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THE USE OF WAVELET ANALYSIS TO ASSESS THE DEGREE OF WEAR OF WORKING ELEMENTS OF FOOD EXTRUDERS

WYKORZYSTANIE ANALIZY FALKOWEJ DO OCENY STOPNIA ZUŻYCIA ELEMENTÓW ROBOCZYCH EKSTRUDERÓW SPOŻYWCZYCH*

The paper presents the evaluation of the wear status of the single-screw extruder working elements on the basis of die pressure and screw load toque load values changes. The changes of this parameters were analyzed as frequency spectrum using the tools of wavelet analysis. In the study plan the hypothesis was formulated that the assessment of extruder elements wear level is possible through observation of the frequency of process parameters changes. Due to the dynamic characteristics of the process in the determination of natural frequencies Morlet wavelet transform was used. Research was carried out for three heights of longitudinal wedges: 4, 2 and 1 mm. During experiment the extruder drive line load and the extruder screw speed were changed. It has been found that based on the observation of changes in resonant frequencies, it is possible to accurately assess the wear degree of friction elements in a single screw extruder. Moreover, it has been noted that the wavelet analysis may be an effective tool for the assessment of the extruder working elements wear level.

Keywords: *wavelet analysis, Short Time Fourier Transformation, Continuous Wavelet Transformation, extruder barrel.*

W pracy przedstawiono ocenę stanu zużycia elementów roboczych ekstrudera jednoślimakowego na podstawie obserwacji zmian składowych częstotliwościowych widma obciążenia układu napędowego ślimaka ekstrudera i ciśnienia w matrycy przy wykorzystaniu narzędzi analizy falkowej. W planie badań sformułowano hipotezę, że możliwa jest ocena stopnia zużycia elementów roboczych ekstrudera przez obserwację częstotliwości zmian parametrów procesowych. Ze względu na dynamiczne cechy procesu przy wyznaczeniu częstotliwości własnych wykorzystano falkę Morlet'a. Badania przeprowadzono dla trzech wysokości klinów wzdłużnych 4, 2 i 1 mm. Podczas eksperymentu zmieniano obciążenia ekstrudera oraz prędkość obrotową ślimaka. Stwierdzono, że na podstawie obserwacji zmian częstotliwości rezonansowych można precyzyjnie oszacować stopień zużycia elementów ciernych w ekstruderze jednoślimakowym. Ponadto zaobserwowano, że analiza falkowa może być skutecznym narzędziem oceny stopnia zużycia elementów roboczych ekstrudera.

Słowa kluczowe: *analiza falkowa, STFT, skalogram CWT,cylinder ekstrudera.*

1. Introduction

The extrusion treatment of food products is one of the most popular production processes of processing starch in the processing industry [12]. The principal process parameters of this process are the die pressure and temperature profile inside the extruder barrel. Those operational parameters have further significant influence on the extruder drive line load [10]. From the technological point of view the outlet die pressure in screw extruders is a function dependent on extrusion process parameters such as: raw material type and their moisture, screw configuration and wear of extruder working elements (screws, barrel) [3, 8]. The outlet die pressure also impacts the quality parameters of obtained products, thus maintaining the stable pressure value level during whole process time is a key factor in industrial production processes. During proper operation of extruder working elements and with constant process parameters, the pressure value change should impact the extruder drive line load change. Pressures generated inside of an extruder barrel are however result variables, which depend on the extrusion process parameters and work quality of extruder elements, among others the wear level of those elements. In single screw extruders transport properties depend on friction forces difference between friction generated by transported material and inner barrel surface from one side and friction generated by transported material and screw surface other side.

Transported material will be able to move along the barrel, only when tangent friction force of the material on inner barrel surface will be greater than the tangent friction force of the material on a screw surface [14]. This is of key importance, both for extrusion process stability and the quality of final products. In case of single screw extruders to ensure the good transport conditions, the grooves milled are done on the inner surface of barrel or in longitudinal trapezoidal shape channels longitudinal wedges are mounted. Both mentioned solutions may be used to improve friction between moved material and barrel surface.

In the observed extruder, constructors used the second solution to improve friction - he mounted longitudinal wedges made from a hard cast steel on the inner barrel surface [Fig.1]. During working the working wedges are gradually being worn down, and along with the reduction of their height, extruder transport properties get worse. As a consequence, this leads to the worsening of the quality of the extrudated product.

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

Currently, the measurement of absolute height of wedges during standard check procedures is the effective method, but for many cases this leads to premature replacement (or regeneration) of the extruder barrel. That procedures are the result of lack of the reliable methods to estimate the influence of wear degree of the extruder wedges on transport properties.

There are methods of verification of their wear level in the literature, however, usually they refer to specific, homogenous materials. For technological reasons, the information on transport properties of the extruder would be important, also for more diverse materials.

Each element or set elements has got their own vibration frequencies which is called "natural frequency". The frequency generated resulting from the shape extruder elements and operating conditions [4, 6]. Extruder load parameters presented as: screw load torque variation and die outlet pressure fluctuations have been shown to depend on working mechanical elements cooperation, the amount and features of treated materials. Thus, in studies of this type hitherto carried out, for the analysis of signals, the Fast Fourier transformation (FFT) was used to extract the frequency components of the process parameters fluctuation [5, 11]. The Fourier transformation, specially FFT is the most common technique used in signal analysis, but FFT assumes that measured signal is stationary, which, in case of non-stationary processes leads to the loss of the information about signal frequency changes in the time domain. The cyclic Fourier transformation have been more reliable method of analysis of non-stationary signal than pure FTT, its procedure consists in segmenting the observed signal into narrow time intervals and then, using the FFT for each range of measured signals.

For that reasons the signal spectrum was observed in the narrow range of time window. The presented method called windowing has been proposed by Gabor [9]. The windows adjacent to each other allow to observe the frequency signal spectrum within time domain. That transformation called Short Time Fourier Transformation (STFT), shows the measured signal frequency spectrum for 3D coordinates: frequency and time [2]. The serious disadvantage of STFT method is the compromise with respect to window size selection, to find non-stationary signal features (then the window should be as narrow as possible), on the other hand, the narrow window size caused the loss of information about the low signal frequencies. So for better frequency resolution the window size should be longer in the time domain.

The main drawback of the constant size window as mentioned is possibility of loss of frequency and time information, so a lot of measure signals need another methods, one of the ways is to employ the changeable window size and overlap windows method. Complementary to the method described above is continuous wavelet transformation (CWT), the CWT uses a window technique also but with variable size windows [13, 15]. The CWT allows the use of large (long time) windows where low frequency signals are treated or small- shorter time windows where high frequency signals are sought for. Owing to the CWT features, some essential information will be found during observation of the non-stationary signals, ignored by other measurement methods, such as: the failure points, discontinuities of higher derivatives or self-similarity [1].

The aim of this work was to present the assessment of wear level of the extruder working elements (height of barrel wedges). The wedges height were evaluated by means of wavelet continuous transformation of the extruder screw load toque and die pressure oscillation.

2. Materials and methods

Measurements were carried out using frequency component of the relative extruder die pressure changes and screw load torque fluctuation. The object of the study was the extrusion process of corn grit processed in the KZM-2 single screw food extruder. The processed corn grit moisture was 14%. Extruder barrel temperatures settings were fixed at: 130, 110, and 80°. The technical data of KZM-2 extruder are shown in Table 1.

Table 1. KZM-2 single screw extruder specification, basic data

ID	Parameter	
1.	Drive motor power	22 (kW)
2.	Extruder screw speed n	200÷500 rpm^{-1}
3.	Die diameter	5 mm
4.	Length to screw diameter ratio L/D	6:1
5.	Compression degree	1.5

The longitudinal grooves on inner extruder barrel surface are used to lock the trapezoidal cross-section longitudinal wedges [Fig.1].

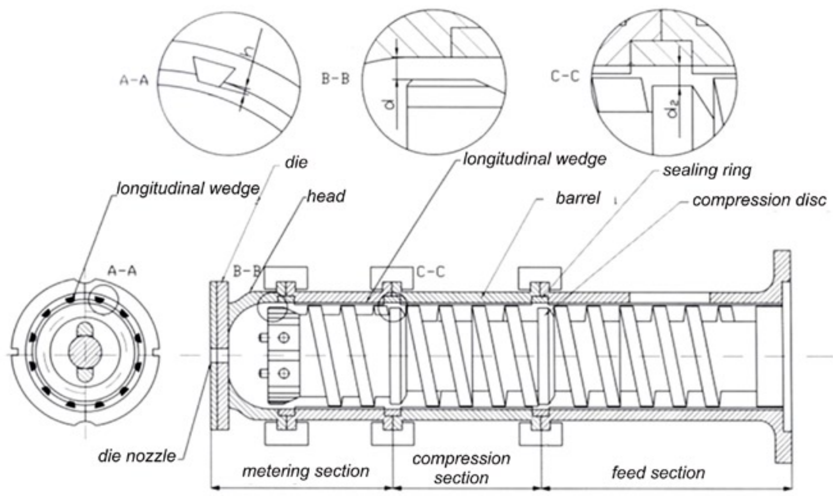

Fig. 1. Diagram of the working part of the extruder KZM-2 [7]

For the acquisition of measurement data (pressure in the matrix and extruder drive line load) National Instruments set was used (measurement sheet – PCI-6024E, module NI SCXI-100 and NI SCXI-1302) and LabView 7.1 software. Data was recorded in 10 Hz frequency.

Wedges protruding beyond the surface of the wall form characteristic grooves. The height of the longitudinal wedges h [Fig. 1, section A-A] was differentiated by replacement of wedges to elements enabling to obtain diversification of friction against inner surface of the extruder barrel. Research was carried out for three working wedges of the extruder: 4, 2 and 1 mm. Also extruder load was changed by means of increase of the mass of the input raw material in time (from 50 $kg \cdot h^{-1}$ to 80 $kg \cdot h^{-1}$) and screw rotation speed (from 200 rpm^{-1} to 300 rpm^{-1}).

For data analysis the continuous wavelet transform (CWT) analysis was used, which analysis was performed using the algorithm realised at the Matlab platform. Wavelet analysis consists in matching the courses of the basic wavelet courses to the course of the examined signal $x(t)$. CWT transformation was also described with an equation (1), [15]:

$$CWT_x^{\psi}(a,b) = W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \cdot \psi^{*}\left(\frac{t-b}{a}\right) dt \qquad (1)$$

where:

a – scale,

b – wavelet shift,

ψ – mother wavelet.

Final effect of CWT transform is the obtaining of values of wavelet coefficients A, dependent on the value of scale a and shift b of the mother wavelet. Value of coefficient A determines the matching ratio of the wavelet imposed on a signal to the course of the examined signal. Its higher values means better matching ratio. Monitoring of the coefficient A value change within time domain and frequency enables the observation of non-standard frequencies occurring during the operation of the device.

Research results are presented in diagrams in the form of scaleograms, i.e. wavelet maps. Due to simplified method of generation, Morlet wavelet has been used here.

3. Results and discussion

In Figure 2, the course of changes of pressure and drive line load using the wedges with height of $h = 4$ mm (unused wedges) has been presented.

Drive line load presents the value of the aggravating moment of the extruder shaft in relations to the value of the moment causing the disconnection of the drive through overload clutch.

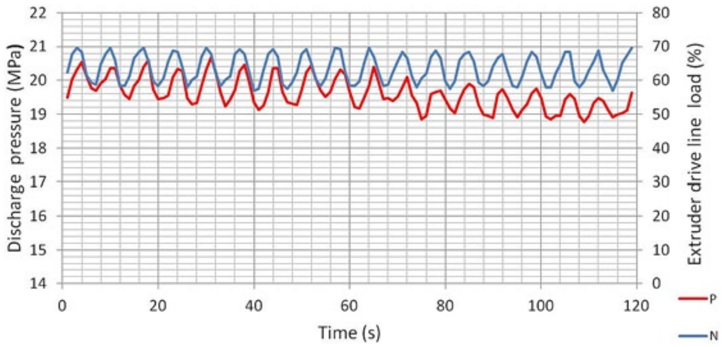

Fig. 2. The course of changes in the pressure P and the load drive system extruder N during constant speed snail n = 200 rpm and the intensity of the feedstock Q = 55 kg·h^-1; the height of the grooves inside the housing extruder h = 4 mm

It has been ascertained that in these conditions, both the pressure values and drive line load of the machine have stable course. Moreover, the course of both diagrams is similar, which means that this is the correct character of extruder operation, which is dependent both on construction features of the device and the process parameters set forth at the beginning.

When using barrels, wedges of which were worn in 50% ($h = 2$ mm), clear differences in the course of pressure values change have been noted [Fig. 3].

Thus, in order to change the parameters of the material course within the device, the rotational speed of the extruded was increased. Increase of the rotational speed of the screw is a typical reaction of the device operation, enabling to extend the operation time of the extruder. In case of starch products, too high wedges (more than 4 mm) as well as too low ones (less than 1 mm) are disadvantageous. When the wedges profile is too high, it gets glued by the material, and if it is too low – too low friction against transported material occurs. Manufacturer of the examined extruder model recommends regeneration of its sleeve or replacement of wedges, if the wedges height is smaller than 1 mm. However, in case of material with high value of coefficient of friction against the barrel, the correct operation of the extruder, even with the lower wedges profile, is possible. Unfortunately, in case of extrusion of the raw materials compounds, very often it can be stated only after the process is initiated.

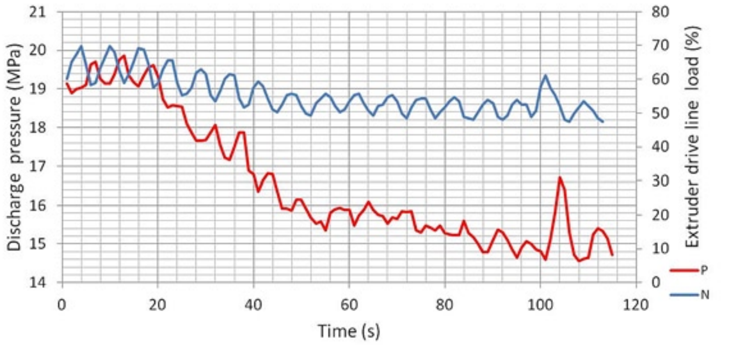

Fig. 3. Number of changes in the pressure P and the extruder drive system load N at which a transient state when changing the screw speed from 200 rpm to 300 rpm and at a constant flow of the feedstock ratio Q = 55 kg·h^-1; the amount of grooves within the housing of the extruder h = 2 mm. snail n = 200 rpm and the intensity of the feedstock Q = 55 kg·h^-1; the height of the grooves inside the housing extruder h = 4 mm

Experienced operator may define the status of such process and assess further transport possibilities of the extruder by observing the process course. Thus, it can be assumed that it is possible to determine the current status of the transporting system through analysis of the frequency of oscillations of the torque value changes loading the transporting screw drive shaft.

Results of wavelet analysis depicting the changes of the scale (CWT) in the function of time and value of the oscillations interval at different settings of the extrusion process parameters have been shown in figures. The diagrams present the results of the wavelet analysis for the drive line load of the extruder N and changes of the pressure values P. Analysing diagrams 4a and 4b it has been noted that both, for the courses of changes of pressure frequencies and drive line load, no frequency with long oscillations interval has been observed.

Thus, the observed oscillations referred mainly to the changes within the scope og high frequencies , which could also constitute so called "noises". Also no change in the frequency at the change of load has been observed. In the 4b diagram ($n = 300$ rpm^{-1}) frequency spectrum moved towards lower values (longer interval). With these settings of the extruder, it has been noted that both, the change of the drive line load of the extruder, resulting from the change of the mass flow of the raw material supplied to the extruder and the change of the rotational speed, did not negatively affect the course of the extrusion process. Such course of the pressure changes is confirmed by the correctness of the process handling.

The use of barrels with wedges worn in 50% ($h = 2$ mm) caused significant changes in the course of wavelet diagrams [Fig. 5a and 5b].

In the lower part of the diagram, the oscillations interval equalling ca. 64 s may be observed; this interval occurs at the mass raw material flow of 55 kg·h^{-1}. Increase of the mass flow of the raw material to 80 kg·h^{-1} causes the disappearance of these frequencies. Such course of changes was observed for frequency changes P and N at two extruder screw speeds.

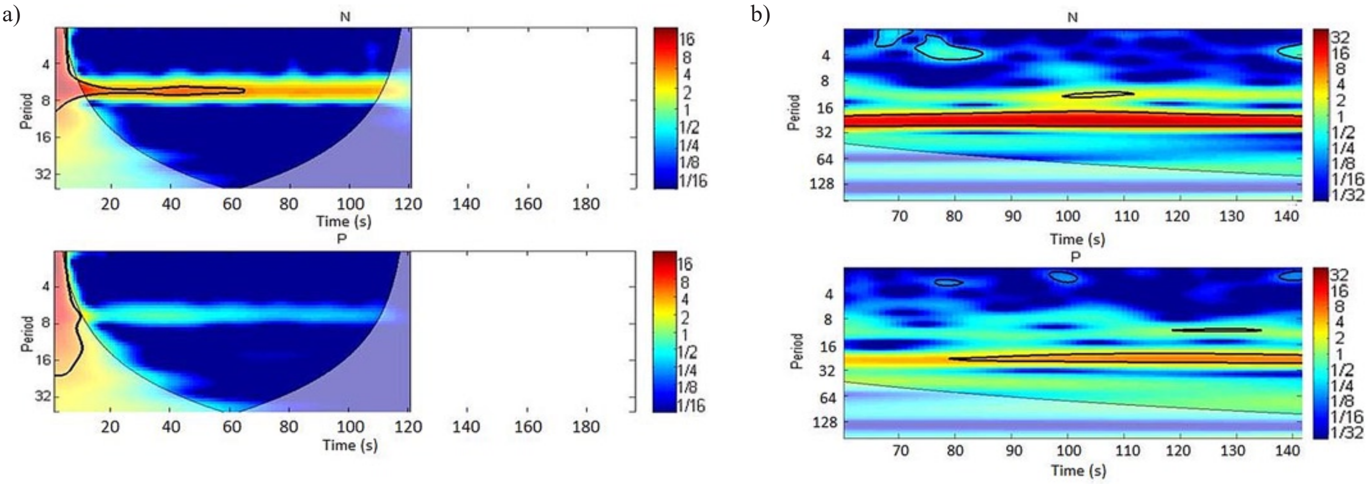

Fig. 4. Scaleogram CWT. h = 4 mm, change in a load of 50 kg·h^{-1} to 80 kg·h^{-1} feed material: a) 200 rpm, b) 300 rpm

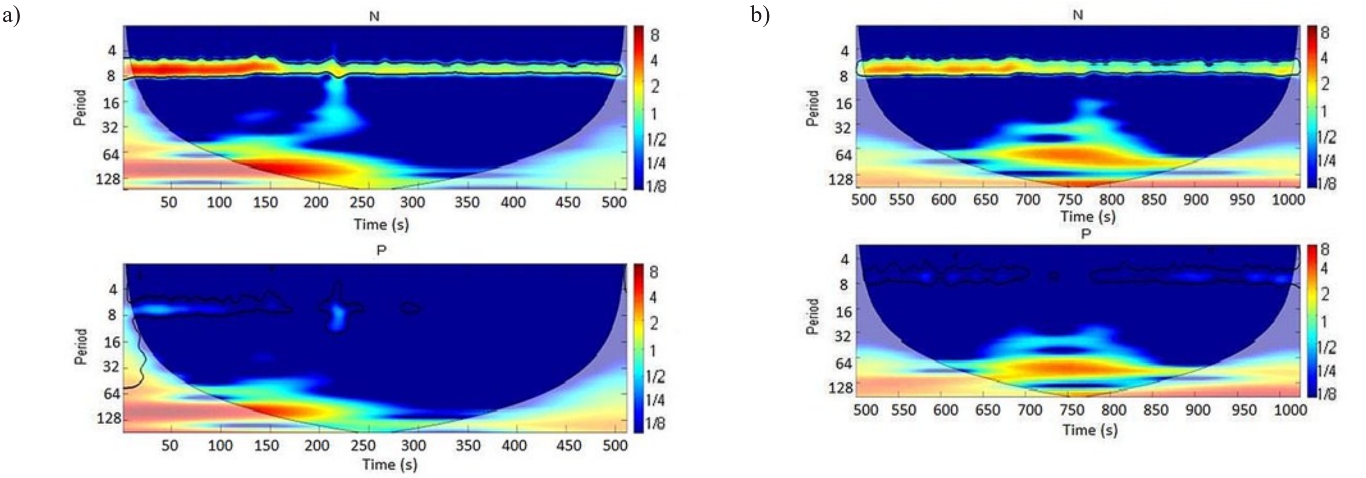

Fig. 5. Scaleogram CWT. h = 2 mm, change in a load of 50 kg·h^{-1} to 80 kg·h^{-1} feed material: a) 200 rpm, b) 300 rpm

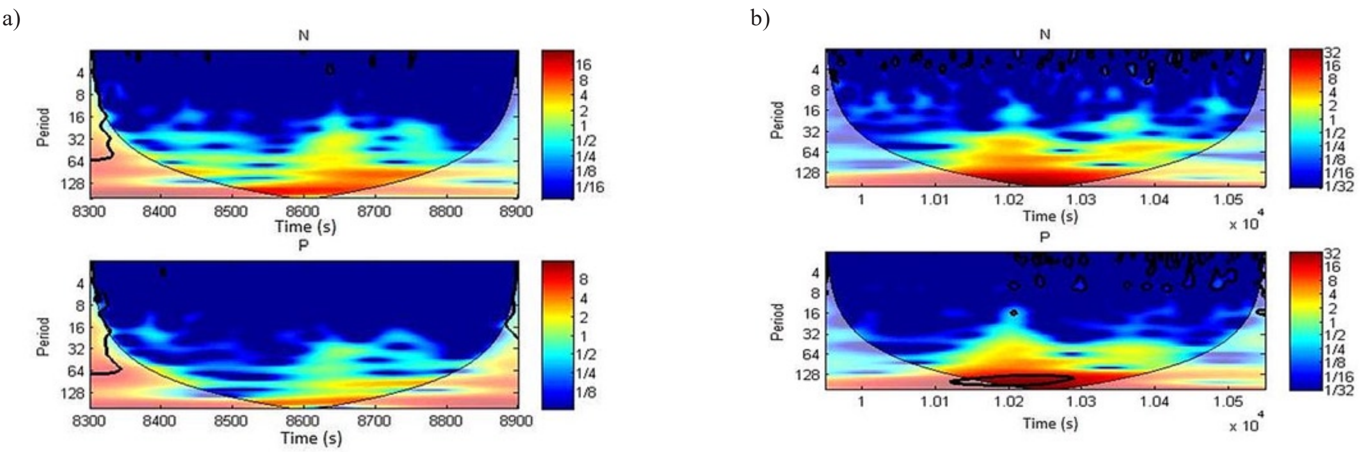

Fig. 6 Scaleogram CWT. h = 1 mm, change in a load of 50 kg·h^{-1} to 80 kg·h^{-1} feed material: a) 200 rpm, b) 300 rpm a) 200 rpm, b) 300 rpm

When using the extruder barrels with wedges of 1 mm in height, it has been noted that short-term oscillations disappeared [Fig. 6a and 6b].

In the examined case, the spectrum with high correlation with studied wavelets may be clearly observed within the scope of long-term oscillations equalling ca. 120 s. Increase of the rotational speed of the screw drive shaft causes the increase of the matching degree of the spectrum to the basic wavelet course. Just as in the diagrams above, changes of values *P* and *N* have similar courses.

To simulate the greater wear level of the operating wedges of the extruder barrel, in point marked as 1.07 [Fig. 7], 2% of the vegetable fat has been added.

A clear frequency changes spectrum within the scope of long-term oscillations connected with the disappearance of the transport proper-

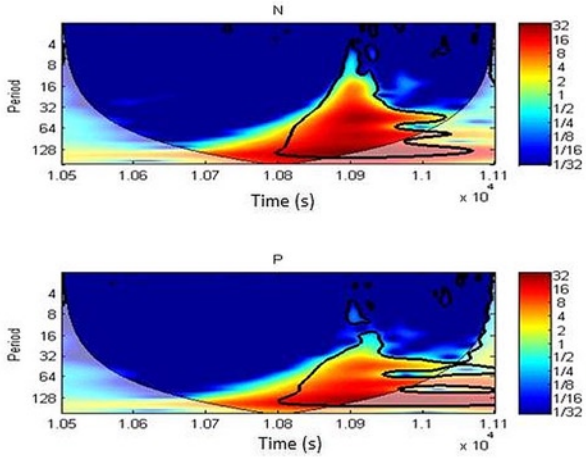

Fig. 7. Scaleogram CWT. h = 1 mm, load of 80 kg·h-1 feed material, 300 rpm

ties of the extruder, may be observed. Such course suggests that in the case of further wear of operating wedges of the extruder, it will be possible to note clearer process frequencies changes.

4. Conclusions

Based on the performed study, the following conclusions have been formulated:

1. Wavelet analysis may be an effective tool for assessment of wear level of operational elements of the extruder (operational wedges).
2. Based on the observation of changes in resonant frequencies, the wear level of friction elements in the single-screw extruder may be assessed.
3. Along with the reduction of height of the working wedges, resonant frequency decreases. At the 2 mm high wedges, the oscillations with an interval of 64 s appear in the spectrum. Oscillations' intensity decreases and it disappears in case of further wear of the wedges. In case of critical (h=1mm) wear of friction elements, oscillations interval exceeded 64 s with a tendency for further growth to ca. 128 seconds [Fig. 6]. Particularly good matching of the native wavelet within the interval of 64 to 126 s took place during long-term work with considerable load [Fig. 7]. Typical measured value of the oscillations interval of the fitted basic wavelet for new elements did not exceed 8-12 s.

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