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AN APPLICATION OF THE SPECTRAL KURTOSIS FOR EARLY DETECTION OF SUBTERRANEAN TERMITES

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ABSTRACT

This paper deals with termite detection in a noisy environment using higher-order statistics (HOS). The results could be extrapolated to all impulse-like insect emissions. Sliding higher-order cumulants offer distinctive time instances, as a complement to the sliding variance, which only reveals power excesses in the signal; even for low-amplitude impulses. The spectral kurtosis reveals non-Gaussian characteristics (the peakedness of the probability density function) associated to these non-stationary measurements, specially in the near ultrasound frequency band. Contrasted estimators have been used to compute the higher-order statistics.

1. INTRODUCTION

This paper deals with the improvement of termite electronic detection (in the frame of a computer-based signal processing unit) with the objective of decreasing subjectiveness, in order to treat the infestation before serious economic damage occurs. In fact, in most situations, the affected structure is irreversible damaged when only the 20 percent of the plague can be detected.

An early targeting of the infestation implies the use of electronic instruments with a deep memory, and high sensitive probes with selective frequency characteristics. These features make the price to be paid very high, and do not guarantee the success of the detection.

Regarding the procedures, the methods in which the instruments are based are very much dependent on the detection of excess of power in the signals; these are the so-called second-order methods. For example, the RMS calculation can only characterize the intensity or level of the signal, and does not provide information regarding the envelope of the signal nor the time fluctuations of the amplitude. Another handicap of the second-order principle, e.g. the classical power spectrum, attends to the energy of the signal during data processing. As a consequence, in these procedures, the eradication of additive noise lies in filter design and sub-band decomposition of signals, like wavelets and wavelet packets.

In the past ten years, a myriad of higher-order methods are being applied in different fields of Science and Technology, in scenarios which involve signal separation and characterization of non-Gaussian signals in a Gaussian background, which usually is the result of summing different noise processes. Concretely, the area of diagnostics-monitoring of rotating machines is also under our interest due to the similarities of the signals to be monitored with the transients from termites.

The main handicap of applying higher-order statistics is the memory consuming algorithms. First of all, the multidimensional data structures contain redundant information; so relevant data directions have to be selected within the tensor data structure. Secondly, the interpretation of higher-order cumulants and poly-spectra are reduced to a set of cataloged noise processes, and only a few attempts have been made in order to characterize the processes via HOS.

In this paper fourth-order cumulants at zero lags, and their associated statistical quantity, the kurtosis, are considered to show the performance of a combined method to detect infestations of subterranean termites in a real-life noisy scenario (southern Spain). Speech and the typical urban background sounds clearly bury the impulses from the termites, which were in the soil, under all of us, and we could not hear the sounds, which by the way were recorded using *ad hoc* sensors. Both in the time and in the frequency domain, the interpretation of the results is focussed on the classical peakedness of the statistical probability distribution, to get a measure of the distance from the Gaussian distribution. In the time domain, the presence of the transient to be detected (an impulse from a termite acoustic or ultrasonic emission) is localized and characterized with a distinctive pattern, which is the result of applying a sliding cumulant for a given window length. In the frequency domain, the spectral kurtosis enhances non-Gaussian signals over the background, specially in the near ultrasound band.

The paper is structured as follows: in Section 2 an overview of termite detection and relevant HOS experiences are mentioned in order to set the foundations; in Section 3 we summarize the definition of cumulants within the statistical context, along with their potential use as a transient detection tool. In Section 4 we make a brief report on the definition of kurtosis, providing the reader with an unbiased estimator of the spectral kurtosis; in this section we also include a trial example, based on the calculations over synthetics, with the goal of setting the basis for understanding the results obtained from complex signals emitted from termites. Results are displayed in Section 5. Finally, conclusions and achievements are drawn in Section 6.

2. TERMITE DETECTION AND HIGHER-ORDER STATISTICS

2.1 Subterranean termites: Fundamentals

Cause more damage to homes in U.S. than storms and fire combined, on the average, there could be as many as 15 to 20 subterranean termite colonies per hectare, which means that for example a typical U.S. home may easily have three to four colonies situated under or around it. Colonies can contain up to 1,000,000 members.

Subterranean termites nest in the soil to obtain moisture, but they also nest in wood that is often wet. If the wood does not contact the soil, they can build mud tunnels or tubes to reach wood several meters above the ground. These tunnels can extend for 15-20 meters (50-70 feet, roughly[1]) to reach wood and often enter a structure through expansion joints in concrete slabs or where utilities enter the house. Termites are able to travel up to 40 meters (∼130 feet) from the colony and once they discover a food source, they leave a *chemical track* for others to follow [2].

Termite detection has been gaining importance within the research community in the last two decades, mainly due to the urgent necessity of avoiding the use of harming termiticides, and to the joint use of new emerging techniques of detection and hormonal treatments (IGR[3] products), with the aim of performing an early treatment of the infestation. A localized partial infestation can be exterminated after two or three generations of the colony's members with the aid of these hormones, which stop chitin synthesis. A chitin synthesis inhibitor kills termites by inhibiting formation of a new exoskeleton when they shed their existing exoskeleton. As a direct consequence, the weakened unprotected *workers* stop feeding the *queen* termite of the colony, which dies of starvation, finishing the reproduction process, and consequently cutting any possible replacement of the members of the colony with a new generation. In this paper the specie *reticulitermes lucifugus* is under study.

2.2 Subterranean termites: Detection towards HOS

The primary method of termite detection consists of looking for evidence of activity. But only about 25 percent of the building structure is accessible, and the conclusions depend very much on the level of expertise and the criteria of the inspector [1]. As a consequence, new techniques have been developed to remove subjectiveness and gain accessibility.

User-friendly equipment is being currently used in targeting subterranean insect infestations by means of temporal analysis of the vibratory data sequences [4]. An acoustic-emission (AE) sensor or an accelerometer is fixed to the suspicious structure. The hits produced by the insects are captured by the transducer and registered by the counting assembly inside the hand-held instrument; at the same time a led diode outputs light signals each time a hit is counted. The user can listen to the sounds in real time and can perform some pre-processing, like filtering or amplifying. A set of hits is defined as an acoustic event, which in fact constitutes the electronic *tracks* of these insects.

This class of instruments is based on the calculation of the root mean square (RMS) value of the vibratory waveform. The RMS value comprises information of the AE raw signal power during each time-interval of measurement (averaging time). This measurement strategy coveys a loss of potentially valuable information both in the time and in the frequency domain. In fact, the events are averaged over time and the instantaneous occurrence of the impulses is omitted. Looking at the frequency content of the signals, the only possible action for the field operator is the option of pre-filtering, which allows the suppression of low-frequency audio signals which mask termites' emissions.

On the other hand, the use of the RMS value can be justified both by the difficulty of working with raw AE signals in the high-frequency range, and the scarce information about sources and propagation properties of the AE waves through the substratum. Noisy media and anisotropy makes even harder the implementation of new methods of calculation and measurement procedures.

A more sophisticated family of instruments makes use of spectral analysis and digital filtering to detect and characterize vibratory signals [2]. Both classes of systems (counting-assemblies and spectrum-based) have the drawback of the relative high cost and their practical limitations, and they will be referred in this paper as second-order-based instruments.

From the practical point of view, the utility of the above prior-art acoustic techniques and equipment for detection depends very much on several biophysical factors. The main one is the amount of distortion and attenuation as the sound travels through the soil (∼600 dB m^{-1}, compared with 0.008 dB m^{-1} in the air). Furthermore, soil and wood are far from being ideal vibratory propagation media because of their high anisotropy, non-homogeneity and frequency dependent attenuation characteristics [2]. This is the reason whereby digital signal processing techniques emerged as an alternative.

On the other hand, second-order statistics (i.e. correlation) and power spectra estimation (the second-order spectrum) fail in low SNR[5] 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, which makes the users' identification criteria (mainly based on frequency-pattern recognition) being difficult to apply without great uncertainty. Complementary 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 [3].

Higher-order statistics, are being widely used in several fields. The following are relevant due to the similarities of the problems they study. The spectral kurtosis has been successfully described and applied to the vibratory surveillance and diagnostics of rotating machines [4],[5].

In the field of termite detection, a cumulant-based independent component analysis algorithm has proven to separate termites' alarm signals from synthetics noise backgrounds [6] in a blind source separation scenario.The information contained in the diagonal of the bi-spectrum data structure has proven to enhance the frequency pattern of the termites' emissions [7].

3. CUMULANTS

Higher-order cumulants are polynomial functions of the moments, and they are related each other via a recursive for-

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[1] 1 feet = 30.48 centimeters

[2] Information obtained from several pest-control companies in U.S.

[3] **I**nhibitor **G**rowth **R**egulators

[4] The system AED2000 (Acoustic Emission Consulting) has proven to be an advance in the detection of several insect species.

[5] Signal-to-Noise Ratio

mula, described in Eq. (1):

$$\kappa_r = \mu'_r - \sum_{k=1}^{r-1} \binom{r-1}{k-1} \kappa_k \mu'_{r-k} \tag{1}$$

In multiple-signal processing it is very common to define the combinational relationship among the cumulants of r stochastic signals, $\{x_i\}_{i\in[1,r]}$, and their moments of order $p, p \leq r$, given by using the *Leonov-Shiryaev* formula [8]

$$\begin{aligned} Cum(x_1,...,x_r) = \sum(-1)^{p-1} \cdot (p-1)! \cdot E\{\prod_{i\in s_1} x_i\} \\ \cdot E\{\prod_{i\in s_2} x_j\} \cdots E\{\prod_{i\in s_p} x_k\}, \end{aligned} \tag{2}$$

where the addition operator is extended over all the partitions, like one of the form $(s_1, s_2, \ldots, s_p)$, $p = 1, 2, \cdots, r$; and $(1 \leq i \leq p \leq r)$; being s_i a set belonging to a partition of order p, of the set of integers *1,. . . ,r*.

4. KURTOSIS AND SPECTRAL KURTOSIS

4.1 Kurtosis, *4*th-order cumulants and its interpretation

In probability theory and statistics, higher kurtosis means more of the variance is due to infrequent extreme deviations, as opposed to frequent modestly-sized deviations. This fact is by the way used in this paper to detect termite emissions in an urban background. Kurtosis is commonly defined as the excess kurtosis:

$$\gamma_2 = \frac{\kappa_4}{\kappa_2^2} = \frac{\mu_4}{\sigma^4} - 3, \tag{3}$$

where $\mu_4 = \kappa_4 + 3\kappa_2^2$ is the *4*th-order central moment; and κ_4 is the *4*th-order central cumulant, i.d. the ideal value of $Cum_{4,x}(0,0,0)$. Excess kurtosis can range from -2 to $+\infty$.

The sample kurtosis is calculated over a sample-register (an N-point data record), and noted by:

$$g_2 = \frac{m_4}{s^4} - 3 = \frac{m_4}{m_2^2} - 3 = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^4}{\frac{1}{N^2}\left[\sum_{i=1}^{N}(x_i - \bar{x})^2\right]^2} - 3, \tag{4}$$

where m_4 is the fourth sample moment about the mean, m_2 is the second sample moment about the mean (that is, the sample variance), and $\bar{x}$ is the sample mean. The sample kurtosis defined in Eq. (4) is a biased estimator of the population kurtosis.

4.2 Spectral kurtosis estimation and interpretation

Ideally, the spectral kurtosis is a representation of the kurtosis of each frequency component of a process. For estimation issues we will consider M realizations of the process; each realization containing N points; i.d. we consider M measurement sweeps, each sweep with N points. The time spacing between points is the sampling period, T_s, of the data acquisition unit.

An unbiased estimator for the spectral kurtosis for M N-point realizations at the frequency index m is given by:

$$\hat{G}_{2,X}^{N,M}(m) = \frac{M}{M-1}\left[\frac{(M+1)\sum_{i=1}^{M}|X_N^i(m)|^4}{\left(\sum_{i=1}^{M}|X_N^i(m)|^2\right)^2} - 2\right]. \tag{5}$$

This estimator is the one we have implemented and it was also used successfully in [9]. The mean square error (MSE) for this estimator tends to zero when the number or realizations M tends to $+\infty$; i.d., the estimator converges in probability to the quantity being estimated as the sample size grows. To show its performance we have tested it with a synthetics. The synthetics matrix consists of M=500 realizations or signals, each register containing N=1921 data. The sampling frequency is F_s=64000 Hz. One realization is the linear combination of 5 signals. Two sine waves with constant amplitude values, at frequencies of 5 kHz and 15 kHz. One sine at 25 kHz with amplitude varying according to a Gaussian distribution. A white Gaussian process and, finally, a colored Gaussian process filtered between 10 and 11 kHz, by a *5*th-order Butterworth digital bandpass filter. Fig. 1 shows the performance of the spectral kurtosis estimator over the synthetics. The kurtosis is negative for each frequency component with constant amplitude value, positive for the component with Gaussian-law amplitude, and null for the colored Gaussian noise. The spectral kurtosis is obviously zero for all the components of the white Gaussian noise.

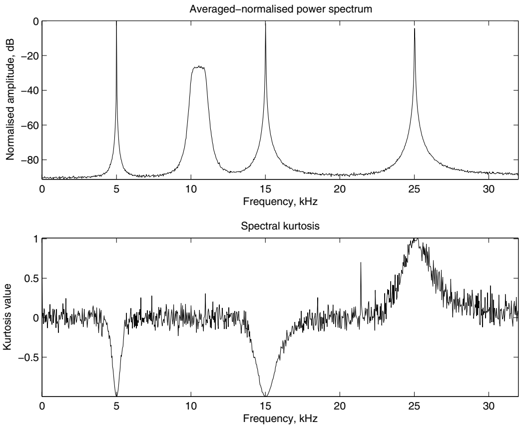

Figure 1: Performance of the spectral kurtosis estimator over a synthetics.

Regarding the experimental signals, we expect to detect positive peaks in the kurtosis's spectrum, which may be associated to termite emissions, characterized by random-amplitude impulse-like events. This non-Gaussian behavior should be enhanced over the symmetrically distributed electronic noise, introduced in the measurement system. Speech should be also reflected in the spectral kurtosis but not in the frequencies were termite emissions take place. Besides, we assume, as a starting point, that non-Gaussian behavior of termite emissions is more acute than in speech. As a consequence, the ultrasonic emissions would be clearly outlined in the kurtosis spectrum. As a final remark, we expect that constant amplitude interferences are clearly differentiate due to their negative peaks in the spectral kurtosis.

5. EXPERIMENTS AND RESULTS

5.1 Experimental arrangement

A piezoelectric probe-sensor (model SP-1L from *Acoustic Emission Consulting*) has been used to obtain the set of results in this paper. A bare waveguide has been used for insertion into soil. Specially important are the ultrasound components in the spectral kurtosis, because neither ambient noise nor human speech is *a priori* present; as a consequence, an increase in non-Gaussian behavior may be interpreted as the presence of termites.

The interface unit for the sensor was connected to the sound card of a lap-top computer, configuring an autonomous measurement unit. The sampling frequency was F_s=64000 Hz for all the registers analyzed in this paper, both in the sliding-cumulant results as in the spectral kurtosis subsection. The recording stage took place in a garden with evidence of infestation and the bare waveguide of the sensor was introduced in the lawn, over the suspicious zone.

The main objective of this experience in the frequency domain is to add ultrasound components by analyzing the spectral kurtosis. In case of presenting this ultrasound information in the spectral kurtosis graph, the presence of termite infestation may be localized earlier. In the time domain, the goal is the same, and it consists of adding information regarding the shape of the *4*th-order bumps, which appear while a sliding cumulant window calculator goes through the stored data.

5.2 Application of sliding cumulants

We work with recordings of 5000 points, each register has the peculiarity of containing human voice (field operators of a plague eradication company), which is almost the unique signal we can ear. The question resides in discovering termites impulses hidden in the speech, by analyzing the behavior of the sliding window. This would help the human-ear-based criterion and, consequently reduce subjectiveness.

A window length of N_w=50 is selected to be neither so short to loose resolution in the time-domain, nor so long to cover a significant percentage of the signal (in this case, transient information may be lost). The *4*th-order cumulant at zero lags (an unbiased estimator) is computed for these 50 points. Then, the window shifts one point (time-unit) and calculates again the cumulant for the next 50 points (49/50 overlapping), and so on. Each computation result is depicted in a graph. For each register we calculate the *second-*, *third-*, and *fourth*-order sliding cumulants. We present the results of analyzing a sample register, in Fig. 2.

In a noisy environment, it may be possible to ignore termite feeding activity even with an *ad hoc* sensor because, despite the fact that the sensor is capable of register these low-level emissions, the human ear can easily ignore them because they are buried in the speech, urban or environmental noise, or even may be confused by the steps or other sounds being propagated through the soil in the moment of the measurement. For this reason we used high-pass filtering as a pre-processing step. As a first opinion, high-pass filtering may be enough for detection purposes, because it suppresses the audio-band noise, being only the ultrasound components of the signal processed by the sliding cumulants. It could be said that filtering decreases the error-detection probability. For example a digital *5*th-order *Butterworth* filter with cut-off frequency of 20 kHz could be used to remove audio components.

But filtering is only a first help for detection. In fact, it cleans the signal and leaves the possible-suspicious acoustic event, eliminating the other non-desired low-frequency signals. This can be seen in Fig. 2. To sum up, it could be said that this pre-processing helps algorithms to work properly.

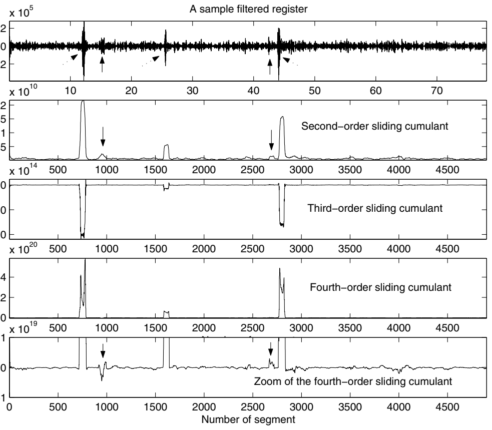

Figure 2: Performance of the sliding cumulants over a high-pass filtered register. Characterization of the impulses can be clearly made. False impulses (not corresponding to termites) are detected and differentiated via the *4*th-order cumulant.

In Fig. 2 we distinguish two intensity-types of vibratory events, which have been discovered via filtering. The events marked with a discontinuous arrow are of higher amplitude levels than those of low amplitudes, marked with a continuous (also vertical) arrow. Higher-amplitude events produce clear bumps in the second an higher-order graphs. They confirm the negative third-order bumps and the peculiar form of the fourth-order graph, associated to termite feeding and excavating activity (compared to results from other types of events). Low-level events are pointed, with a continuous arrow, as candidates in the variance graph, and confirmed in the fourth-order graph, if we observe the bottom graph, with zoom in Fig. 2.

5.3 Application of spectral kurtosis

The kurtosis as a global indicator, considered as the average of the kurtosis computed for each individual frequency component, is not a valid tool to target termite activity. The key of the spectral kurtosis detection strategy used in this work lies in the potential enhancement of the non-Gaussian behavior of the emissions, in the near-ultrasound band. If this happens, i.d. if an increase of the non-Gaussian activity (increase in the kurtosis, peakedness of the probability distribution) is observed-measured in the spectral kurtosis graph, there may be infestation in the surrounding subterranean perimeter, where the transducer is attached.

Termite emissions are non-stationary, so the treatment of data has been performed by ensemble averaging. The original long-duration recording is swept and 5000-point realizations are extracted, without overlapping between adjacent realizations. Each spectrum and spectral kurtosis graph presented in this subsection is the result of averaging the spectra of the sample registers, or realizations.

We present the results for averaging over 100 registers (realizations), each of which previously filtered (20000 Hz, high pass, not presented in the paper) and non-filtered (in Fig. 3). It is observed that the main activity in the power spectrum graphs is concentrated in the sound-band, where speech and any other parasitic signals are present. Three frequency bands are distinguished. A main frequency interval, below 5 kHz, a bump between 5 and 10 kHz, and two bumps in the surroundings of 15 kHz.

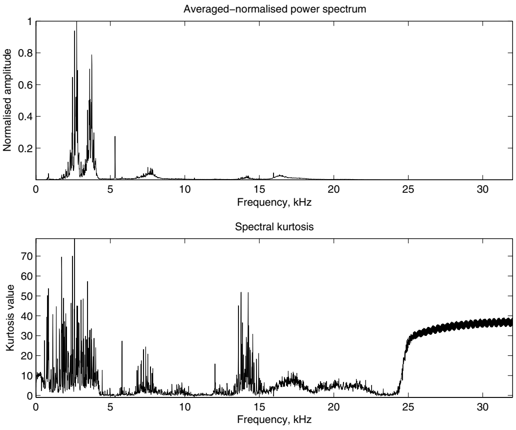

Figure 3: Averaged spectrum and spectral kurtosis for 100 realizations, without filtering.

The bumps, near 5 kHz and 15 kHz, are associated to the resonances of the transducer and we usually use them for detection in the audio band, using second-order methods and the spectral kurtosis. The question that arises is if the spectral kurtosis adds extra information. Looking at the couple of graphs in Fig. 3, two observations are addressed. First, the band near 15 kHz is enhanced in the kurtosis to almost the same order of magnitude as of the frequencies below 5 kHz. Second, a new frequency bump appears, this time in near the ultrasound region, 22 kHz centered. The relative amplitude of this bump centered in 22 kHz, is 0.07 (≈5/75); which is also bigger than the relative amplitude near the band of 15 kHz, with a value of 0.01 roughly, in the power spectrum graph. These results are confirmed after calculating the spectral kurtosis over high-pass filtered data.

6. CONCLUSIONS AND ACCOMPLISHMENTS

Assuming the starting hypothesis that the insect emissions may have a more peaked probability distribution than any other simultaneous source of emission in the measurement perimeter, we have design a termite detection strategy based in the calculation of the *4*th-order cumulants for zero time lags, which are indicative of the signals' kurtosis.

The signal processing engine has been chosen to be in a medium point between power spectrum and multidimensional data processing in higher-order spectra calculations. In the time domain the sliding cumulant window enables the detection of the excess of peakedness, along with a characteristic pattern which vanishes as the impulse ceases. A high-pass filter has proven to be a useful pre-processor because it cleans the signal, enhancing all the possible impulse-like events.

Looking at the frequency-domain, an estimator of the spectral kurtosis has been used to perform a selective analysis of the peakedness of the signal. It has been shown both in pre-filtered registers and non-filtered ones, that new frequency components around the resonance peaks of the transducer gain in relevance in the spectral kurtosis graphs.

It is of special mention the enhancement of the near-ultrasound components which complement the classical sound-components. As a consequence, in unfavorable conditions, where the breaks and movements are almost non-audible, the enhancement over the ultrasound components may help the operator reach a decision.

Acknowledgement

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