Different approaches for the local fault detection in case of the signal with non-Gaussian noise

dr inż. Justyna Hebda-Sobkowicz

Wroclaw University of Science and Technology, Faculty of Geoengineering, Mining and Geology

Digital Mining Center

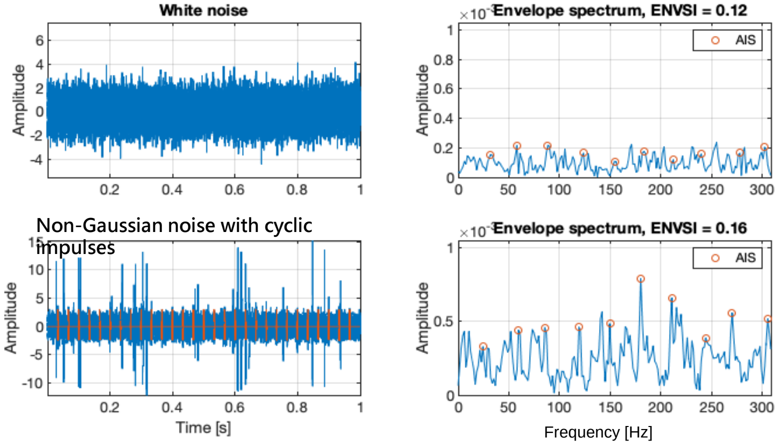
Fundusze Europejskie
Wiedza Edukacja Rozwój

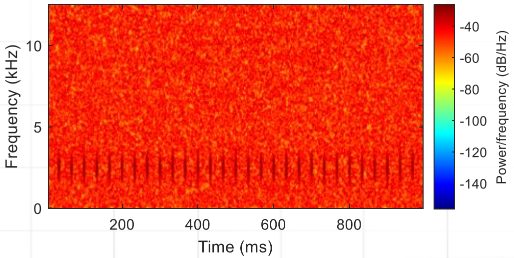
Unia Europejska
Europejski Fundusz Społeczny

HR EXCELLENCE IN RESEARCH

Politechnika Wrocławska

Condition monitoring of mining machines





Non-cyclic impulses

More difficult analysis

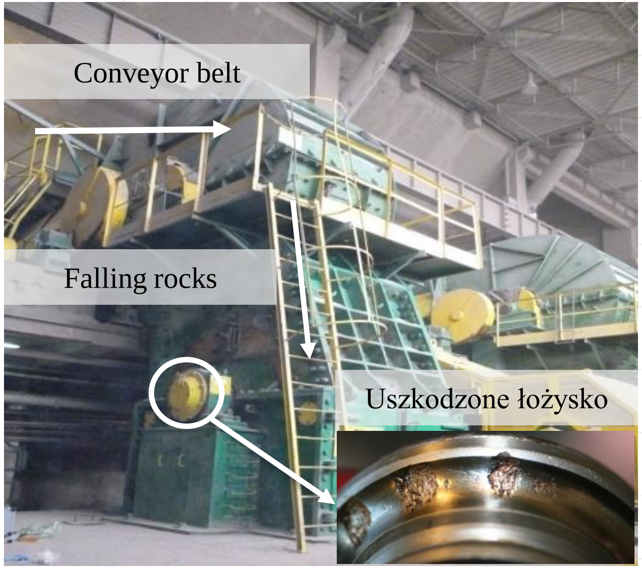
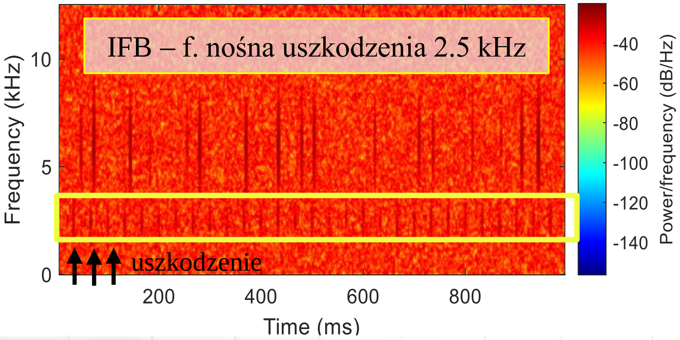


Figure 1. Hammer crasher used for copper ore defragmentation



Detection of local bearing damage using damage characteristics: impulsivity and cyclicity

Impulsive characteristic	Cyclic characteristic	Both characteristics
CVB vs. known kurtosis, alpha parameter, Gini index, spectra smoothness index	**CORRELATION MAPS** (Spearman, Kendall, Quadrant, Trimmed vs. known Pearson, autocovariation)	**IMPROVED INFOGRAM** vs. known classic infogram

Informative frequency band (IFB) selection from the *t/f* map (spectrogram) - Conditional Variance Based Selector (CVB)

Impulsive characteristic

- Inspired by the 20/60/20 Rule (3 subsets) - a state of balance:
- New defined statistic – extension of the 20/60/20 Rule for describing the condition state of a machine with non-Gaussian noise:

$$\widehat{C}_7(x) := \left(\frac{\hat{\sigma}^2_{A_3} - \hat{\sigma}^2_{A_4}}{\hat{\sigma}} + \frac{\hat{\sigma}^2_{A_5} - \hat{\sigma}^2_{A_4}}{\hat{\sigma}}\right)^2 \sqrt{n}.$$

- For a machine in an undamaged state, the statistic values are close to 0.
- Otherwise, the value of the statistic increases.
- The most important property**:**

  tails of the distribution (non-cyclic impulses with large amplitudes) are ignored.

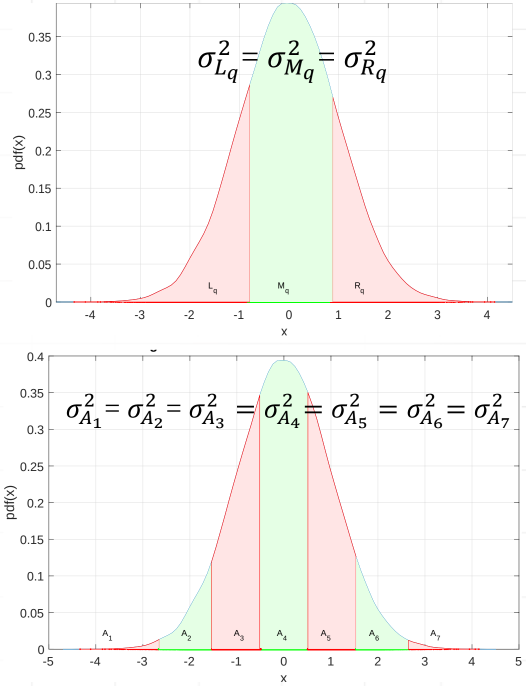


Fig. 2. The cumulative distribution functions of Gaussian distribution with marked divisions on 3 and 7 unique subsets.

Informative frequency band (IFB) selection from the t/f map (spectrogram) - Conditional Variance Based Selector (CVB)

Graphical comparison of selectors:

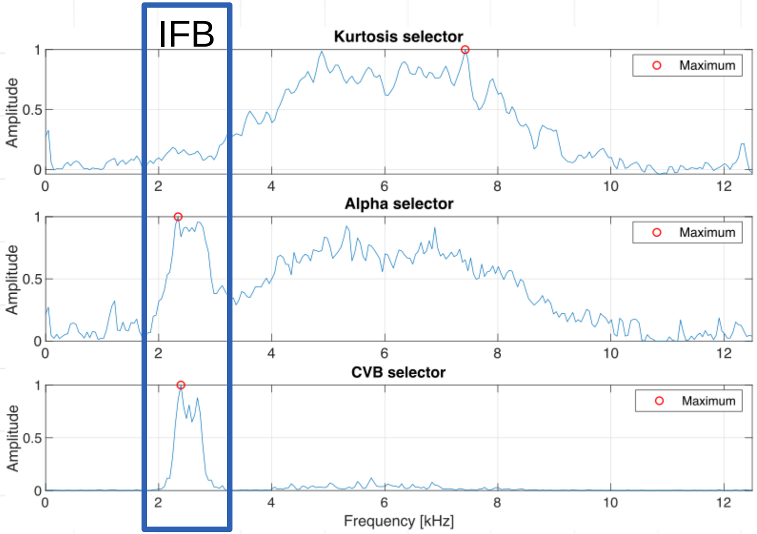
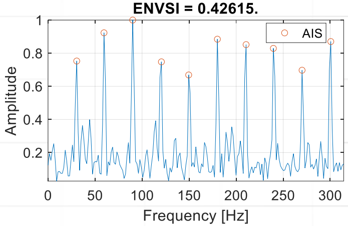


Fig. 3. IFB selectors

- The best selectivity of IFB in case of CVB selector in comparison to the known selectors

- ENVSI (Envelope Spectrum Based Indicator) as the numerical indicator verifying the performance of the methods:

$$ENVSI = \frac{\sum_{i=1}^{M_1} AIS^2}{\sum_{k=2}^{M_2} SES} \quad (4)$$



AIS – amplitude of harmonics of the fault,
SES – squared envelope spectrum,
M_1 – number of harmonics of the fault frequency (10 was taken as enough),
M_2 number of frequencies considered for calculating the total energy of the SES.

Informative frequency band (IFB) selection from the t/f map (spectrogram) – Conditional Variance Based Selector (CVB)

- MC simulations using the crusher signal model and ENVSI to determine:

- the influence of the non-cyclic impulses amplitude (*ANCI*) and their amount (frequency ratio of non-cyclic to cyclic impulses FIM_2/FIM_1) on the methods effectiveness,

- consequences of overlapping of the frequency bands of cyclic and non-cyclic impulses.

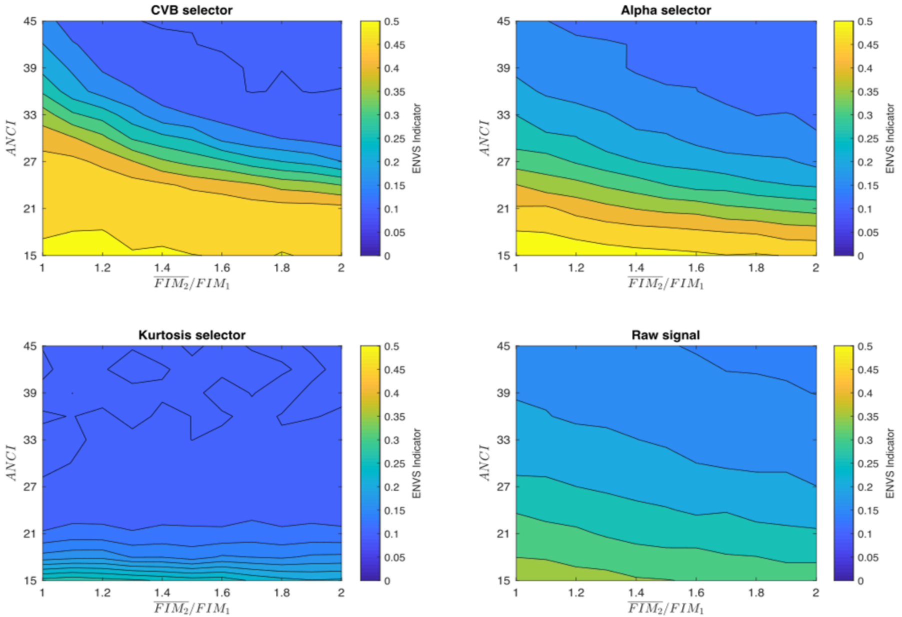
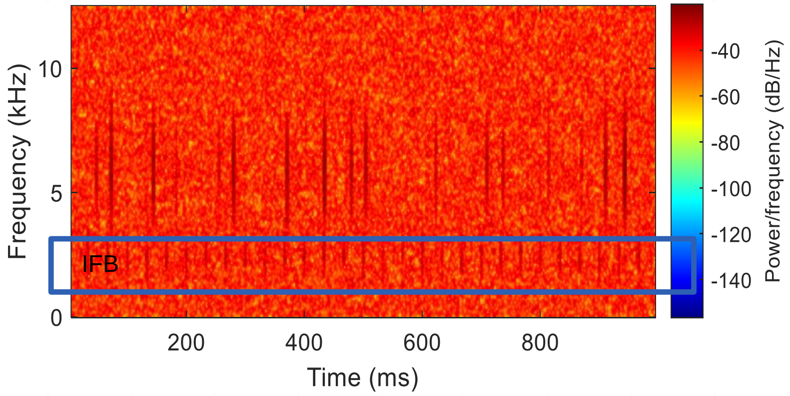


Fig. 4. Monte Carlo simulations of the ENVSI indicator for variable parameters of the simulation signal (frequency and amplitude of non-cyclic pulses) - for different selectors

Informative frequency band (IFB) selection from the *t/f* map

- Another diagnostic approach fucuses on **cyclic characteristic**.



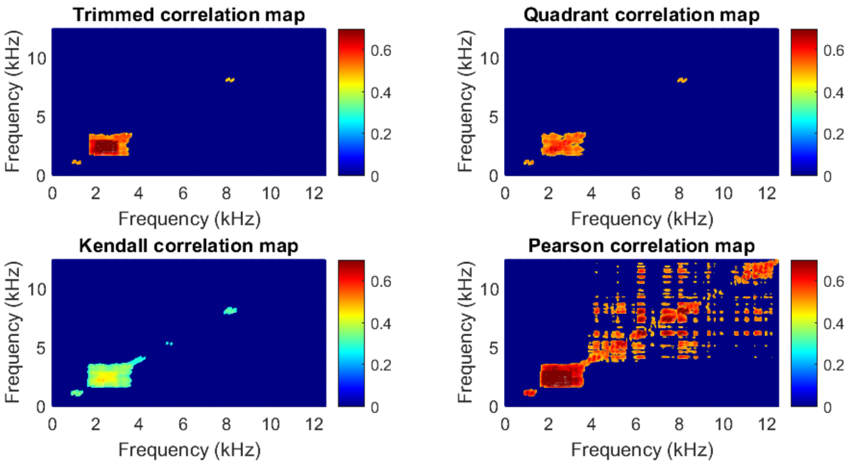
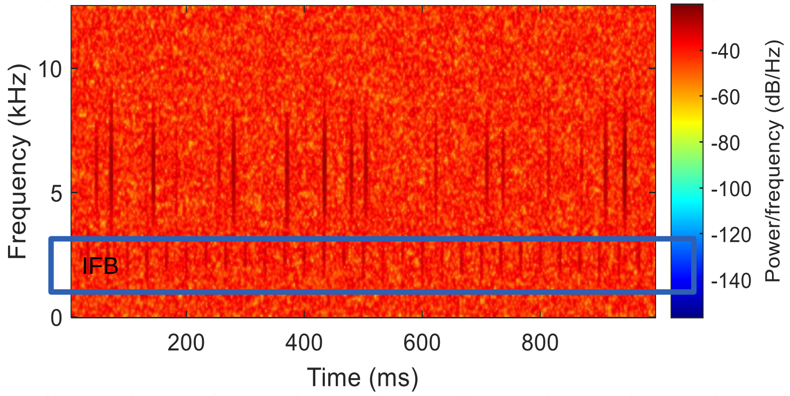


Fig. 5. Correlation maps

- Generalized, automatic procedure for identifying cyclic behavior in a signal (cross-correlation of frequency bands of the spectrogram) in shape of correlation map or IFB selector.

Informative frequency band (IFB) selection from the *t/f* map

- Another diagnostic approach fucuses on **cyclic characteristic**.



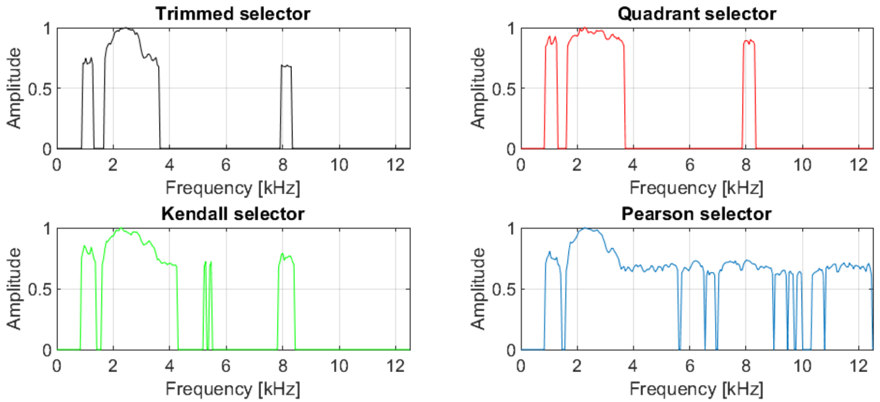


Fig. 6. IFB selectors

- New measures proposed for IFB selection:
- **Quadrant and Trimmed correlations**
  - more resistant to non-Gaussian noise.

Informative frequency band (IFB) selection from the t/f map

- New measures proposed for IFB selection: **Quadrant and Trimmed correlations** - more resistant to non-Gaussian noise.

The Quadrant correlation is defined as follows:

$$(1) \quad quad = \frac{(N_1 + N_3) - (N_2 + N_4)}{N},$$

$Q_1, Q_2, Q_3, -$ quadrants formed by dividing the two-dimensional database using the mean of the X and Y, creating 4 spaces of abundance N_1, N_2, N_3, N_4 respectively.

N_i denotes the number of observations in Q_i quadrants, for $i = 1,2,3,4$ and N is the total value of the observations. The Quadrant correlation is calculated by first normalizing the data by coordinates median.

The Trimmed correlation for sample vectors x and y can be defined as a Pearson correlation ρ_{xy} calculated for special prepared data included in sample vectors z_x^c and z_y^c:

$$trim = \rho_{z_x^c, z_y^c},$$

$$z_x^c = (x_1 L_1, x_2 L_2, \dots, x_n L_n),$$
$$z_y^c = (y_1 L_1, y_2 L_2, \dots, y_n L_n).$$

$x = (x_1, \dots, x_n), y = (y_1, \dots, y_n), z = (x_1 y_1, \dots, x_n y_n)$
and L is a $0 - 1$ function defined as:
$L_i = 1$ if $z^{(k)} < z_i < z^{n-k+1}$, and 0 otherwise,
where $k = \lfloor c \cdot n \rfloor$ for $0 \leq c < 0.5$,
c is a trimming constant or fraction of data in the sample z of the predicted number of outliers and $z^{(j)}$ is an ordered vector in ascending order.

IFB selection form $f/\Delta f$ map - IMPROVED INFOGRAM

- Infogram - combines **both** characteristics of damage.
- Application of negentropii (I) – measured in the time domain of the signal (I_{SE}) and in the frequency domain (I_{SES}) for different $f/\Delta f$.
- Aggregated diagnostic information using the arithmetic mean from both I_{SE} and I_{SES}.

Negentropii:

$$\hat{I}(x) = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_i^2}{\frac{1}{N}\sum_{i=1}^{N} x_i^2}\ln\frac{x_i^2}{\frac{1}{N}\sum_{i=1}^{N} x_i^2}\right)$$

Infogram:

$$\Delta I(f,\Delta f) = \frac{I_{SE}(f,\Delta f) + I_{SES}(f,\Delta f)}{2}$$

SE – squared envelope, *SES* – squared envelope spectrum

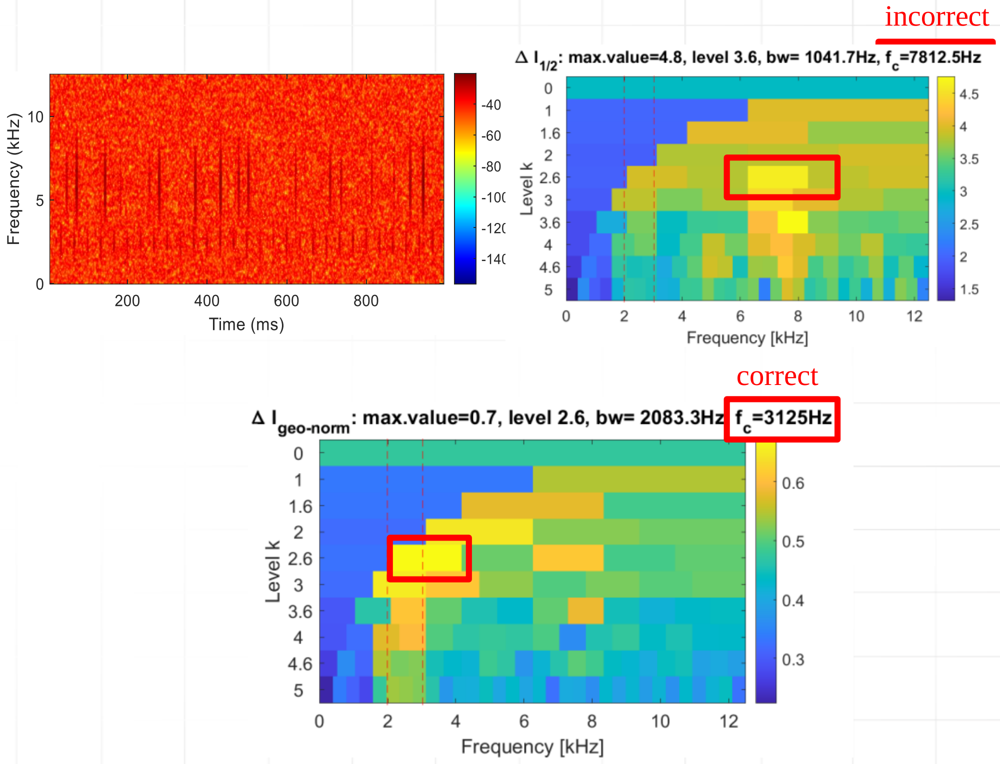
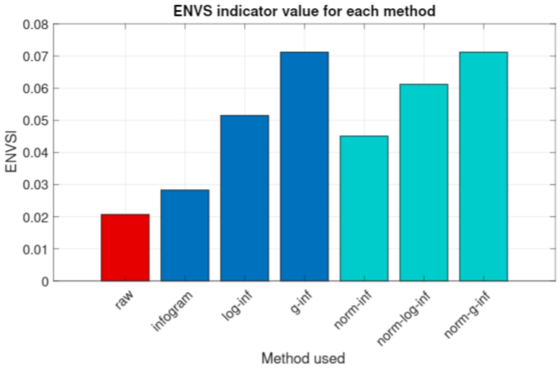


Fig. 9. Infogram and **geometric infogram** for the vibration signal from the bearing of the crushing machine

IFB selection form $f/\Delta f$ map - IMPROVED INFOGRAM

- Proposed **extensions of the classic infogram include alternative averaging measures**

Type of mean		
Arithmetic mean	Logarithmic mean	Geometric mean
classical infogram	log-infogram	g-infogram
$\Delta I_{1/2}(f, \Delta f)$	$\Delta I_{ln}(f, \Delta f)$	$\Delta I_{geo}(f, \Delta f)$
norm-infogram	ln-norm-infogram	g-norm-infogram
$\Delta I_{norm}(f, \Delta f)$	$\Delta I_{ln-norm}(f, \Delta f)$	$\Delta I_{geo-norm}(f, \Delta f)$



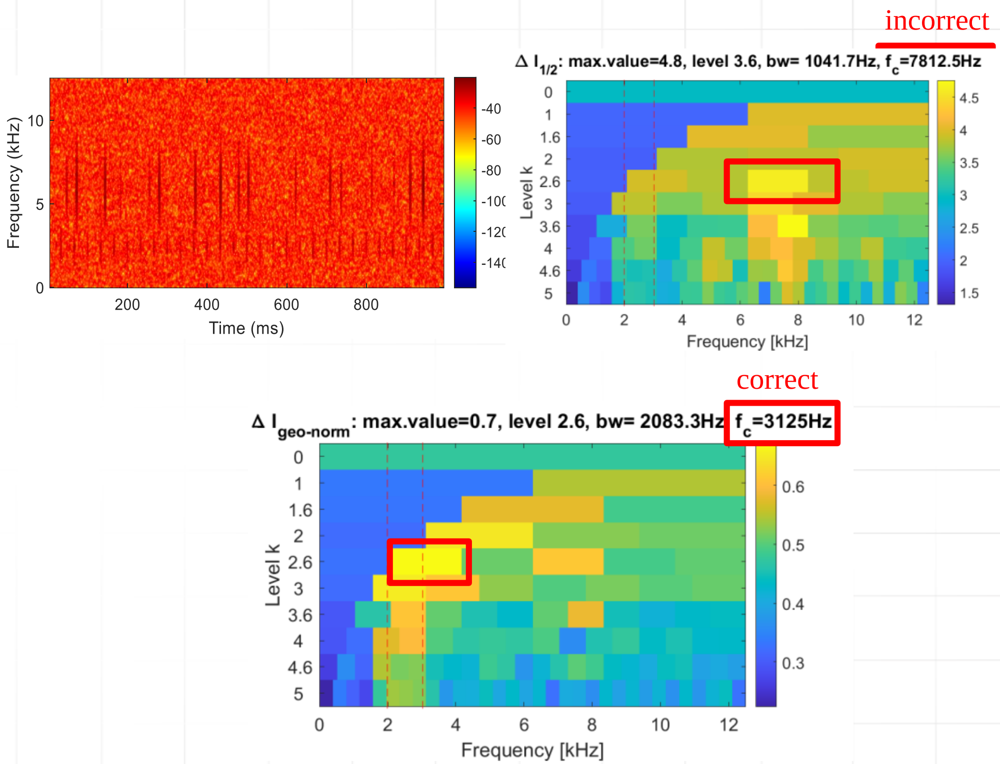


Fig. 9. Infogram and **geometric infogram** for the vibration signal from the bearing of the crushing machine

Detection of local bearing damage using damage characteristics: impulsivity and cyclicity

Impulsive characteristic	Cyclic characteristic	Both characteristics
CVB vs. known kurtosis, alpha parameter, Gini index, spectra smoothness index	**CORRELATION MAPS** (Spearman, Kendall, Quadrant, Trimmed vs. known Pearson, autocovariation)	**IMPROVED INFOGRAM** vs. known classic infogram

Proposed methods:

- **new solutions**, simply defined (CVB, cross-correlation maps) or utilizing advanced signal processing techniques,
- modifications of known tools (new correlation maps, **new infogram**s),
- compared with classical methods, in terms of many changeable variables,
- **especially effective** in case of signals with: **low signal-to-noise** ratio and **with non-Gaussian noise**.

Thank you for the attention

dr inż. Justyna Hebda-Sobkowicz