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Higher-order Spectral Characterization of Low-level Emissions in Wood using Ultrasonic-Piezoelectric Transducers

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Abstract: Third and fourth-order spectral characterization of acoustic and ultrasonic events are developed using two high-sensitivity piezoelectric sensors, in order to expand the possibilities of getting the *tracks* of low-level transients produced when wood fibres are broken. Although the power spectral density is a valid tool for a prior characterization, third-order spectra slices shows better performance under the assumption of symmetrically distributed noise, focussing on a lower number of frequency components. Fourth-order slices can be used as an alternative when the resolution in the bi-spectrum is not as much satisfactory.

Keywords: Cumulants, higuer-order statistics, low-level signals, polyspectra, transient characterization, ultrasound.

1 Introduction

Computational intelligence for measurement systems is being introduced to enhance the performance of embedded data acquisition units, devoted to detect and characterize low-level transients, which constitute the symptoms of machinery faults or insect infestations (our research interest). The struggle between computational cost and performance is being overcome by means of new emerging techniques which comprise new characterization criteria.

In the frequency domain, during the last 15 years a myriad of tools have been introduced to enhance the detection of low-level transients. Second order statistics and power spectra estimation (the second order spectrum) fail in low SNR conditions even with *ad hoc* piezoelectric sensors. Spectrum estimation and spectrogram extract time-frequency features, but ignoring phase properties of the signals. Besides, second-order algorithms are very sensitive to noise.

Other prior-art second-order tools, like wavelets and wavelet packets (time-dependent technique) concentrate on transients and non-stationary movements, making possible the detection of singularities and sharp transitions, by means of sub-band decomposition [1].

As an alternative, higher order statistics (HOS) have proven useful in different characterization applications, like insects detection [2],[3], machinery faults [4],[5] and tremor recognition [6]. The conclusions of these works were funded in the advantages of cumulants; in particular, in the capability of enhancing the SNR of a signal buried in symmetrically distributed noise processes.

In this paper third-order spectra slices are used to characterize termite emissions. The results help the HOS researcher to better understand the higher-order frequency diagrams; in particular in the field of insect characterization by AE signal processing. The conclusions are based in records which were acquired within the surrounding perimeter of the infestation. The quality of the signals has been established using the criteria of audibility and the levels of quantization used in the digitalizing process by the data acquisition equipment. The accelerometer used is the SP1-L probe from AED2000 instrument, with a high sensitivity and a short bandwidth.

The paper is structured as follows: Section 2 recalls the theoretical background of HOS, focussing on the computational tools. Experiments are drawn in Section 3, which is intended as a tool to interpret results from HOS-based experiments. Finally, conclusions are explained in Section 4.

2 Higher-Order Statistics (HOS)

The motivation of the poly-spectral analysis is three fold: (a) To suppress Gaussian noise processes of unknown spectral characteristics; the bi-spectrum also suppress noise with symmetrical probability distribution, (b) to reconstruct the magnitude and phase response of systems, and (c) to detect and characterize nonlinearities in time series.

Before cumulants, non-Gaussian processes were treated as if they were Gaussian. Cumulants and their associated Fourier transforms, known as poly-spectra [7], reveal information about amplitude and phase, whereas second order statistics (variance, covariance and power spectra) are phase-blind [8].

The relationship among the cumulants of stochastic signals, x_i, and their moments can be calculated by using the *Leonov-Shiryayev* formula. The second-, third-, and fourth-order cumulants are given by [2], [8] equation 1:

$$Cum(x_1, x_2) = E\{x_1 \cdot x_2\}. \tag{1a}$$

$$Cum(x_1, x_2, x_3) = E\{x_1 \cdot x_2 \cdot x_3\}. \tag{1b}$$

$$\begin{aligned} Cum(x_1, x_2, x_3, x_4) = {} & E\{x_1 \cdot x_2 \cdot x_3 \cdot x_4\} \\ & - E\{x_1 \cdot x_2\}E\{x_3 \cdot x_4\} \\ & - E\{x_1 \cdot x_3\}E\{x_2 \cdot x_4\} \\ & - E\{x_1 \cdot x_4\}E\{x_2 \cdot x_3\}. \end{aligned} \tag{1c}$$

In the case of non-zero mean variables x_i have to be replaced by x_i-$E\{x_i\}$.

Let $\{x(t)\}$ be a *r*th-order stationary random real-valued process. The *r*th-order cumulant is defined as the joint *r*th-order cumulant of the random variables $x(t)$, $x(t+\tau_1)$,..., $x(t+\tau_{r-1})$,

$$\begin{aligned} & C_{r,x}(\tau_1, \tau_2, \ldots, \tau_{r-1}) \\ & \quad = Cum[x(t), x(t+\tau_1), \ldots, x(t+\tau_{r-1})]. \end{aligned} \tag{2}$$

The second-, third- and fourth-order cumulants of zero-mean $x(t)$ can be expressed using equations 1 and 2, via:

$$C_{2,x}(\tau) = E\{x(t) \cdot x(t+\tau)\}. \tag{3a}$$

$$C_{3,x}(\tau_1, \tau_2) = E\{x(t) \cdot x(t+\tau_1) \cdot x(t+\tau_2)\}. \tag{3b}$$

$$\begin{aligned} & C_{4,x}(\tau_1, \tau_2, \tau_3) \\ & = E\{x(t) \cdot x(t+\tau_1) \cdot x(t+\tau_2) \cdot x(t+\tau_3)\} \\ & - C_{2,x}(\tau_1)C_{2,x}(\tau_2-\tau_3) \\ & - C_{2,x}(\tau_2)C_{2,x}(\tau_3-\tau_1) \\ & - C_{2,x}(\tau_3)C_{2,x}(\tau_1-\tau_2). \end{aligned} \tag{3c}$$

We assume that the cumulants satisfy the bounding condition given in equation 4:

$$\sum_{\tau_1=-\infty}^{\tau_1=+\infty} \cdots \sum_{\tau_{r-1}=-\infty}^{\tau_{r-1}=+\infty} |C_{r,x}(\tau_1, \tau_2, \ldots, \tau_{r-1})| < \infty. \tag{4}$$

The higher-order spectra are usually defined in terms of the *r*th-order cumulants as their (*r*-1)-dimensional Fourier transforms

$$S_{r,x}(f_1, f_2, \ldots, f_{r-1}) = \sum_{\tau_1=-\infty}^{\tau_1=+\infty} \cdots \sum_{\tau_{r-1}=-\infty}^{\tau_{r-1}=+\infty} C_{r,x}(\tau_1, \tau_2, \ldots, \tau_{r-1}) \cdot \exp[-j2\pi(f_1\tau_1 + f_2\tau_2 + \cdots + f_{r-1}\tau_{r-1})]. \quad (5)$$

The special poly-spectra derived from equation 5 are power spectrum (r=2), bi-spectrum (r=3) and try-spectrum (r=4). Only power spectrum is real, the others are complex magnitudes. Poly-spectra are multidimensional functions which comprise a lot of information. As a consequence, their computation may be impractical in some cases. To extract useful information one-dimensional slices of cumulant sequences and spectra, and bi-frequency planes are employed in non-Gaussian stationary processes [3].

Once summarized the foundations of the experiment, hereinafter we present que results obtained by means of the tools described here.

3 Experimental results

Two ultrasonic piezoelectric transducers have been selected to perform characterization. Ten sample registers have been recorded (for each transducer) using the oscilloscope *Agilent-54622A* and the ICP[1] interface units for the piezoelectric sensors (from *Acoustic Emission Consulting*). Each register comprises a vibratory event, produced by breaking wood fibres. The goal is to get the spectral track of this breaks according to HOS and analyze the advantages that this characterization technique exhibits versus the traditional power spectral density. The SNR is pointed as 40 dB.

The following figures summarize battery of experiments developed to characterize the sensors. Comparing Figs. 1 and 2 it is obvious that the frequency response is far different. In fact, the SP1H is a wide-band transducer. On the other hand, numerous resonance peaks are found. Because these are not resonance

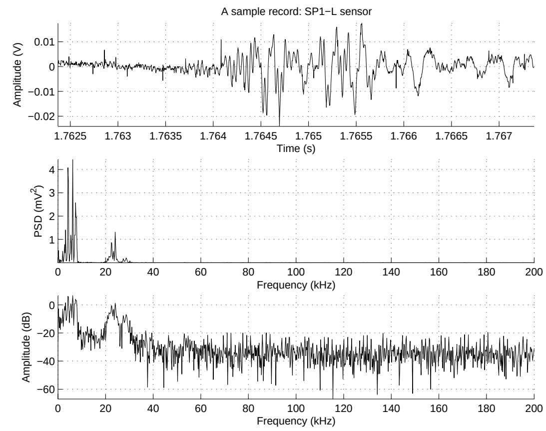

Figure 1: One sample register and its spectrum representing a vibratory event recorded with the sensor SP1-L.

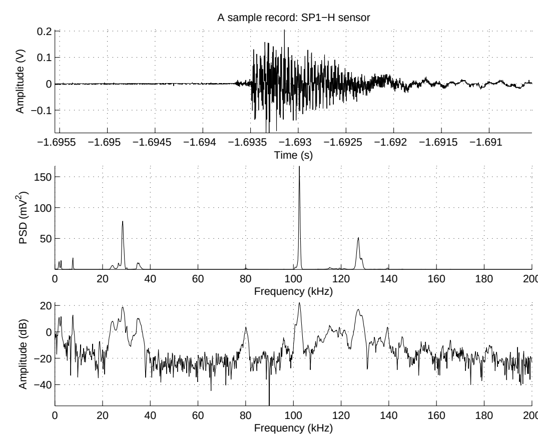

Figure 2: One sample register and its spectrum representing a vibratory event recorded with the sensor SP1-H.

On the basis of these results we establish the conclusions related to the identification criterion proposed.

4 Conclusions

In this work it has been shown that the diagonal slices of the bi-spectrum and trispectrum are valid and convenient tools for characterization of low-level ultrasonic transients. We have funded this conclusion on three arguments:

[1]Integrated Circuit Piezoelectric protocol

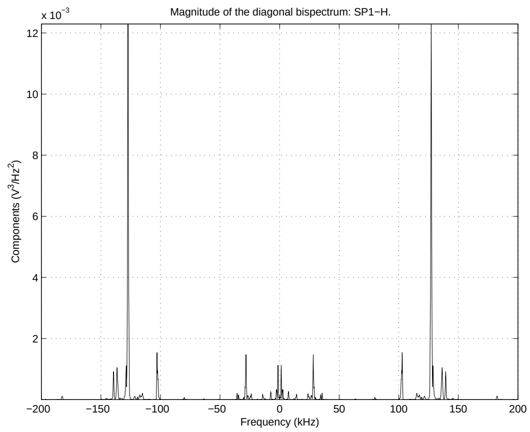

Figure 3: Average diagonal bispectrum for the sensor SP1-H.

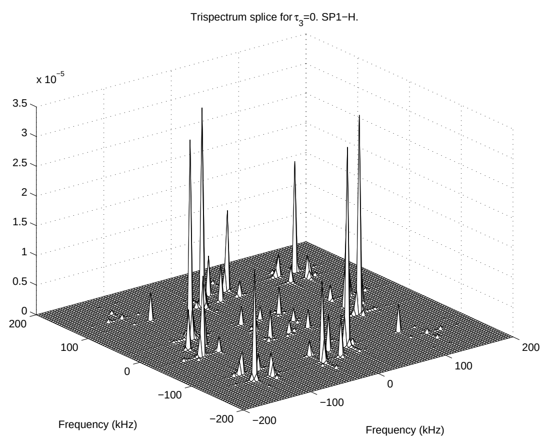

Figure 4: Trispectrum slice of one sample register for $\tau_3 = 0$: SP1-H.

First, higher-order cumulants and spectra, as defined herein, enable the signal analysis procedure to have access to waveform information that is typically unavailable when using prior art (second-order) methods. In particular, we remark the enhancement of the frequency diagrams. This is due to the rejection exerted on symmetrically distributed noise processes. In fact, non-Gaussian processes are completely characterized by means of HOS.

Secondly, the potentially valuable information contained in an ultrasonic signal (most part of its spectrum) is related to the impulses. The average spectrum reveals amplitude information (the resonance peaks) but phase information is not shown. Higher-order spectra are arrangements of complex numbers and contain this additional information which can be valuable in a pattern recognition or identification criterion context.

Finally, using different sensors the criterion changes the frequency *set-point*. Besides, the probability of a false alarm is very low, considering the fact that we had to provide, intentionally, the worst case of background noise. Repeatability has been estimated in a 75 per cent.

Future work is focussed on reducing the computational complexity of HOS in two directions. On one side, we are using compact functions, like *FFT* and *FFTshift*. Secondly, we have to adopt a compromise between the maximum lag (χ) and the resolution, in order to save storage memory and time. These actions are oriented to implement the algorithms in a digital signal processor, in an autonomous hand-instrument for insect detection.

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