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Time – frequency analysis of non-stationary magnetic fields

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Abstract- This paper considers applying the quadratic joint time – frequency transform for the spectral analysis of the non-stationary magnetic fields. The general properties, advantages and disadvantages of the quadratic algorithms from Cohen's class like the short – time Fourier transform (STFT) spectrogram and the pseudo Wigner – Ville (PWV) distribution as well as the adaptive spectrogram are discussed. The selected results of the off-line time-frequency analysis of the recorded signals of magnetic field of ship bow thruster drive with frequency converter are presented.

I. Introduction

The problem of measurement of electromagnetic disturbances is especially serious onboard seagoing ships because of high concentration of different power electronic and electronic devices present in a small area. The magnetic field of high intensity can be found, due to running generators and several electrical energy high power consumers, like electrical motors or power electronic converters. In the recent years a lot of frequency converters were applied at seagoing ships, in various drive systems with squirrel-cage motors. The good efficiency of modern frequency converters results from the possibility of precise speed control of the motors. This can be achieved by changing the supplying voltage frequency, which gives the big energy savings and reduces the exploitation costs of the vessel. One of the disadvantages of such frequency controlled drives is not only the generation of a wide spectrum of harmonics components (derived from the main fundamental frequency of power supply voltage), but also a significant amount of noncharacteristic harmonics (derived from the voltage frequency at the output of frequency converter and its switching frequency) and their interharmonics. The frequency content of magnetic field intensity observed near the running bow thruster electric drive is rapidly changing over time [1]. The standard method (e.g. FFT) for evaluating signal spectrum, in such case, doesn't allow to find out how the spectral content evolves over time. In order to identify of the time-varying signal in time periods and its spectrum distribution, time-frequency methods of analyzing can be used. These methods enable to determine with some time resolution the moments, when the analyzed signal components of different frequencies occur. This way, the sources of high level magnetic fields can be localized in the tested environment.

II. Joint time-frequency analysis

Representation of the signal in time and frequency domain has been of interest in signal processing areas, especially when analyzing time-varying non-stationary signals. This kind of signals is categorized into two types: evolutionary and transient, depending on how the spectral content changes over time [2]. Evolutionary signals usually contain time-varying harmonics. The time-varying harmonics relate to the underlying periodic time-varying characteristic of the system that generates the signals. Evolutionary signals 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.
Cohen introduced a general class of time-frequency distributions of the form [3]:

$$C(t,\omega)=\frac{1}{2\pi}\iiint e^{j\nu(u-t)}\phi(\nu,\tau)x^*\left(u-\frac{\tau}{2}\right)x\left(u+\frac{\tau}{2}\right)e^{-j\omega\tau}d\nu du d\tau \qquad (1)$$

where t denotes the time, ω is the angular frequency, τ is the time shift, $x(t)$ is the analyzed signal and $\phi(\nu,\tau)$ is a two dimensional function called the kernel.

Since the kernel $\phi(\nu,\tau)$ in (1) is independent of t and ω, all time-frequency distributions of Cohen's class are shift-invariant. Therefore all possible shift-invariant time-frequency distributions can be generated by choosing $\phi(\nu,\tau)$. The kernel determines the distribution and its properties.
If the kernel $\phi(\nu,\tau)$ is the ambiguity function of the impulse response $h(t)$ [3]:

$$\phi(\nu,\tau)=\int_{-\infty}^{\infty} h^*\left(t-\frac{\tau}{2}\right)h\left(t+\frac{\tau}{2}\right)e^{-j\nu t}dt \qquad (2)$$

the distribution (1) can be expressed in the form [3]:

$$C(t,\omega)=\left|S_t(\omega)\right|^2=\left|\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{-j\omega\tau}x(\tau)h(\tau-t)d\tau\right|^2 \qquad (3)$$

The equation (3) determines the short – time Fourier transform (STFT) spectrogram.
A discrete-time STFT spectrogram is defined as [4]:

$$SP[m,n]=\left|\sum_{i=mdM-\frac{L}{2}}^{mdM+\frac{L}{2}-1} x[i]h[i-mdM]e^{-j2\pi ni/N}\right|^2 \qquad (4)$$

where N is the number of frequency bins, L is the window length, dM denotes the time step and $h(i)$ is the window function.

The STFT spectrogram can be a good first choice to perform a quadratic time-frequency analysis because this method is simple and fast. The STFT is based on the assumption that the signal can be considered as stationary for a short time period. The STFT spectrogram typically provides a coarse time-frequency resolution as a result of window effects determined by the window type and the length. A narrow window results in a fine time resolution but a coarse frequency resolution, because narrow windows have a short time duration but a wide bandwidth. Increasing the window length allows an improvement in frequency resolution. However, it causes the nonstationarities occurring during this interval to be smeared in time and frequency.
Using smoothing kernel in the form:

$$\phi(\nu,\tau)=w(\tau) \qquad (5)$$

where $w(t)$ is the weighting function (usually Gaussian window function),
the pseudo Wigner – Ville (PWV) distribution is obtained. The PWV distribution in the discrete-time form is calculated using [4]:

$$PWVD[i,k]=\sum_{m=-L/2}^{L/2} w[m]R[i,m]e^{-j2\pi km/L} \qquad (6)$$

where the function $R[i,m]$ is the instantaneous correlation, given by $R[i,m]=x[i+m]x^*[i-m]$.

The PWV distribution has the best joint time-frequency resolution of commonly used joint time-frequency algorithms. However it possesses a serious disadvantage, which is a crossterm interference. Crossterms are artifacts that appear in the PWV representation between autoterms, which correspond to physically existing signal components. These crossterms falsely indicate the existence of signal components between autoterms.
An adaptive spectrogram can be used in order to alleviate the crossterm interference. 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 analyzed signal. The adaptive expansion represents a signal $x(t)$ as the linear

combination of a series of elementary functions $g_{\gamma_n}(t)$ (the time-frequency atoms). It can be approximately expressed by the following equation [5]:

$$x(t) = \sum_{n=0}^{M-1} a_n g_{\gamma_n}(t) \qquad (7)$$

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 $g(t)$ [4]:

$$g_{\gamma}(t) = \frac{1}{\sqrt{s}} g\left(\frac{t-u}{s}\right) e^{j\xi t} \qquad (8)$$

The dictionaries are selected in order to best match the signal structures. The linear Gaussian chirplet is often chosen as the elementary function, which is shown by the following equation [2]:

$$g_{\gamma_n}(t) = (\sigma_n^2 \pi)^{-0.25} \exp\left\{ -\frac{(t-t_n)^2}{2\sigma_n^2} + j\left(\omega_n (t-t_n) + \frac{\beta_n}{2}(t-t_n)^2\right) \right\} \qquad (9)$$

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 chirp rate β_n determines a linear changes of the instantaneous frequency of elementary function (Fig. 1). The linear Gaussian chirplet turns into Gaussian pulse when β_n equals 0 (Fig. 2).

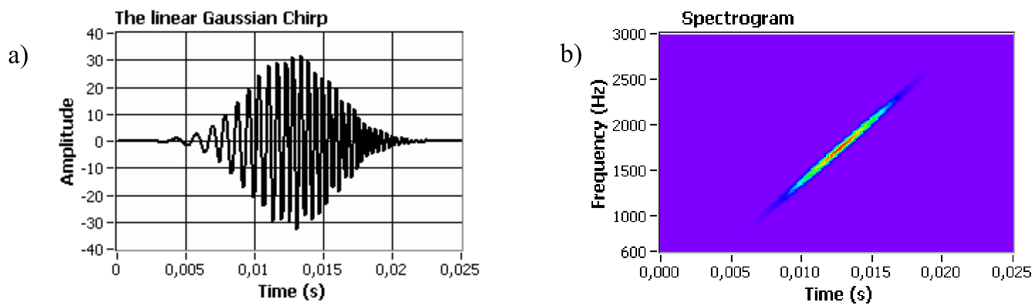

Fig. 1. The exemplary time waveform (a) and time –frequency adaptive spectrogram (b) of the Gaussian chirplet ($\beta_n \neq 0$)

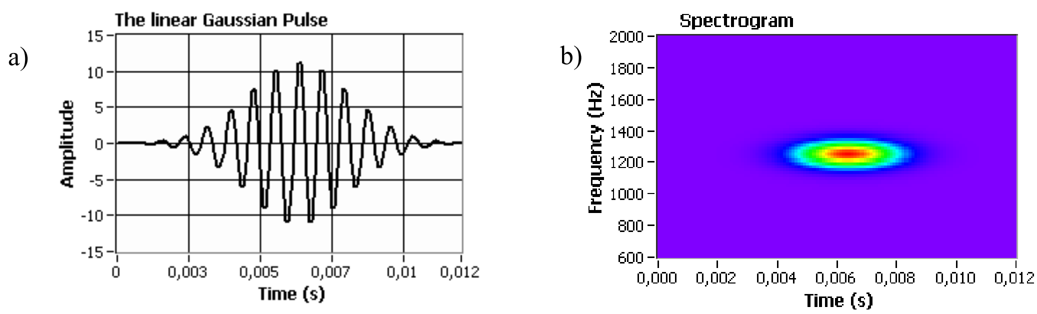

Fig. 2. The exemplary time waveform (a) and time –frequency adaptive spectrogram (b) of the Gaussian pulse ($\beta_n = 0$)

The estimated Gaussian chirplets or Gaussian pulses can be distributed in the time-frequency domain arbitrarily. The time and the frequency centers of the Gaussian chirplets or Gaussian pulses are not fixed in a grid. The envelopes of the Gaussian chirplets or Gaussian pulses are arbitrary too [2].
The parameters of each elementary function are computed by using the matching pursuit method, which is a commonly used implementation of the adaptive transform [5], [6], [7], together with a fast refinement algorithm [2]. The dictionary size in the matching pursuit algorithm determines the speed and accuracy of the resulting analysis. A small dictionary requires less computing time but has poorer accuracy. A large dictionary results in better accuracy but requires more computing time. The applied implementation uses the matching pursuit method with a small dictionary size as a coarse estimation step and then follows with a refinement step to achieve an accurate estimation. The small dictionary size and a refinement step make the adaptive transform more efficient and accurate. The adaptive spectrogram in the discrete-time form is calculated using [2]:

$$AS[i,k] = 2\sum_{n=0}^{M-1} |a_n|^2 \exp\left\{ -\frac{[i-i_n]^2}{\sigma_n} - (2\pi)^2 \sigma_n [k - f_n - \beta_n i]^2 \right\} \quad (10)$$

The adaptive spectrogram has a fine and adaptive time-frequency resolution, which matches to the signal characteristics. The adaptive spectrogram does not include crossterm interference because it ignores all the crossterms.

III. Investigation and results

Measurements of the magnetic field were performed for the running bow thruster electric drive [1]. Bow thruster was fitted in the fore part of the research-training vessel hull, under the water, and had fixed propeller. Using the bridge wing controllers, it was possible to change the speed and direction of revolutions of the propeller, what helped to turn the bow of the vessel during maneuvering. Bow thruster was driven by squirrel cage asynchronous motor, which is supplied from frequency converter with IGBT (Isolated Gate Bipolar Transistors) (Fig. 3).
The measurements of the magnetic field intensity were carried out for different voltage frequencies at the output of frequency converter. During the experiments, the converter output frequency was increased from 0 to 50 Hz, and subsequently decreased from 50 to 0 Hz with the step 5 Hz. Data recording of the magnetic field intensity instantaneous values was carried out with a/d converters data acquisition (DAQ) board (with sampling frequency equal to 2000 Hz), connected to the analogue outputs of ESM-100 M/E field meter [1].
The discrete signals were then off-line analyzed with the use of virtual instruments in LabVIEW programming environment.
The time waveform of the magnetic field intensity is presented on Fig. 4. It's shown, the level of amplitude of examined signal also depends on the output frequency of the converter.

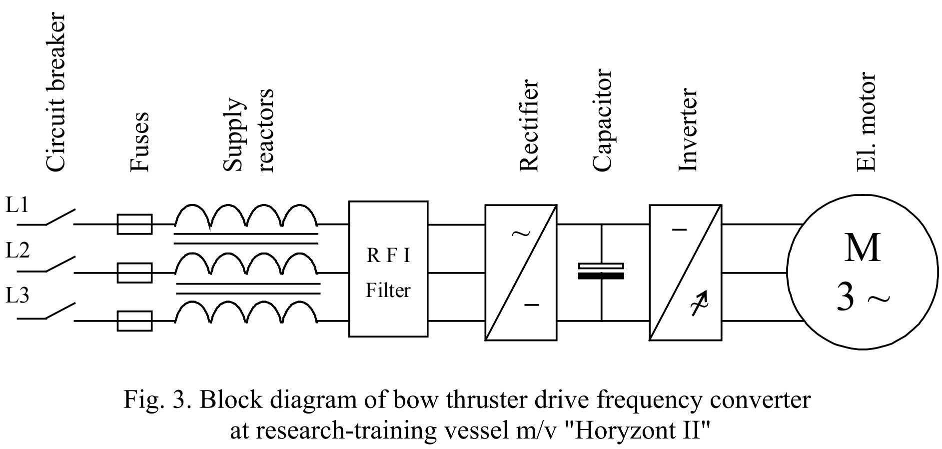

Fig. 3. Block diagram of bow thruster drive frequency converter
at research-training vessel m/v "Horyzont II"

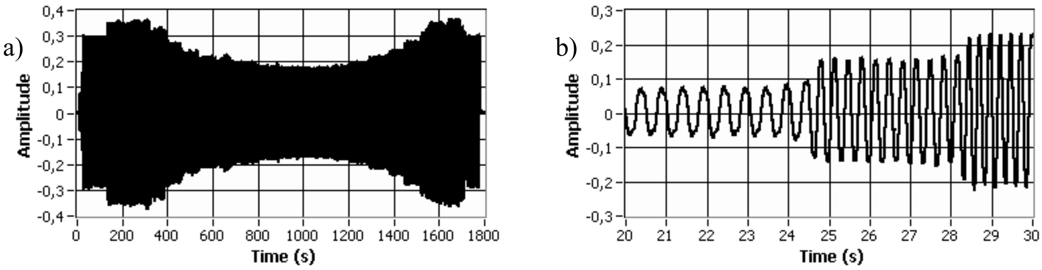

Fig. 4. The time waveform of the magnetic field intensity during the whole observation time (a) and during the part of its, for 10 s (b)

The results obtained when the STFT spectrogram was applied, are shown on Fig. 5. On the time-frequency plane there are components resulting from the converter output frequency, their harmonics, as well as, the basic component 50 Hz and its harmonics existing in examined signal during the whole observation time.

Comparing Fig. 6a with Fig. 6b, which show the time-frequency plane obtained using PWV distribution, we can notice how the Gauss window variance depends on the resolution and crossterm interference. Presented method for signal analyzing does not allow detecting the stationary harmonics components occurring in analyzed signal, regardless of the values of the Gauss window variance.

The adaptive spectrogram is characterized by the most accurate detection of investigated components (Fig. 7). Notice that in contrast to Fig. 6, no crossterms are shown on its time-frequency plane. Also the stationary signals like the basic component 50 Hz and its harmonics don't appear in the spectrogram.

This algorithm effectively determines signal features from a examined waveform that contains mainly nonstationary components.

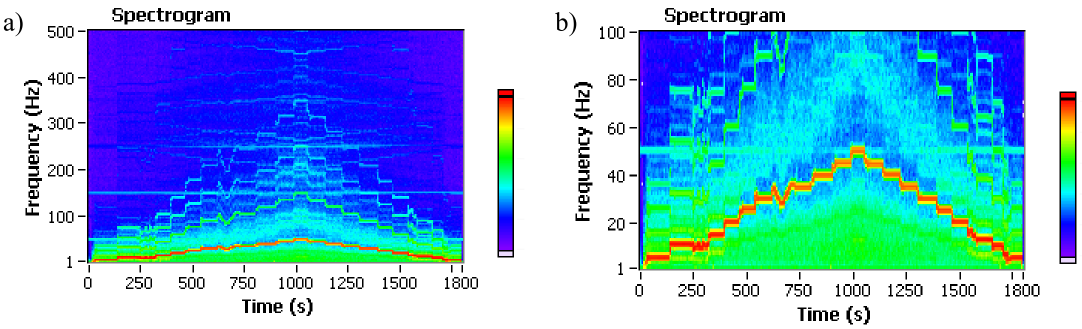

Fig. 5. The STFT spectrogram with the Blackman window in the wide frequency range from 1 to 500 Hz (a) and from 1 to 100 Hz (b), the window length equal to 2048 samples

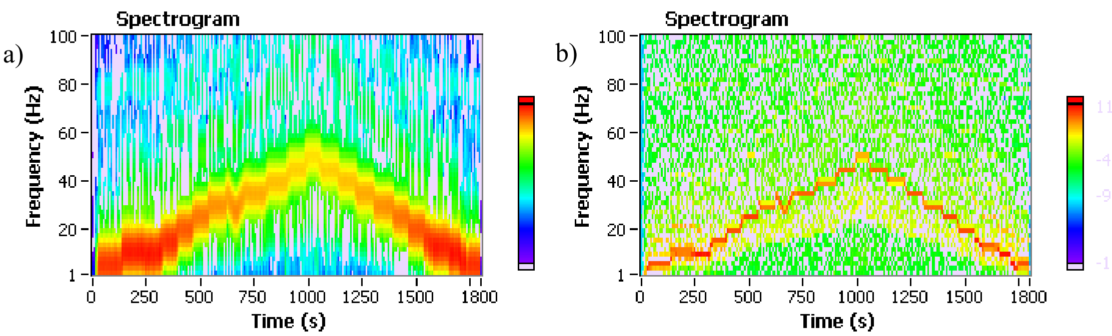

Fig. 6. The PWV distribution with the Gauss window in the frequency range from 1 to 100 Hz, for Gauss window variance equal to 1e3 (a) and 1e5 (b) respectively

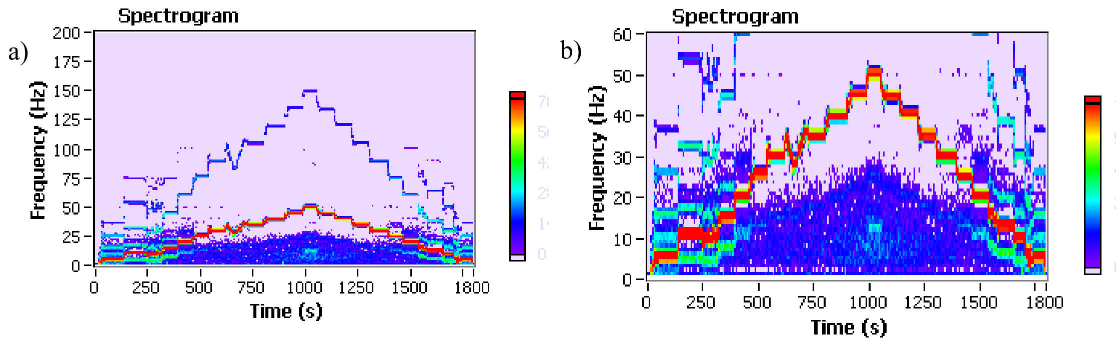

Fig. 7. The adaptive spectrogram in the frequency range from 1 to 200 Hz (a) and from 1 to 60 Hz (b), the number of the elementary functions equal to 12

IV. Final remarks

Performed time-frequency analysis of the recorded time waveforms of magnetic field intensity enabled the signal identification in time periods. If the frequency contents of the analyzed signal don't change rapidly, then the STFT spectrogram can be applied with relatively wide window function, to obtain a good frequency resolution. The PWV distribution is useful for analyzing signals that have widely separated components for which a fine time-frequency resolution is required. This method effectively extracts signal features from a signal that contains only a single component. The adaptive algorithm has better joint time and frequency resolution, then the other ones, but it requires more computation time, which is suitable only for off-line analysis.

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