ARCHIVES OF ACOUSTICS
30, 2, 255–265 (2005)

INVESTIGATION OF ACOUSTIC PROPERTIES OF COMPRESSED WHEAT BRAN FLAKES

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(*received November 5, 2004; accepted March 15, 2005*)

The authors of this paper analysed Acoustic Emission (AE) signal generated during compression test of wheat bran flakes. Three AE descriptors were applied to process the results of the tests: counting of total number of EA events, average event duration and partition power spectrum slope. It was found that the presented descriptors correlate with the measured level of specimen structural moisture and one descriptor can be used in investigation of the effect of the loss of the perceived crispness in moistured product. The described methods of data processing can be applied to food product quality assessment procedures.

Key words: food texture evaluation, crispness evaluation, acoustic emission.

1. Introduction

Brekfast cereals (i.e. biscuits, crackers, balls, flakes, etc.) have been objects of mass production for over 100 years. During the last two decades, a significant consumption growth of the mentioned products is reported. The average per capita yearly consumption in the USA and UK has reached 5 kg level, while in Poland it is circa 0.8 kg. To win in a continuous competition, the food producers still make their market offer more attractive. Breakfast cereals are subject of intense research leading to structure improvements to reach the features preferred by the consumers. The features mentioned above are named a food texture and defined as "the attribute of a substance resulting from a combination of physical properties and perceived by the senses of touch, sight and *hearing*" [1]. Auditory texture perception results from the sounds food makes when chewed.

The first investigation of that effect was made by Z. VICKERS in the seventies [2] and her papers are frequently referred until now.

Several investigations were made in different centres in the eighties and later on to assess the optimal level of food crispness [3, 4]. The product specimens were subject of compression or of three-point bending tests while the emitted sounds were picked by the standard microphone. The industrial solution of a tester used for a mentioned investigation is presented in Fig. 1.

Fig. 1. The texturometer of type TA XT plus, produced by Stable Microsystems LTD, equipped with the microphone probe and the acoustic amplifier to capture the sounds generated in the mechanically loaded food sample.

The registration of weak sounds emitted by food specimens with a microphone is affected by a significant drawback caused by the interferring noises received from the environment. The first author of the paper has proposed in 2000 to use the alternate way and apply the accelerometer fixed to the tool, loading the food sample mechanically during the test. This solution was introduced in the Faculty of Food Technology of the Warsaw Agricultural University as a modification of two testing machines serving for the current research in the place. The texturometer of type TA XT 2i/25 was equipped by the accelerometer placed in conical adapter designed to prevent the accelerometer from the damage caused by static load produced by the machine. The technical specifications of the accelerometer were the following: the manufacturer – Brüel and Kjær, type 4371, sensivity – 1 pC/ms^{-2}, 3 dB frequency band (with amplifier) – 1 to 45000 Hz. Considering the fact that the instrumentation described above was capable to register the elastic waves propagated from the food source via steel waveguide to the accelerometer in the same way as it is done when the acoustic emission signal is investigated in technical applications, the authors of the paper (as it was practised in [5]) define the recorded signal as *acoustic emission (*AE). The texturometer used in the investigation is presented in Fig. 2.

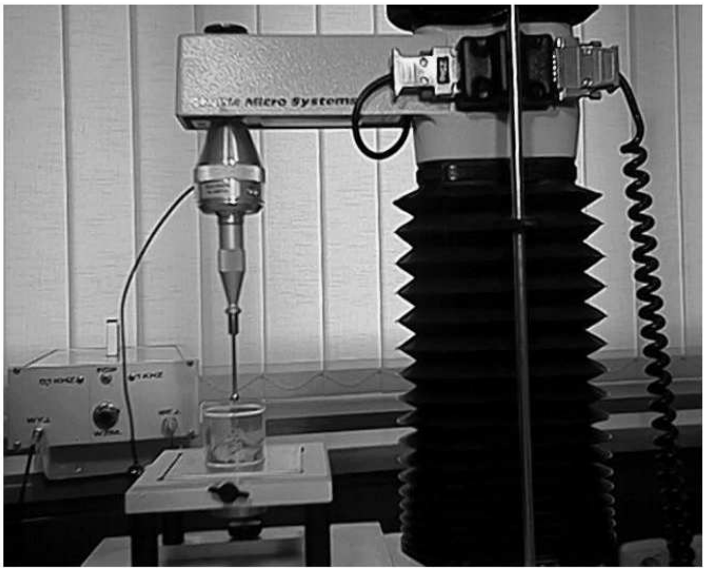

Fig. 2. The texturometer of type TA XT plus, produced by Stable Microsystems LTD, equipped with a contact microphone (accelerometer) to register acoustic emission emitted by food specimens.

2. Experimental results

The flakes prepared for test were placed in the probe cylinder of 30 mm diameter and have formed a pile of 60 mm height. The mechanical load was realised by compressing of a pile with a constant speed of 50 mm/min. Measurements were done using 10 replicates. Six groups, ten specimens each of wheat bran flakes were prepared for tests. Before the tests the specimens have been removed from the package and stored for three months in evacuated desiccators in controlled humidity and temperature. Using this method it was possible to introduce the equilibrium of certain humidity level for each group as it is stated below:

- Group A: 3% of structural moisture,
- Group B: 4% of structural moisture,
- Group C: 5% of structural moisture – this group was tested after the purchase,
- Group D: 6% of structural moisture,
- Group E: 8% of structural moisture,
- Group F: 10% of structural moisture.

The recorded AE signal was edited in that way that the central part of 10 seconds length of AE generated by each specimen was analysed. The authors of the paper have prepared three procedures for the analysis. The aim of the investigation was to find the descriptors of the AE signal correlating with the changes of the specimens mechanical properties induced by the different structural moisture level.

The investigated product consists mostly of starch (some 70%), proteins (about 9%), and minor quantities of fat and cellulose. From the mechanical point of view the structure can be considered as that of a porous composite with a matrix formed of starch and embedded proteins [6, 7]. All the structural components listed above are partly plastic polymers and their rheological behaviour highly depends on the amount of absorbed water. It is essential that at a certain structural humidity level (ca. 5%), an optimal (from the consumer's point of wiev) product crispness is observed. With the structural humidity increase the effect of crispness vanishes. The influence of water on the AE signal energy is explained by the difference in the spatial distribution of stress in dry and wet material. In dry material the structure is stiff and the stress is not evenly distributed in space. Adsorption of water causes glass-rubber material phase transition and dissipation of elastic energy. In consequence internal stress is relaxed and probability of brittle breaks is low [8, 9]. A good illustration of that effect is Fig. 3, what presents the results of three-point bending test made on flat bread wheat specimen. The six curves with gradual shift to the right side (– plasticisation effect) are measured in the same material with increasing structural moisture level (3.8–12.8%).

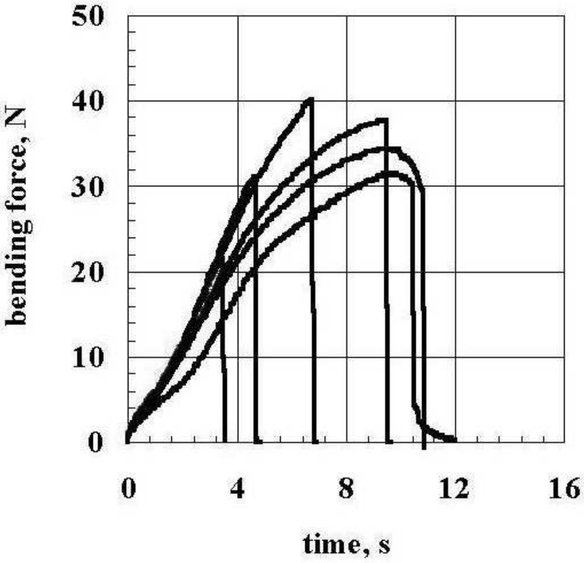

Fig. 3. The results of three-point bending test made on flat bread wheat specimen. The six curves with gradual shift to the right side are measured in the same material with increasing structural moisture level (3.8–12.8%).

3. Time-domain presentation of registered AE signals

First three seconds of AE signals representative for each specimens group are shown in Fig. 4. The voltage indicated on the vertical axis is proportional to the momentary

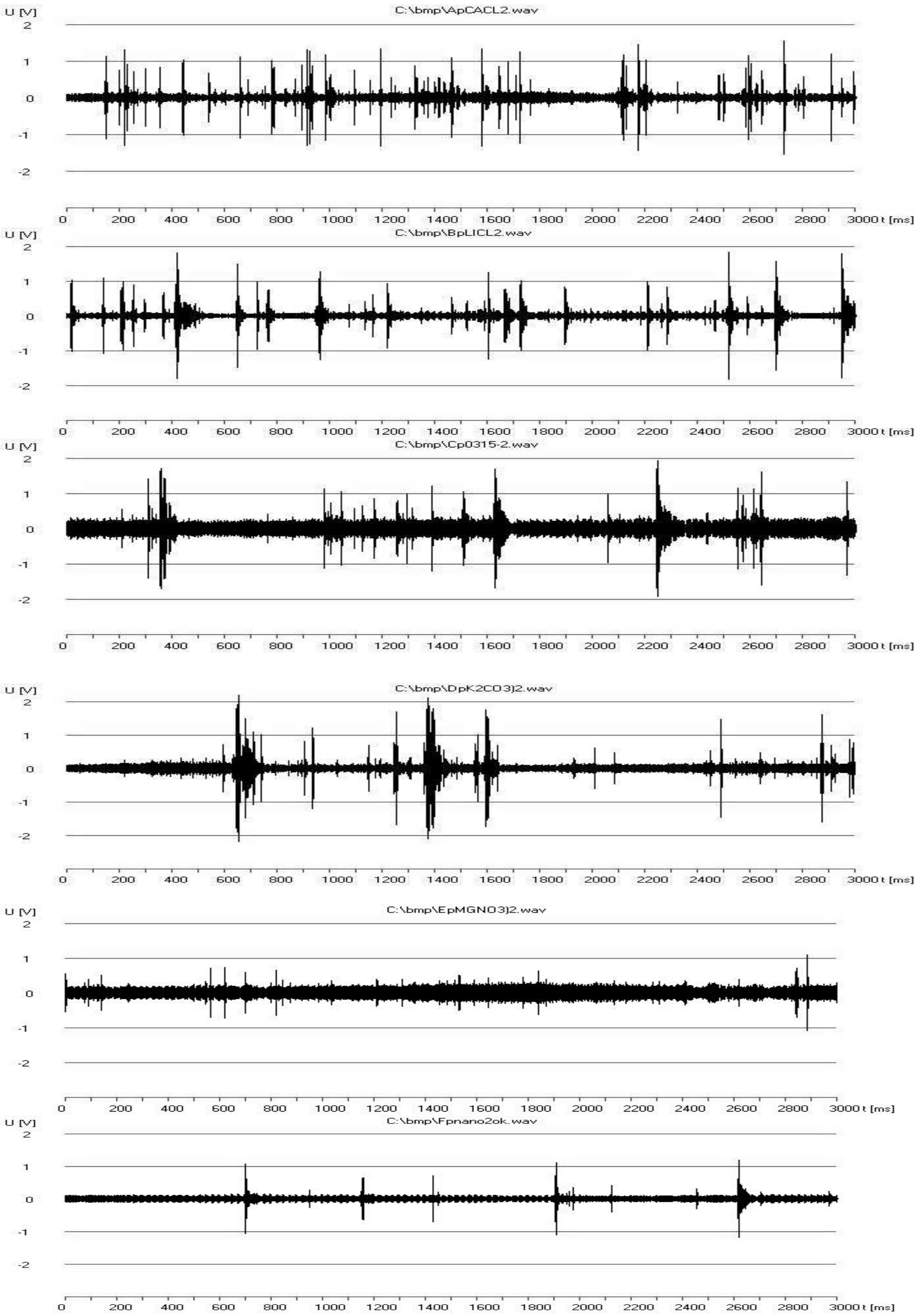

Fig. 4. Amplitude versus time plots of the AE records representative for each specimens group. The structural moisture levels gradation is (from top to the bottom) 3%, 4%, 5%, 6%, 8% and 10%, respectively.

value of stress relaxation level in the sample and the time of the experiment is presented on the horizontal axis. The time resolution of the graph (one pixel on the horizontal axis) is set to 5 milliseconds. It should be noted that the first four records, representing A, B, C and D specimens groups, do not differ remarkable in signal amplitude nor in the number of AE events (shown as signal pulses). The plasticisation effect is visible on the last two bottom plots. Increasing structural moisture level results in remarkable reduction of both AE amplitude and AE events number. The total AE events number tended to change from several hundreds to fifteen. A procedure designed to calculate the parameters of single AE event is presented in the next section.

4. Analysis of the parameters of a single AE event

A procedure to calculate the parameters of a single AE event was capable of analysing the records of 10 seconds of AE signal converted into a set of digital samples with a sampling rate of 44.1 kHz and resolution of 8 bits. The first task to deal with the signal was to recognise the occurrence of the AE event. The results of the investigation of recorded events had proved that at the moments of the greatest AE activity, AE events lasted 10 milliseconds. AE event duration is measured as a time period when the signal level was greater than the average noise level. Within this period the record included an average amount of 20000 units of sample readings (millivolts). A procedure used to detect a beginning of the AE event calculated the sample readings in each milliseconds of the record. Two thresholds were applied that the number of AE events detected at the lower threshold was approx. two times higher than the number of the events detected at the higher one. Threshold condition to recognise the occurrence of AE event was set to 2000 units for higher level and to 1000 units for lower level per millisecond. This assumption looked realistic compared with the fact that average noise level per millisecond did not exceed 400 units. The end of AE event was also registered when sample readings per millisecond declined under the threshold level. The following parameters were calculated after detection of the occurrence of the AE event:

- event duration,
- peak amplitude of AE signal within the event.

Results of AE event processing for the all groups of specimens are summarised in Table 1. The presented AE events features can be described in the following conclusions. The number of AE events detected at the lower and upper threshold generally decreases with the increase of structural humidity. However specimen group C, including food specimens of the best quality (product tested immediately after the purchase) presents the increased number of low energy AE events. There is no reflection of the described feature on other AE parameters presented in the table. This lets the authors of the paper to emphasise that the number of low energy AE counts can be regarded as a measure of crispness in the process of evaluation of food product. The plastification effect can be recognized when the average event duration is analyzed. The structures where the glass-rubber phase transition has undergone present a ca. ten percent loss of the event duration. More detailed analysis of the recorded AE signal, including its spectral characteristics is presented in the next section.

Table 1. Results of AE event processing for the all groups of specimens. Standard deviation of 10 measurements are presented in percents of the calculated values in brackets.

Specimens family code	Structural humidity, percents	EA events number, registered at the higher threshold level	EA events number, registered at the lower threshold level	Peak amplitude of AE signal within the event, mV	Event duration registered at the higher threshold level [milliseconds]
A	3	257 (22%)	481 (23%)	124.5 (0.8%)	3.2 (14%)
B	4	233 (25%)	460 (33%)	123.2 (2.3%)	3.0 (0%)
C	5	204 (29%)	974 (65%)	120.1 (2.4%)	3.2 (14%)
D	6	121 (34%)	260 (45%)	124.7 (1.2%)	3.0 (0%)
E	8	61 (31%)	170 (41%)	124.5 (1.4%)	2.8 (14%)
F	10	15 (41%)	39 (56%)	119.8 (9.1%)	2.6 (27%)

5. Spectral characteristics of the recorded AE signal

The procedure to calculate the parameters of single AE event enabled the authors to recognize the effect of AE event duration change caused by the plastification of the material. This effect can be also investigated using the procedure of signal processing in the frequency domain. The continuous AE signal can be, in frequency domain f, characterised by its power spectrum function $A(\omega)$ where ω is a linear analogue of frequency f, $\omega = 2\pi f$. A computer procedure was used to derive a discrete image of $A(\omega)$. The procedure analysed recorded the AE signal samples in time windows of 0.25-second length. To reject the influence of background noise, one dominant AE burst was detected (if any was present) in each section. All the bursts were processed to obtain its power spectrum function keeping the same phase of each burst at the transformation process. This algorithm is sometimes called, “event filtering” enabling to suppress the random noise accompanying the recorded signal. As the result for each time window, the procedure produced a series of coefficients c_n and each of them represented AE signal power in the frequency range of 11 Hz. The whole series of c_n covered the desired spectral range of 100–1500 Hz. The recorded time-depending AE signal, $u(t)$ of each recording was converted into a vector of digital samples where T_1 is an inverse of a sampling frequency. The algorithm performing the change of discrete AE record into a frequency domain, i.e. $v(mT_1) \to c_n$ transform, was based on the standard approximate formula [10]:

$$c_n \approx \frac{1}{N} \sum_{m=0}^{N-1} v\left(mT_1\right) \operatorname{mod} \left(e \frac{jn2\pi m}{N} \right), \tag{1}$$

where j denotes $\sqrt{-1}$ and mod denotes the modulus of a complex number. It was found experimentally that in the investigated material there are two regions in frequency domain where the high level of power spectrum function is observed. These regions are 7–9 kHz and 14–15 kHz. This has let the authors to propose dimensionless AE signal descriptor independent of the sample volume. This coefficient is called *partition power spectrum slope* (β) and is calculated as a ratio of AE signal power spectrum registered in the frequency range 14–15 kHz, labelled as P_{14-15} and AE signal power registered in the frequency range 7–9 kHz, labelled as P_{7-9}.

$$P_{14-15} = \sum_{n \mapsto 14\,\mathrm{kHz}}^{n \mapsto 15\,\mathrm{kHz}} c_n, \quad P_{7-9} = \sum_{n \mapsto 7\,\mathrm{kHz}}^{n \mapsto 9\,\mathrm{kHz}} c_n, \quad \beta = P_{14-15} / P_{7-9}. \tag{2}$$

Spectral characteristics of two samples with low structural humidity level (group A and B) and high structural humidity level (group E and F) are presented on the acoustograms (vide Figs. 5 and 6). The values of the partition power spectrum slope for all investigated specimen groups are summarized in Table 2.

Table 2. The values of the partition power spectrum slope β for all investigated specimen groups.

Specimens family code	Dimensionless averaged partition power spectrum slope coefficient β	Standard deviation of ten measurement results (%)
A	0.83	34
B	0.72	16
C	0.94	17
D	0.88	35
E	1.23	29
F	1.69	52

The increase of power spectrum slope coefficient is caused by the increase of high frequency components in the registered signal. It is possible that the specimens with higher humidity level include less powerful EA sources than those in dryer specimens, but elastic wave propagation is significantly improved in moistured product.

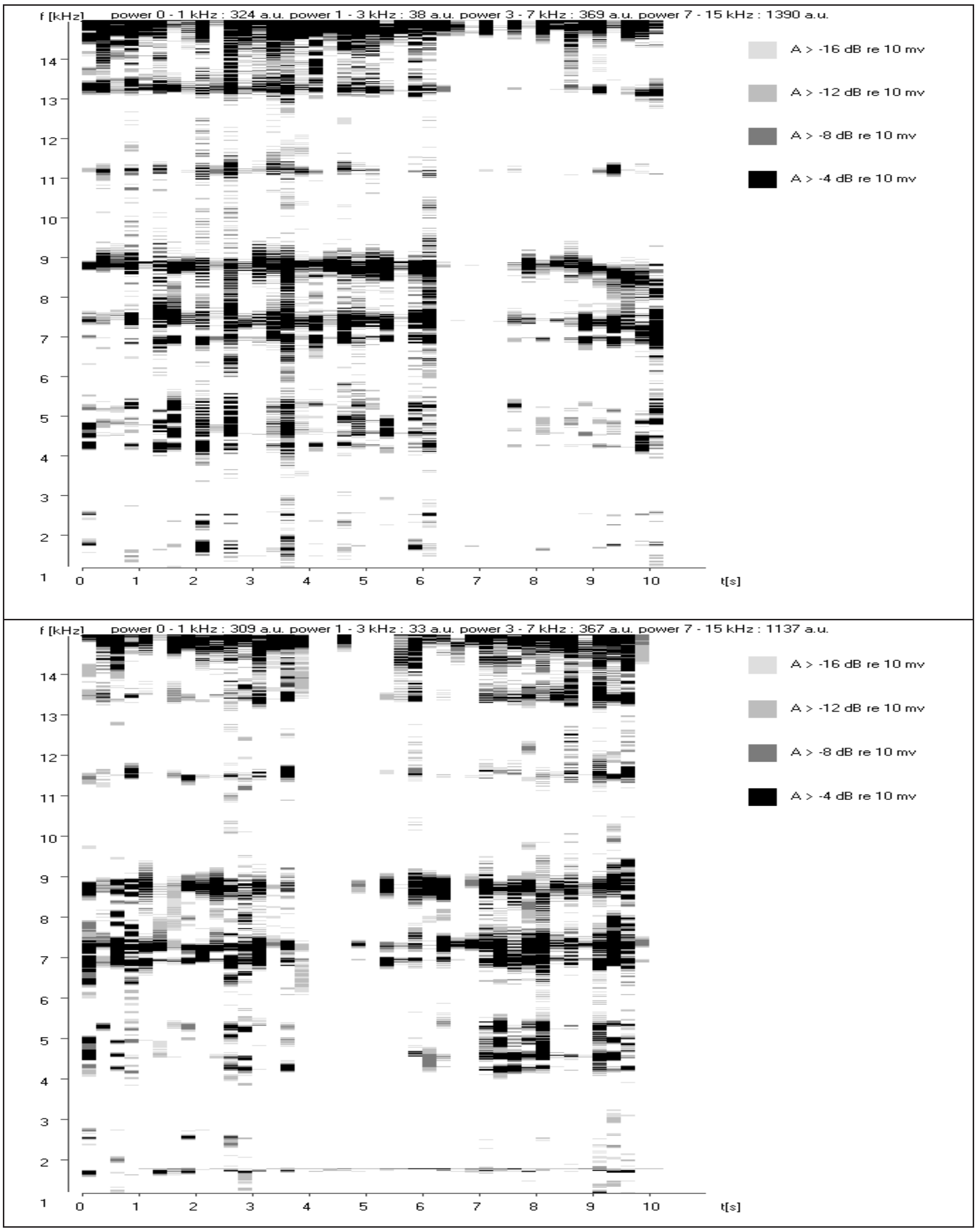

Fig. 5. Spectral characteristics of two samples with low structural humidity level (group A – above and B – beneath). Analysed frequency band (1–15 kHz) is presented on the vertical axis, horizontal axis denotes time in seconds.

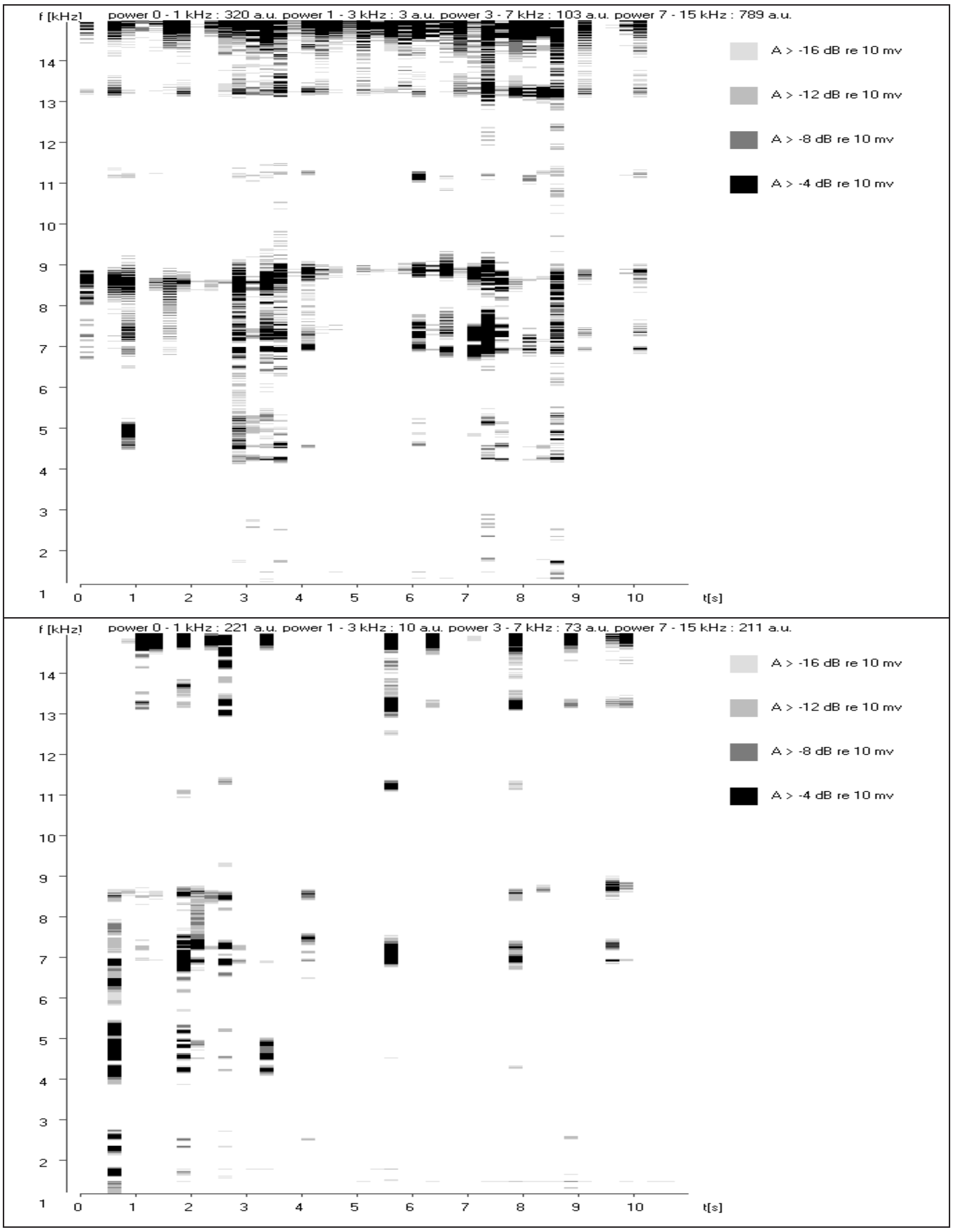

Fig. 6. Spectral characteristics of two samples with high structural humidity level (group E – above and F – beneath). Analysed frequency band (1–15 kHz) is presented on the vertical axis, horizontal axis denotes time in seconds. The acoustograms presented in Figs. 5 and 6 demonstrate the effect of low frequency energy loss in the AE signal with respect to the increase of structural humidity level.

6. Conclusions

The following changes of recorded AE signal descriptors were registered as a result of the structural humidity level increase :

- decrease of the number of AE events detected at the lower and upper detection threshold,
- reduction of AE event duration after the glass-rubber phase transition (i.e. the transition from the amorphous into crystalline order of the texture matrix),
- increase of dimensionless averaged partition power spectrum slope coefficient observed in the structures where reduction of AE event duration has occurred.

Since there are no standard procedures to measure crispness of food products, the authors of the paper conclude that AE event counting and investigation of spectral characteristic of AE signal can serve as useful tools for cereal food testing.

Acknowledgment

This work was supported by the grant no. 3 P06T 040 25 (2003–2006) of Polish State Committee for Scientific Research.

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