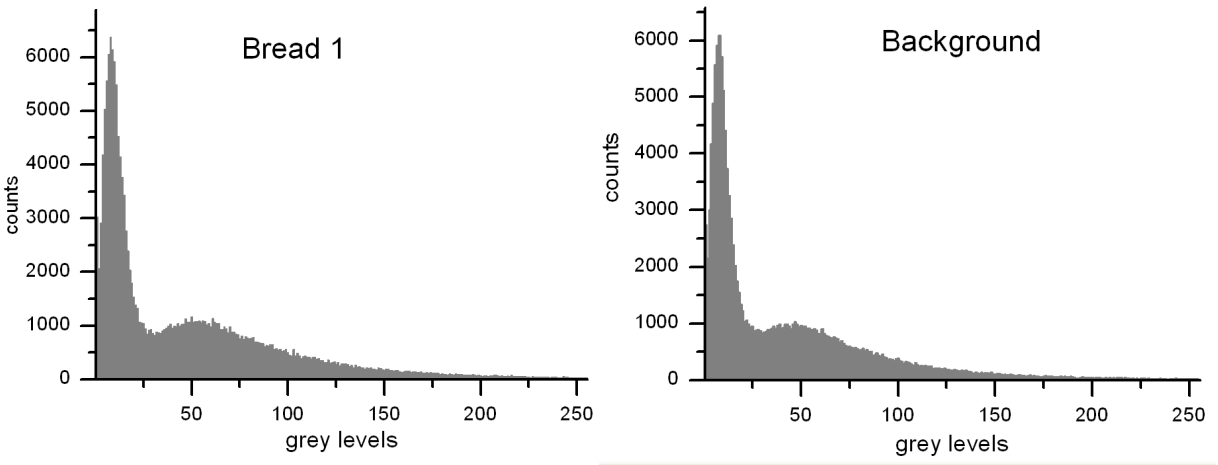

Fig.2. Intensity histograms of the recorded speckle patterns for the bread sample (left) and the background surface (right).

To have an effective texture estimator for the case of a non-uniform average intensity distribution in the recorded speckle patterns of the bread samples, we chose to detect their activity in time by estimation of the so called temporal structure function

$$S(\tau)=\frac{1}{M-l}\frac{1}{N_1N_2}\sum_{k=0}^{M-l}\sigma^{-1}(k)\sigma^{-1}(k+\tau)\sum_{i=1}^{N_1}\sum_{j=1}^{N_2}\left[I(i,j,k)-I(i,j,k+\tau)\right]^2 \qquad (1)$$

where $I(i,j,k)\equiv I(i\Delta, j\Delta, k\Delta t)$ is the intensity recorded at a pixel with coordinates $(i\Delta, j\Delta)$ at moment $k\Delta t$, and $\tau = l\Delta t$ is the time lag; here Δ is the pixel pitch of the CCD camera and Δt is the time interval between two successive images in a sequence of M images; the size of the processed area is $N_1 \times N_2$ and $i = 1..N_1$, $j = 1..N_2$, $k = 1..M\text{-}l$. In Eq.(1) the variance of the recorded random field is estimated from

$$\sigma^2(k)=\frac{1}{N_1N_2}\sum_{i=1}^{N_1}\sum_{j=1}^{N_2}\left[I(i,j,k)-A(k)\right]^2 \qquad (2)$$

where $A(k)$ is the average value estimate at moment (k):

$$A(k) = \frac{1}{N_1 N_2} \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} I(i, j.k) \tag{3}$$

Obviously, the increase in $S(\tau)$ corresponds to a larger mean difference between the compared images. The huge amount of data in the recorded images ensures high accuracy of the first and second moments estimates. One is able to obtain an accurate estimate of $S(\tau)$ even for the case $l = M - 1$. It is interesting to compare the structure function approach both with Fujii method and generalized differences methods. The output of these methods is an image which is built by accumulation of the differences between the images in the recorded sequence. The Fujii method constructs the image using the expression

$$D(i, j) = \sum_{k=1}^{M} \frac{|I(i, j, k) - I(i, j, k+1)|}{I(i, j, k) + I(i, j, k+1)} \tag{4}$$

whereas the method of generalized differences yields the image

$$U(i, j) = \sum_{k=1}^{M} \sum_{l=1}^{M-k-1} |I(i, j, k) - I(i, j, k+l)| \tag{5}$$

If we put $N_1 = N_2 = 1$ or m in (1), where $m << N_x, N_y$ and $N_x \times N_y$ is the size of the CCD image, we could obtain a series of 2D images showing the spatial distribution of the temporal structure function at different time lags. However, comparison between the approaches (1), (4) and (5) is beyond the scope of this paper.

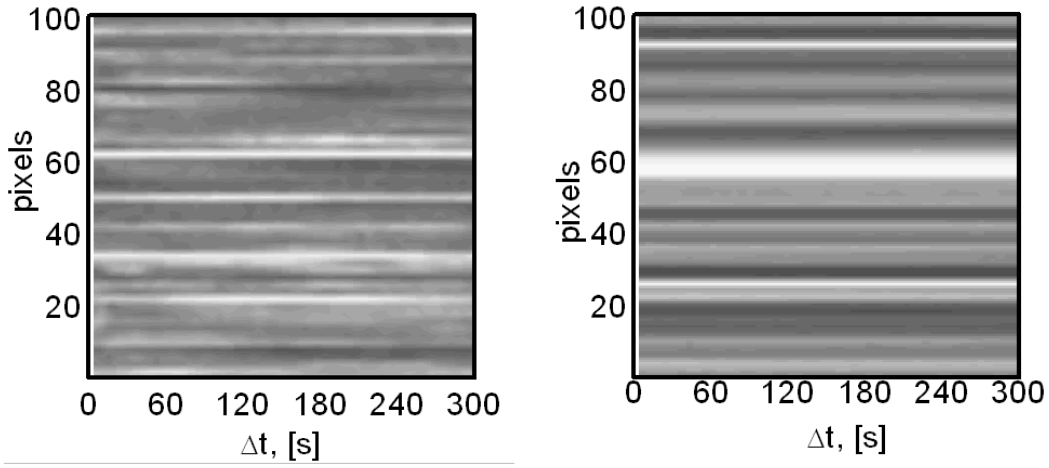

Fig.3. Time histories of the speckle patterns in the case of a sample (left) and a still screen (right); the intensity values are given as grey levels from 0 to 255.

Figure 4 depicts exemplary $S(\tau)$ curves obtained for the Bread 1. As it can be seen, the rate of activity in the bread sample is rather slow within the spanned time interval. This is also confirmed by Fig.3 left. To check the repeatability of the results, we performed two measurements one after another and calculated the corresponding structure functions. The plotted curves show excellent coincidence of the results which proves the fact that the observed changes of the statistical parameter are induced by the changes in the sample. As it should be expected, the structure function of the background shows a very slow decrease in comparison with the sample structure function that can be due to small vibrations and fluctuations of the refractive index in the optical path between the screen and the CCD.

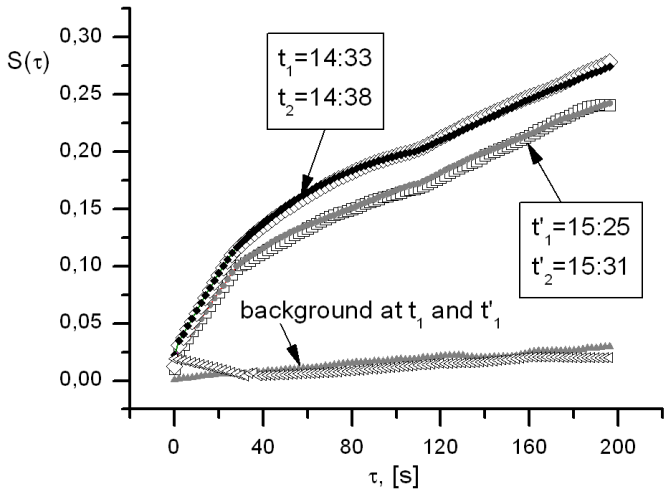

Fig.4. Sample structure functions corresponding to two records made within 5 minutes and background structure functions corresponding to these measurements (the end of the baking process is at 12:30).

3. RESULTS AND DISCUSSION

In Ref. 18 bread is described as unstable, elastic solid foam. Its solid part consist of i) a continuous phase which is composed partially from a network of cross-linked gluten molecules and partially from leached starch polymer molecules, and ii) a discontinuous phase of starch granules which are entrapped, gelatinized and swollen. The complex nature of the bread system makes the staling a phenomenon with a very complex mechanism whose comprehensive understanding has not been yet achieved. Many studies have been carried out to find the factors affecting the staling rate as well as to test suitable anti-staling agents.

Physical changes in bread start immediately after the end of the baking process, and they are mainly connected with the change of its temperature and humidity[19]. There are distinguished crust staling and crumb staling[18]. The temperature of the crust of fresh-baked bread is 130-180°C whereas the temperature in the bread center is 93-97°C. About 3 hours are required for bread cooling; complete equalization of the bread temperature with that of the environment is achieved after 6-8 hours. The humidity of the crust of fresh-baked bread is also strongly decreased. Redistribution of moisture between different regions in the bread also leads to its alteration.

The main purpose of the conducted experiments was to prove the ability of the dynamic speckle method to indicate activity within a cooling bread sample as well as during its staling. The structure functions obtained for the two types of the baked bread are shown in Fig.5. We see the steady decrease in activity in the process of bread cooling; this decrease is very well expressed during the first 6-8 hours. The second interesting result is the different shape of the structure function curves corresponding to the two types of bread. For Bread 1 the structure function exhibits more or less constant slope whereas for Bread 2 it demonstrates rapid rise during the first 50 s followed by a linear section with very small inclination with respect to the lag axis.

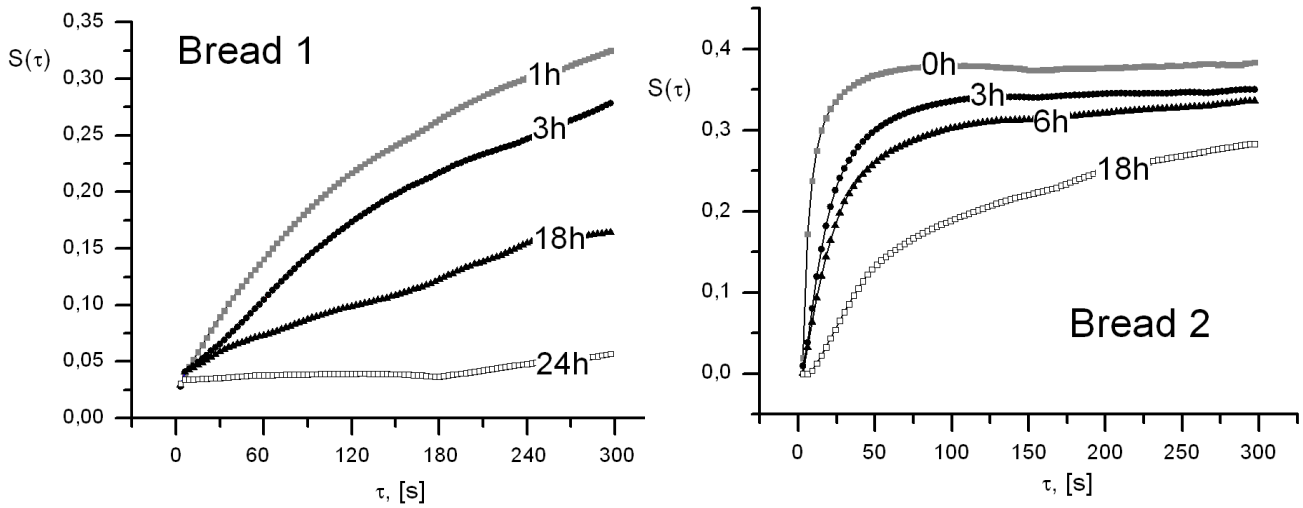

Fig.5. Sample structure functions at different moments after bread baking; (left) – Bread 1; (right) – Bread 2

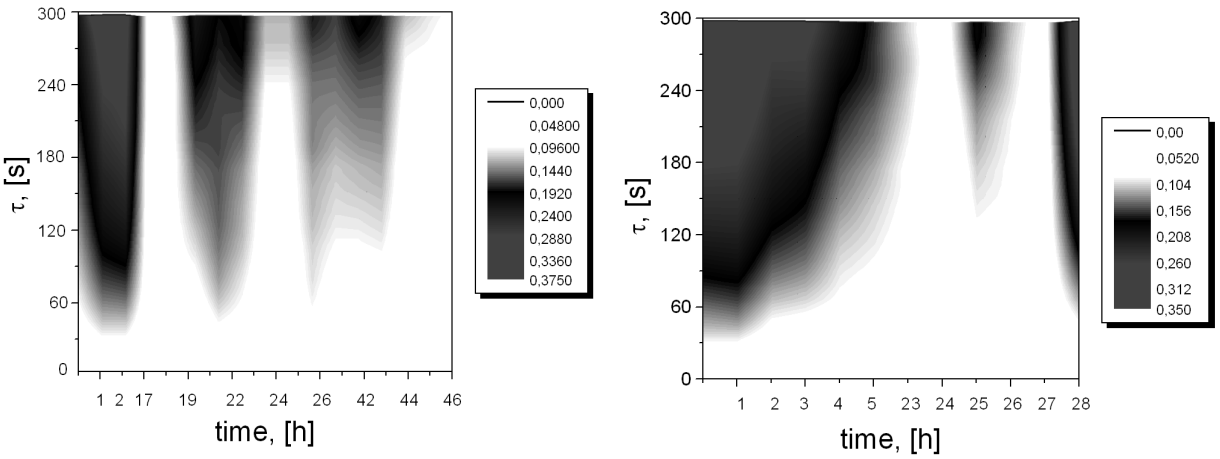

Fig.6. 2D contour map representation of the time evolution of the sample structure function; the shown maps correspond to two samples of Bread 1: (left) – Bread 1; (right) – Bread 1 with addition of flour from a Jerusalem artichoke.

To characterize the changes in the bread samples, we processed the time sequences of speckle patterns recorded at different moments. The structure functions corresponding to these moments were used to build a 2D contour map which shows the evolution of this parameter in time. We give along the horizontal axis the time in hours which has elapsed since the end of the baking process. The vertical axis shows correspondingly the time lag τ in seconds. The obtained contour maps are shown in Figs.6-9. Note that the time scales along the horizontal axis in Figs.6-9 are different due to a different observation periods for each bread sample. The results for Bread 1 are presented in Fig.6 (left). The map in Fig.6 (right) is obtained for another sample of Bread 1 in which 10 g of the used flour were replaced with the same quantity of flour produced from an Jerusalem artichoke (Helianthus tuberosus). As is known, the Jerusalem artichoke can be considered as an anti-staling agent. As it can be seen, the calculated contour maps clearly reveals that, after several hours from the end of the baking process, there exist periods of strongly diminished activity in the bread samples that are followed by new outbursts. Obviously, this phenomenon requires more thorough study. The contour maps in Fig.7 show results obtained for the Bread 2; in this case two samples were monitored. Periods of rise and fall in activity can be also clearly distinguished. Note that in this case the calculated values of $S(\tau)$ are twice higher. Figure 8 corresponds to the Bread 2 with addition of flour from a Jerusalem artichoke. Again we obtain that the values of $S(\tau)$ are larger in comparison with Fig.6, and activity remains non-negligible during the four and a half days of monitoring.

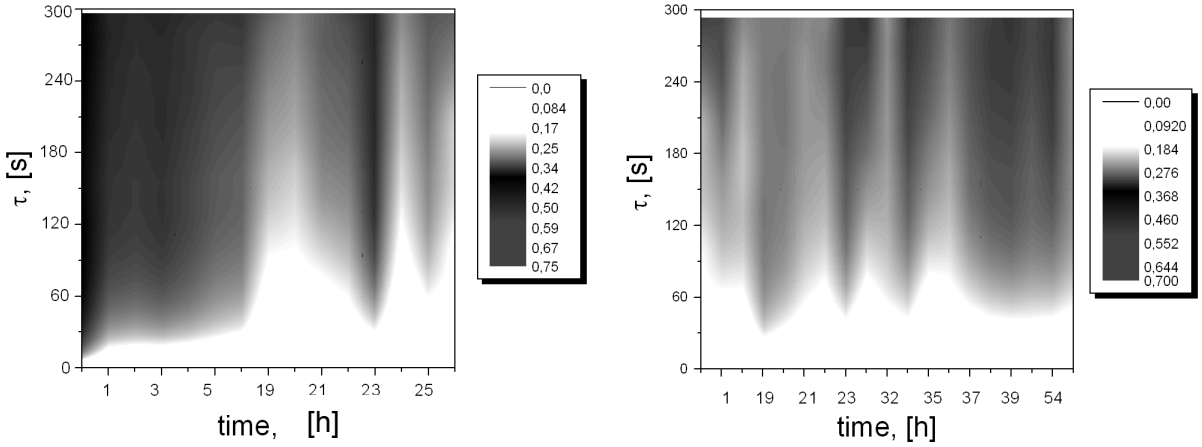

Fig.7. 2D contour map representation of the time evolution of the sample structure function; the shown maps correspond to two samples of Bread 2: (left) – Bread 2; (right) – Bread 2 with addition of flour from a Jerusalem artichoke.

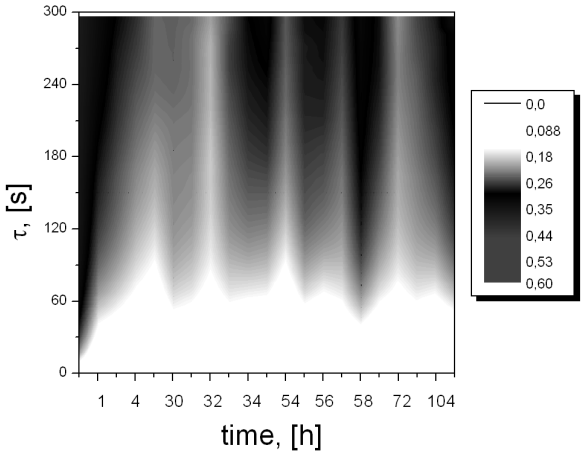

Fig.8. 2D contour map representation of the time evolution of the sample structure function; Bread 2 with addition of flour from a Jerusalem artichoke.

We also performed observations of two samples of Bread 1 (with and without addition of flour from a Jerusalem artichoke) starting the records two weeks after the baking. During these two weeks the bread samples were kept in the laboratory at temperature of 18°C. Figure 9 presents the results. We see that practically two days after the start of the measurements we register increase of activity in both samples. Measurements for both samples were made simultaneously. The processes in the bread sample without Jerusalem artichoke flour were more active.

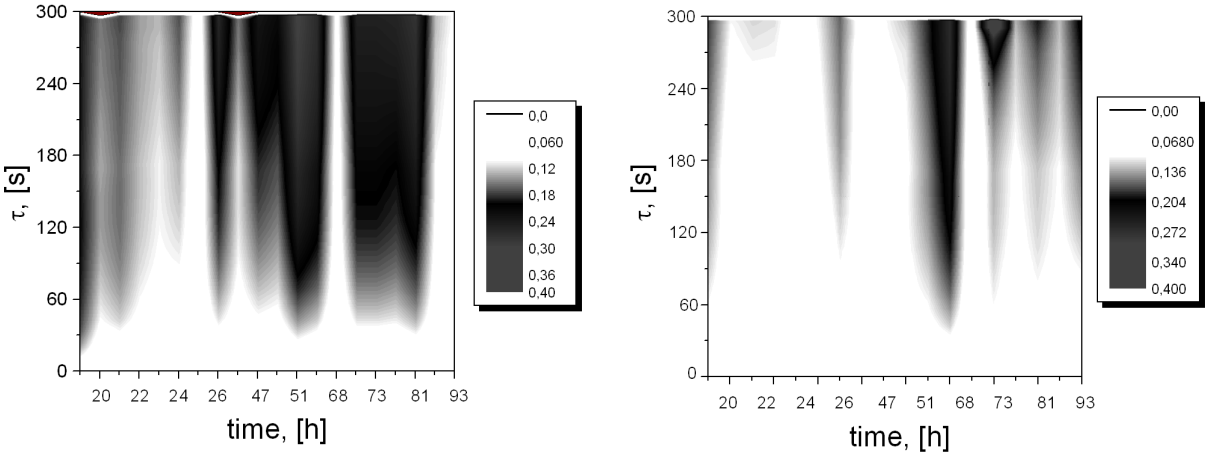

Fig.9. 2D contour map representation of the time evolution of the sample structure function; the shown maps correspond to two samples of Bread 1 without (left) and with flour from a Jerusalem artichoke; recording has started two weeks after the bread baking.

CONCLUSION

In summary, we proved the potential of dynamic speckle approach to display the local activity in bread samples during their cooling and staling. The main advantage of this approach is ability to perform non-invasive full-field measurements with high spatial and temporal resolution without requirement for sophisticated equipment. Monitoring of the samples can be performed incessantly for observation time given by the user. This feature makes the method especially valuable for industrial applications.

Randomly varying interference patterns of laser light, reflected from the bread surface, were recorded as time sequences. They allowed for detection and visualization of activity in the samples through statistical description of laser speckle dynamics. In total, 7 samples of two types of bread were monitored. In average, about 20 separate recordings of time-sequences per a bread sample were made during 3 or 4 days. For 5 of the samples, the measurements were performed with fresh-baked bread. The acquisition for the rest two samples started two weeks after the end of the baking process. We used a temporal structure function as a statistical estimator because it is suitable for processing of patterns with non-uniform intensity distribution. It was calculated using the full images or their segmented areas in the sequence. Segmentation of images into matrices of isometric fragments was also utilized. The structure functions, calculated for the used two types of bread, showed different behavior.

We may conclude that the obtained encouraging results confirm the potential of dynamic speckle as effective means for monitoring the process of bread staling and ability of this approach to differentiate between different types of bread. Development of a robust procedure for quality assessment of bread samples will make possible industrial implementation of this technically simple non-destructive whole-field real-time method for indicating activity in a bread sample and for determination of quantitative measures to characterize the rate of underlying processes.

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