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Technical Note

Assessment of amplitude modulation in environmental noise measurements

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ABSTRACT

This paper introduces a method to assess the parameters of amplitude modulation as applicable to environmental noise monitoring tasks. It is based on the analysis of time histories of sound pressure levels correlated with a reference cosine signal. The method brings accurate results in situations where the time history does not exhibit a clear modulation pattern or the signal-to-noise ratio is poor. These features make the suggested technique attractive for practical implementation.

The results of analysis using the suggested method of modulation assessment are represented for test cases with different degree of influence of extraneous noises as well as for actual measurements of noise from a wind farm. This method can deliver accurate estimates of amplitude modulation parameters whereas alternative technique could not bring conclusive results.

1. Introduction

The annoyance of listeners when exposed to different types of noise is frequently linked not only to the average levels the listener is exposed to, but also to presence of characters in the noise. Periodic variations of sound pressure level are inherent features of some noise sources such as helicopter rotors or wind turbines [1–4] and are sometimes referred to as the amplitude modulation noise character. Noise possessing this character may be more annoying to a listener. Different standards and regulatory documents address this issue by applying penalties to the measured noise levels [5]. However the methods of assessment of some noise characters do not allow for reliable detection of its parameters. Consequently, this means that it is more difficult to determine whether the noise character is excessive and requires the application of the penalties.

One uncertainty in determining whether a noise character is excessive lies in the evaluation of amplitude modulation as an environmental noise character. Some degree of modulation, which is sometimes characterised by listeners as the “swoosh” sound, is expected in the vicinity of a wind farm. Correct assessment of the character can be crucial in deciding whether noise from such sources as wind farms is considered acceptable.

Modern noise monitoring equipment is capable of reporting a wide range of acoustic descriptors. Equivalent sound pressure levels (SPLs) are typically utilised to specify acceptable noise limits. The assessment of noise characters should be based on the analysis of standard descriptors from the perspective of practical benefit in testing and/or result reporting. Many acoustic instruments are capable of logging the equivalent levels with a 100 ms interval. It is considered sufficient to analyse amplitude modulation with very low modulation frequencies. Some research works and regulatory documents suggest to make assessment of modulation parameters by post-processing weighted or unweighted time histories of the measured SPLs [5–9]. The results of actual measurements are frequently affected by extraneous noise sources and do not show a clear modulation pattern, however the character can be clearly perceivable. Many of these methods introduce significant error in the final results or do not produce a reliable estimate [10].

It is suggested to utilise another method of the modulation parameters assessment. This method comprises the analysis of correlation functions of equivalent SPL time traces and reference signals with the same frequency as the frequency of modulation. Where other procedures may produce unreliable results this method enables the extraction of the amplitude modulation parameters with higher accuracy.

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Nomenclature

A	amplitude of modulation, dB
C	real part of cross-spectrum
$F(\omega)$	Fourier transform of signal
G	spectral density (one-sided)
j	imaginary unit
L, L_0	sound pressure level and its constant component, dB
$M(L)$	mean of the sound pressure time series, dB
m	an integer number
$N(\omega)$	spectral density of pseudo noise
$n(t)$	pseudo noise, dB
Q	imaginary part of cross-spectrum
$R(\tau)$	cross-correlation function
S_N	signal-to-noise ratio, dB
T	averaging period, s
t	time, s
X	amplitude of cosine signal
α	phase angle of signal of interest, rad
$\delta(\omega)$	the Dirac delta function
ε	relative error
τ	time displacement, s
θ	phase angle of pseudo noise, rad
σ^2	variance
φ	phase angle of reference signal, rad
ω	angular frequency, modulation frequency, rad/s
ω_0	angular frequency of reference signal, rad/s

Subscripts

N	denotes pseudo noise
S	denotes cosine signal
SS	auto spectrum of reference signal
SN	cross- spectrum of reference signal and pseudo noise

Superscripts

$\bar{}$	quantity with zero mean
$\hat{}$	estimate of function
$*$	complex conjugate

2. Calculation methods

2.1. Overview of methods to extract the modulation parameters

It is preferable to enable the detection of basic amplitude modulation parameters (frequency of modulation and modulation amplitude or depth) based on readily available acoustic descriptors. Sometimes modulation depth for the purpose of environmental noise assessment is understood in a generic sense and is replaced by peak-to-trough level. There are also more complex descriptors [10,11] that can be utilised to characterise amplitude modulation of a wind turbine generator. Earlier works on the perception of amplitude modulation suggested analysis of equivalent SPL time history [12] and some of the recent regulatory documents and research works also recommended the use of SPL traces (100 ms estimates) for modulation depth or peak-to-trough level analysis [5,6,10]. There is no general consensus on what kind of SPL time histories should be used for the evaluation of amplitude modulation. The assessment methods can be based on the analysis of A-weighted, C-weighted or unweighted noise level magnitudes. There are many current methods that involve the post-processing of A-weighted time histories of SPL. This may lead to underestimation of the modulation depth due to the nature of the weighting which has negative corrections below 1 kHz. If sound energy is mainly modulated in the low to mid-frequency range, the modulation depth (or maximum peak-to-trough difference) computed from A-weighted signals can be significantly less than from unweighted ones [9,13]. Current studies focus on a method to extract amplitude modulation parameters and do not discuss in detail the influence of the weightings on perception of the modulated sound.

The New Zealand standard [5] for the assessment of noise from wind farms considers the peak-to-trough method acceptable for assessing excessive modulation. A research by Renewable UK [10] gives a good overview of techniques that can be potentially utilised to extract amplitude modulation parameters from SPL time histories. The methods presented typically require a clear modulation pattern to be present in the time histories for reliable assessment of the modulation. Furthermore, the accuracy of such assessment is doubtful for signals with a low degree of modulation, affected by extraneous noises or the irregular shape of the time traces [10]. From a practicability perspective, this leads to certain implications, for example, when a listener perceives modulation but the contribution from noise sources other than the source of interest significantly influences overall noise levels. Therefore, the need for the development of a relatively simple and reliable method for assessment of amplitude modulation in environmental noise measurements is still not satisfied and requires further investigation.

2.2. Simple method for assessment of modulation depth

Modern industrial turbines are inertial systems where some time is required to adjust operational regimes in response to a change of wind speed or direction. Therefore, it is possible to assume that there are time frames when SPL due to a noise source of interest does not vary significantly and the process can be considered as locally stationary. For example, in the case of wind turbines, such time intervals can be chosen by taking into account the time constant of the turbine rotor or the recommendations of relevant standards. In this case it is assumed that the time histories of measured total noise can be represented in the form:

$$L = L_0 + A \cdot \cos(\omega t + \alpha) + n(t), \tag{1}$$

where $n(t)$ is the time varying pseudo noise. The term "pseudo" is used here because total noise is typically considered as a result of the energy summation of contributions from different sources, whereas in this case it is considered as the result of a simple algebraic summation. The phase angle is important in the total noise SPL representation because in a general case the position of the cosine component relative to the zero time of the analysed time history is unknown. The frequency at which the sensations of fluctuation strength are caused by varying SPL is typically below 20 Hz. Noise modulated by higher frequencies up to 300 Hz is perceived as possessing the sensation of "roughness" [12].

Since the parameters to be found are related to the amplitude modulation, it is more convenient to analyse signal $\bar{L}$ with zero mean. It can be easily obtained from expression (1) by removing the mean of the time trace:

$$\bar{L} = (L_0 + A \cdot \cos(\omega t + \alpha)) + n(t) - M(L) = A \cdot \cos(\omega t + \alpha) + \bar{n}(t). \tag{2}$$