XXI IMEKO World Congress “Measurement in Research and Industry”
August 30 – September 4, 2015, Prague, Czech Republic

ASSESSMENT OF NON-STATIONARY MAGNETIC FIELD EMISSION USING MATCHING PURSUIT

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Abstract – This paper considers applying the matching pursuit algorithm with chirplet dictionary for an adaptive time-frequency analysis of the non-stationary magnetic fields. The way of the assessment of the exposure level to low-frequency magnetic field emissions, in reference to admissible levels, proposed by International Commission on Non-Ionizing Radiation Protection, is presented. The selected results of the analysis of the low-frequency magnetic field are presented.

Keywords: magnetic field measurement, matching pursuit, time-frequency analysis

1. INTRODUCTION

The admissible reference levels of low-frequency magnetic-field emissions have been defined by international committees both in the context of the electromagnetic compatibility of technical equipment as well as in the assessment of limiting human exposure to magnetic field emissions [1], [2], [3]. It is extremely important from a practical point of view to propose the measurement method and the way of the evaluation of the exposure level to low-frequency magnetic field emissions, guaranteeing the accuracy and repeatability of the measurement results. The preliminary results of magnetic field measurements performed on board the Gdynia Maritime University research-training vessel during manoeuvring and sea voyage showed the areas with the high level of magnetic field intensities [4], [5]. The high dynamics of magnetic field changes was observed, especially occurred in areas with high level of the magnetic flux density (MFD). The magnetic field spectrum spreads out mainly in low frequency range below 2 kHz. The measuring signals, representing magnetic field density waveforms contain time-varying harmonics, which magnitude, frequency and phase changing over time. This kind of signals has an evolutionary spectrum and can also contain time-varying broadband spectral content.

The quadratic time-frequency analysis methods for estimation of the energy of an evolutionary signal as a function of time are used successfully. The application of an adaptive time-frequency method certainly provides a significantly better joint time-frequency resolution in comparison with other quadratic joint time-frequency distributions [6], [7].

In the paper, the way of the estimation of the exposure level to a low-frequency magnetic field in reference to admissible levels, proposed by International Commission on Non-Ionizing Radiation Protection (ICNIRP) is presented.
In the special case of simultaneous exposure to multiple frequency fields, conditions of the admissible exposure were defined with the time-dependent summation formula [1].
The instantaneous values of the summation formula were estimated with the adaptive joint time-frequency analysis of the digitized magnetic-flux density waveforms, acquired by measurement. The adaptive transform, based on the matching pursuit algorithm, was implemented in the LabVIEW software. Matching pursuit (MP) is an iterative algorithm, which uses a redundant dictionary of functions in order to select the functions, which best match the signal components [6], [7], [8]. Linear Gaussian chirplets are used as the elementary functions. Thanks to the varying window size and modulation frequency, MP enables an adaptive (i.e. fitting local structures) signal representation.

2. REFERENCE LEVELS OF MAGNETIC FIELD EMISSION

The international standards establish the exposure limits of magnetic field (MF) emissions that provide protection against known adverse health effects. They based on the results of laboratory and epidemiological studies on both direct and indirect effects of MF [9]. The most representative recommendations from this point of view are published by the International Commission for Non-Ionizing Radiation Protection (ICNIRP) [1]. The magnetic flux density B is the parameter used by the ICNIRP for the definition of the reference levels for general public and occupational exposure to time-varying magnetic fields. In the special case of simultaneous exposure to multiple frequency fields within the frequency range 1Hz…65kHz conditions of the admissible exposure, based on summation formula defined in ICNIRP guidelines [1], can expressed as

$$\sum_{i=1}^{M} \frac{B_i(t)}{B_{L,i}} \leq 1 \qquad (1)$$

where B_i is the magnetic flux density (MFD) at frequency f_i, $B_{L,i}$ is reference level defined in [3] and M is the upper index, which determines a sinusoidal component with frequency less than or equal 65 kHz.
In the low frequency range (below 40 kHz), the formula (1) is modified as follows

$$\sum_{m=1}^{M_1} \frac{B_m(t)}{B_{L,m}} + \sum_{l=M_1+1}^{M_2} \frac{B_l(t)}{B_r} \le 1. \qquad (2)$$

The upper index M_1 determines a sinusoidal component with frequency less than or equal 800 Hz for general public and 820 Hz for occupational exposure. The upper index M_2 corresponds to a sinusoidal component with frequency less than or equal 40 kHz. The field reference level B_r in (2) equals 6.25 μT for general public and 30.7 μT for occupational exposure respectively [1].
The above summation formula assumes worst-case conditions among the fields from the multiple sources. According to [1] safety conditions are ensured if the inequality in (2) is satisfied at any time instant.

3. ADAPTIVE TIME – FREQUENCY ANALYSIS

An estimation of the magnitude of the k th frequency component $B_k(t)$ in (2) is obtained by an adaptive spectrogram $AS(t, f)$ of the digitized MFD time series $b(t)$ acquired by measurement. The joint time-frequency representation, called a spectrogram, describes the energy density of a signal in the time-frequency domain.

The adaptive spectrogram method first uses an adaptive expansion of signal and then sums the Wigner-Ville distribution (WVD) of all the elementary functions to compute the quadratic time-frequency representation of the analysed signal. The adaptive expansion represents a signal $b(t)$ as the linear combination of a series of elementary functions - the time-frequency atoms $g_{\gamma_n}(t)$ can be approximately expressed by the following equation [6]

$$b(t) = \sum_{n=0}^{M-1} a_n g_{\gamma_n}(t) \qquad (3)$$

where a_n is the corresponding complex amplitude of $g_{\gamma_n}(t)$ and M specifies the number of the elementary functions.
A set of elementary functions $g_{\gamma_n}(t)$ called a dictionary, can be generated by scaling $(s > 0)$, translating (u) and modulating (ξ) a single window function [6]

$$g_\gamma(t) = \frac{1}{\sqrt{s}} g(\frac{t-u}{s}) e^{j\xi t} \qquad (4)$$

The dictionaries are selected in order to best match the signal structures.

The adaptive spectrogram $AS(t, f)$ is defined as [4]

$$AS(t, f) = \sum_{n=0}^{\infty} |a_n|^2 WVDg_{\gamma n}(t, f) \qquad (5)$$

where $AS(t, f)$ is the WVD of the atom $g_{\gamma_n}(t, f)$.
The parameters of each elementary function are computed by using the matching pursuit (MP) decomposition.

3.1. Matching pursuit method with chirplet dictionary

Matching pursuit (MP) algorithm is an iterative procedure, which projects the signal onto a large and redundant dictionary of elementary functions and selects a time-frequency atom, which can best match the local signal structure. The linear Gaussian chirplets were chosen as the elementary functions mainly due to the fact that it is the function that has the highest joint time-frequency resolution [7]. The Gaussian chirplet atom is a four-parameter wave packet with a Gaussian envelope, defined by [6]

$$g_{\gamma_n}(t) = \\ = (\sigma_n^2 \pi)^{-0.25} \exp\left\{ -\frac{(t-t_n)^2}{2\sigma_n^2} + j\left(\omega_n (t-t_n) + \frac{\beta_n}{2}(t-t_n)^2\right) \right\} \qquad (6)$$

where (t_n, ω_n) is the time-frequency centre of the chirplet, σ_n is the standard deviation of the Gaussian envelope, and β_n is the chirp rate.

The first step ($n = 0$) of the MP procedure is to choose the chirplet atom g_{γ_0} from the dictionary so that the amplitude of the inner product (chirplet coefficient) $\left| \langle R^n b,\ g_{\gamma 0} \rangle \right|$ between this atom and signal $b(t)$ is largest. Then the residual signal $R^1 b$ obtained after extracting the approximation of b in the direction of $g_{\gamma 0}$ from b , is decomposed in the similar way. Iterative procedures are applied to the subsequent residua [6]

$$\begin{cases} R^0 b = b \\ R^{n+1} b = R^n b - \langle R^n b,\ g_{\gamma n} \rangle g_{\gamma n} \end{cases} \qquad (7)$$

In each iterative step the chirplet atom is chosen such that

$$g_{\gamma n} = \arg\max_{g_{\gamma i}} \left| \langle R^n b,\ g_{\gamma i} \rangle \right| \qquad (8)$$

In this way the signal b is decomposed into a sum of chirplet atoms that best match its residues

$$b(t) = \sum_{n=0}^{m} \langle R^n b,\ g_{\gamma n} \rangle g_{\gamma n} + R^{n+1} b \qquad (9)$$

The residue $R^{n+1}b$ is the approximation error of b after choosing $n+1$ atoms in the dictionary.

This error decreases exponentially with each iterative step, hence

$$b(t) = \sum_{n=0}^{\infty} \langle R^n b,\ g_{\gamma n} \rangle g_{\gamma n} \qquad (10)$$

The dictionary size in the matching pursuit algorithm determines the speed and accuracy of the resulting analysis.

The WVD of the chirplet atom is expressed by the following equation

$$WVDg_{\gamma n}(t, f) =$$

$$= 2(\sigma_n^2 \pi)^{-0.25} \exp\left\{ -\frac{(t-t_n)^2}{2\sigma_n^2} - (2\pi)^2 \sigma_n [\, f - f_n + \beta_n (t-t_n)]^2 \right\} \quad (11)$$

The WVD of an individual chirplet is positive.

The adaptive spectrogram $AS(t, f)$ is given by

$$AS(t, f) = 2 \cdot$$

$$\cdot \sum_{n=0}^{M-1} |a_n|^2 \exp\left\{ -\frac{[t-t_n]^2}{\sigma_n} - (2\pi)^2 \sigma_n [\, f - f_n - \beta_n (t-t_n)]^2 \right\} \quad (12)$$

Fig. 1 and Fig. 2 present the time waveform and the spectrogram of the Gaussian chirplet, respectively. The adaptive spectrogram based on the chirplet dictionary is non-negative and doesn't include cross-term interference.

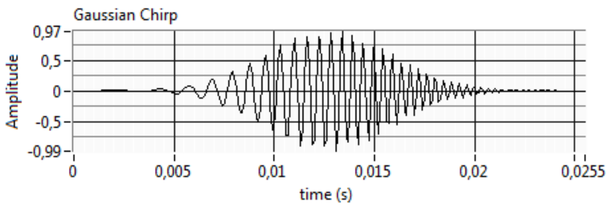


Fig. 1. The exemplary time waveform of the Gaussian chirplet.

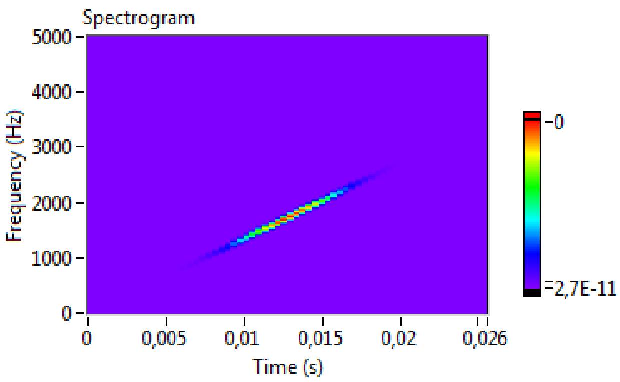


Fig. 2. The exemplary time –frequency adaptive spectrogram of the Gaussian chirplet ($\beta_n \neq 0$).

3.2. The optimal size of the dictionary in the MP

An adaptive expansion of the signal in the form of (3) contains a certain number of elementary functions. Number of waveforms in the expansion can be based on the percentage of signal's variance explained by the decomposition. But at some stage of decomposition the choice of the next atom from a dictionary does not cause a noticeable increase in energy of the reconstructed signal [6], [7], [8].

Figure 3 presents the normalized energy of signal representation versus number of algorithm's iterations for different types of signals. In the case of RF noiseless signal, which is composed of the sine waveforms of different frequencies, the energy of the reconstructed signal represents more than 90% of the total energy in just a few steps of iteration. It follows that the chirplet dictionary is coherent with most of the signal's structures. Once the shape of the test signal is identical with the atoms of the dictionary then as expected just one elementary function to reconstruct the signal with 100% compatibility. However, the presence of a broadband noise in the signal requires a much larger size of the dictionary for efficient approximation. The maximum size of the dictionary for noisy chirps presented in Fig. 3 provides representation of signal only at 52%.

Sometimes too large size of dictionary can lead to a situation that the MP algorithm adjusts to structures, which don't occur in the signal. Figure 4 shows the time-waveform of the test signal, that is composed of several chirps and Gaussian noise for which the value of the signal-to-noise ratio S/N is equal to -10 dB. Using the MP algorithm the adaptive signal approximations were made for three different sizes of the time-frequency dictionary (Fig. 5). Then, the adaptive spectrogram for each representation of the signal was determined (Fig. 6). In the case of a small number of atoms of the dictionary, the obtained representation of the signal represents 36% of the total signal's energy (Fig.6a). On the time-frequency plane the dominant signal structures, describing the four chirp type signals, appear (Fig. 5a, 6a). Increasing the size of the dictionary allows for detection of broadband components, related to the presence of noise in the signal (Fig. 5b, 6b). However, ut to 50 atoms explain only 61% of the total energy. Figure 5c and 6c show disadvantages of using too many atoms in the expansion of a signal. Dictionary consisting of 100 atoms in this case represents only 73% of the energy of the total signal (Fig. 5c). There are time-frequency structures not corresponding to the signal (Fig. 6c).

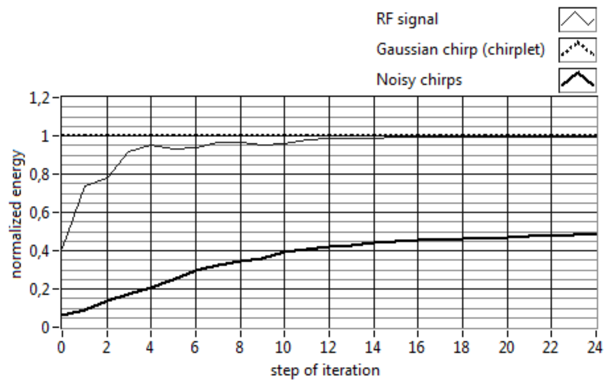


Fig. 3. The normalized energy of the reconstructed signal as a function of number of iterations for the RF signal, Gaussian chirplet and noisy chirps.

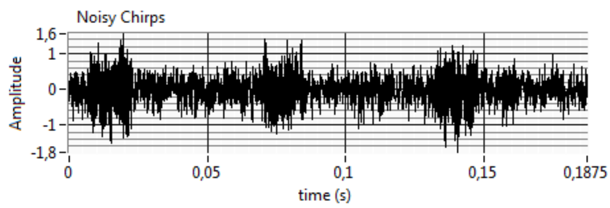
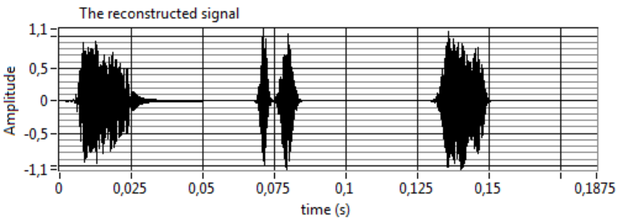
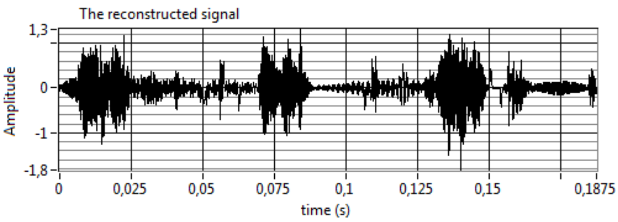


Fig. 4. The time waveform of the test signal with a length of 1875 samples and the sampling frequency equals 10 kHz.

a)



b)



c)

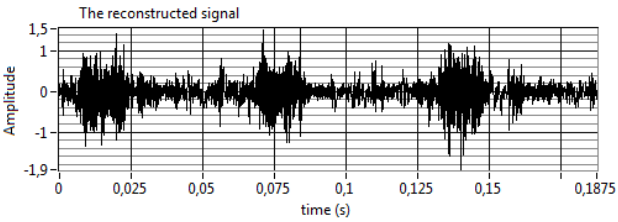


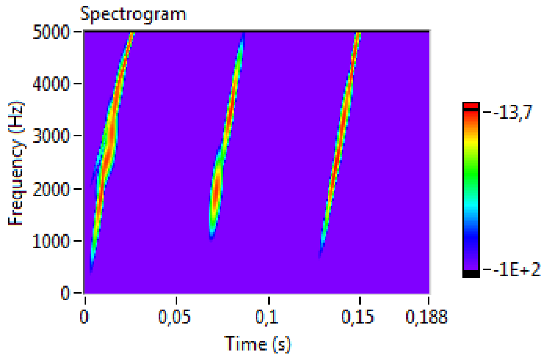
Fig. 5. The time waveforms of the adaptive expansion of a test signal for the size of a dictionary equal to 10 (a), 50 (b) and 100 (c) respectively.

4. EXEMPLARY ANALYSIS RESULTS

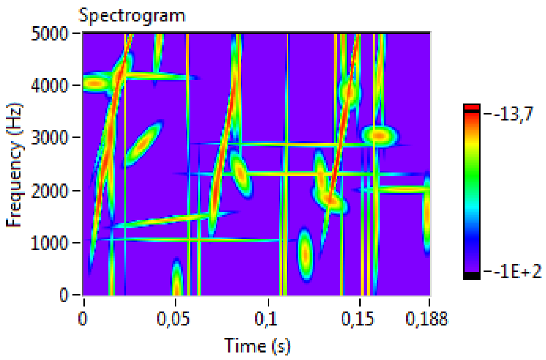
The presented measurement procedure was applied to assessment of the instantaneous values of the exposure level to low-frequency magnetic field emissions in surroundings of the ship's motor drive with the power frequency converters. Figure 7 presented the hardware part of the virtual measuring system used to perform measurement [10]. The instantaneous values of the MFD waveform was recorded during the sea voyage (Fig. 8). Next, the adaptive analysis of the digitized measuring signal was carried out. The impact of the size of the dictionary (the number of elementary functions) on the accuracy of the analysis was observed (Fig. 9). According to the requirement (2) the instantaneous value of the summation formulae was computed over the whole duration of the measurement by applying the MP algorithm (Fig. 10). It is noticed that safety conditions aren't ensured at the whole time of experiment, it means that the inequality in (2) isn't fulfilled.

The simultaneous exposure to magnetic fields of different frequencies exceeded the admissible reference levels for occupational exposure, originally defined in the ICNIRP guidelines [1], for the special case of multi-frequency fields.

a)



b)



c)

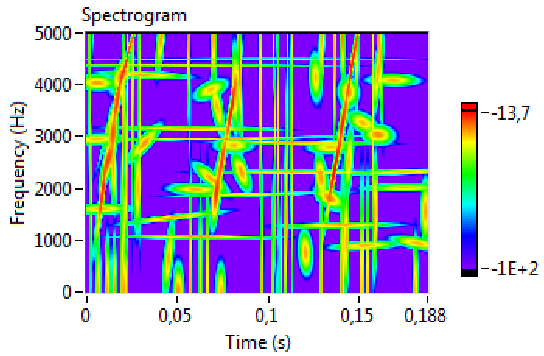


Fig. 6. The adaptive spectrograms of the adaptive expansions of the test signal presented on Fig.5 for the size of a dictionary equal to 10 (a), 50 (b), and 100 (c) respectively.

5. CONCLUSIONS

The adaptive time-frequency analysis has been applied successfully to assessment of the exposure level to a low-frequency magnetic field, assuring protection against an undesirable MFD emissions. The instantaneous values of the summation formula were estimated with the adaptive joint time-frequency analysis using the matching pursuit procedure to digital signal processing. The MP algorithm iteratively decomposes the signal into a linear expansion of waveforms chosen to match best the signal structure. Thanks to the varying window size and modulation frequency, MP enables an adaptive signal representation.

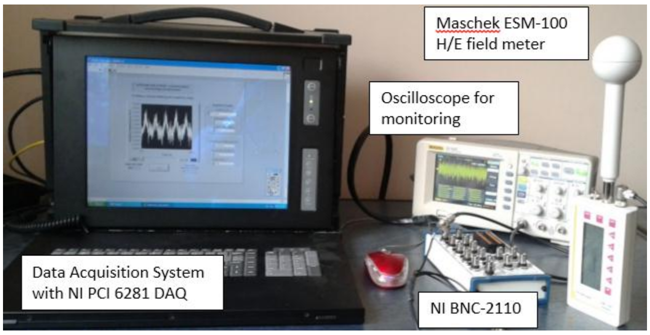


Fig. 7. The hardware part of the virtual measuring system [10].

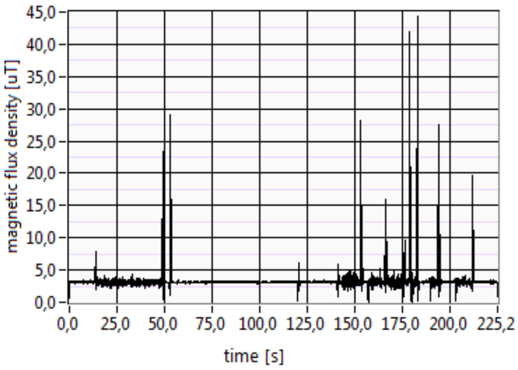


Fig. 8. The time waveform of the MFD in surroundings of the ship's motor drive with the power frequency converters, during the sea voyage.

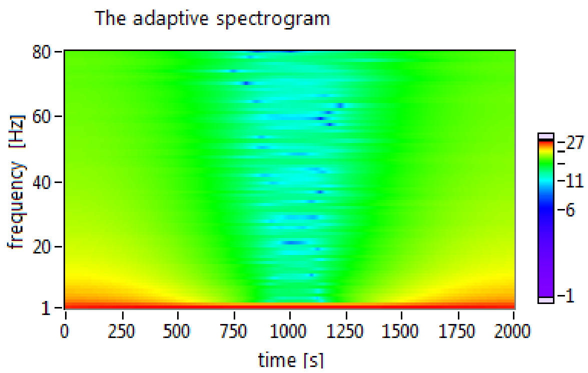


Fig. 9. The adaptive spectrogram in the frequency range from 1 to 80 Hz. The number of the frequency and time lines equal to 2048.The number of the elementary functions equal to 50.

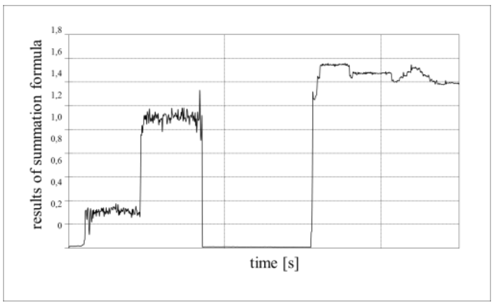


Fig. 10. The instantaneous values of summation formula defined in (2) in the time function.

The choice of the dictionary is of high importance, since its atoms should ideally be able to fit the features of the investigated signals. The Gaussian chirp atoms are very well adapted to the representation of non-stationary magnetic field induction.

Furthermore, the spectrogram based on the chirplet dictionary is non-negative and doesn't include cross-term interference. The dictionary size in the MP algorithm determines the speed and accuracy of the resulting analysis.

The optimal number of elementary functions is a compromise between the resolution of the analysis and required computing time. Excessive increase in the size of the dictionary doesn't lead to effective approximation of the signal.

Due to the relatively long processing time, which depends on the accuracy of the analysis, this method may be effectively used in the off-line analysis.

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