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AN OPTIMIZED MATLAB SOFTWARE PACKAGE FOR THE ANALYSIS AND CHARACTERIZATION OF UNDERWATER SOUND PRODUCED BY WIND FARMS

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ABSTRACT

Ocean sound is an Essential Ocean variable. As such, it requires detailed study and monitoring. Within this framework, this study comprises the process of development of an optimized Matlab software package for the analysis and characterization of underwater sound recordings from wind farms. This software package is based on a Matlab script produced by one of the authors. This script was analyzed, and the following modifications were done: 1- The one-third-octave band filters were replaced by stable filters that meet the IEC 61260-1 standard. 2- The low band and band pass filters were replaced by a single bandpass filter 3- Five additional metrics were included, in such a way that the script generates the following metrics: SPL (Sound Pressure Level), L_{eq} (Equivalent Level), L_1, L_5, L_{10}, L_{50}, L_{90}, L_{95}, and L_{peak} (Peak level). 4- The computational load of each line of code was measured and the software modified to increase the speed of execution. 5- The results are saved in the hdf5 file format. As a result, a Matlab software package was created that generates the desired metrics, performs faster than the original script, and saves the results in a standard file format.

Keywords: *Ocean sound, underwater radiated noise, acoustic analysis, sound pressure level, Matlab.*

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1. INTRODUCTION

Ocean sound is an essential ocean variable[1], which implies that this variable is one of the key parameters that measures the health and state of our ocean. Ocean sound is recognized by the Global Ocean Observing System (GOOS) under the Biology and Ecosystems category[1] as a variable, since it plays a crucial role in marine ecosystems. Monitoring ocean sound allows us to detect and understand the communication and behavior patterns of marine species[2,3], ocean biodiversity[4,5], human impact[6], and environmental changes[7,8]. Among the challenges in ocean sound monitoring, we find: Data volume, processing and analysis[9], standardization[10], noise pollution and accessibility. The objective of this study is to tackle the first and second challenges, by developing an optimized software package to speed up processing of the large data volumes, and by implementing a set of variables that could potentially serve to characterize the underwater sound produced by wind farms.

2. THE STARTING POINT

The Matlab[11] programming language was chosen for this work mainly due to the speed for developing and testing experimental code, and the availability of a license in our institution. One of the authors provided a base Matlab script for acoustic analysis of ocean sound with the following main characteristics:

- Ability to read .wav files.
- Adaptation to the hydrophone parameters.
- Creation of bandpass and one-third-octave band filters.
- Calculation of the Sound pressure Level (SPL) [12], Peak level, 90th percentile (L10), and 10th percentile (L90) metrics for the full-band, filtered and one-third octave band signals.
- Storing the results.

This code served as the base script.

3. SOFTWARE DEVELOPMENT AND OPTIMIZATION

3.1 Selection of the metrics

There are no standard metrics nor procedures for ocean sound analysis. Consequently, during the development of the PURE WIND project, several discussions took place where the issue of the metrics to be used in the project was raised. Finally, it was decided to implement the following metrics for the full-band, filtered (20 Hz to 20 KHz) and one-third-octave band (from 20 Hz to 20 Hz) signals:

- Sound pressure Level (SPL) [12]
- Equivalent Level (L_{eq}) [13]
- Peak level
- L1 (99^{th} percentile)
- L5 (95^{th} percentile)
- L10 (90th percentile)
- L50 (50th percentile)
- L90 (10th percentile)
- L95 (5th percentile)

The analysis window for the SPL was chosen to be 1 s to follow the Marine Strategy Framework Directive (MSFD) [14], and for all other metrics the window was set to 5 s to adapt to the "Offshore wind farms measuring instruction for underwater sound monitoring[15]" and compare the results generated by this software with this study.

3.2 Loading the hydrophone specific parameters

The first step involved loading the value of the parameters of the hydrophone used for recording. The values used were the following:

- Hydrophone sensitivity = -183,41 dB re 1 μPa^2
- Inverse gain = 1/5.62341
- Inverse gain correction = 1
- Channel = 1
- Observation windows = 1 s and 5 s

The first four parameters were obtained from the equipment used, which was an RTSys Sylence EA-SDALP. Two observation windows were chosen: 1 s for the calculation of the SPL, and 5 s for the rest of the metrics (see section 3.1).

3.3 Filter analysis, selection and implementation

The analysis of the filters used by the base software revealed that the broadband filter was implemented with a cascade of a high-pass and a low-pass filter. The specifications of these filters were:

- Hi-pass filter:
  - Type: Butterworth
  - Cut-off frequency = 20 Hz
  - Order = 4
  - Design method = transfer function
- Low-pass filter:
  - Type: Butterworth
  - Cut-off frequency = 20 KHz
  - Order = 8
  - Design method = transfer function

A better solution would involve the use of a single Chebyshev type I bandpass filter. The specifications of this filter were:

- Type: Chebyshev type 1
- Low cutoff frequency = 20 Hz
- High cutoff frequency = 20 KHz
- Design method = second order sections
- Number of second order sections = 4

Figure 1 shows a comparison between the magnitude response of the low-pass Butterworth filter and the Chebyshev bandpass filter at the low cutoff frequency. Both filters provide good attenuation, but the Butterworth filter presents instability.

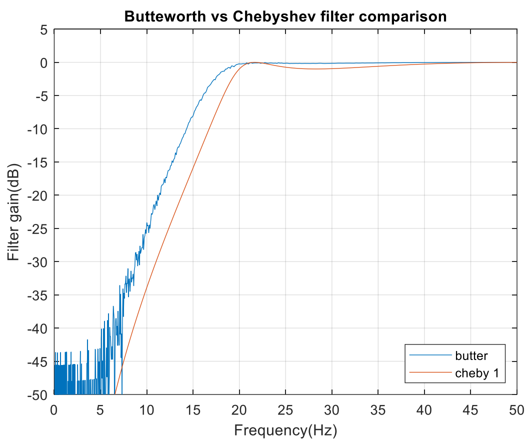

Figure 1. Comparison of the magnitude response of the Butterworth and Chebyshev filters at the low cutoff frequency.

Figure 2 shows a comparison of the magnitude response Butterworth and Chebyshev filters at the high cutoff frequency. In this case both filters provide good attenuation and are stable.

The speed of execution of both types of filters was measured with a test file. The characteristics of this file were the following:

- File type: .wav
- File length = 85 s
- Sampling frequency = 256 KHz
- Sampling resolution = 24 bits
- Type: Bandpass
- Mid-band center frequencies from 20 Hz to 20 KHz
- Design method: second order sections
- Number of second order sections = 3

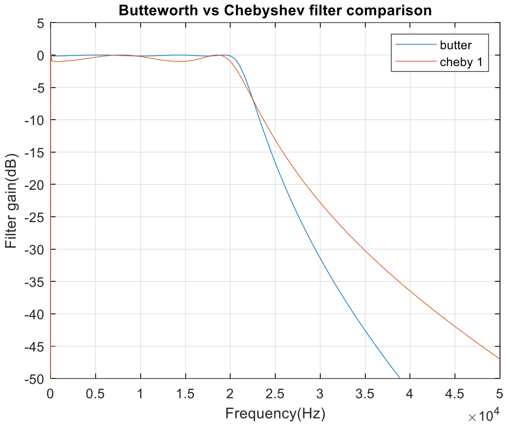

Figure 2. Comparison of the magnitude response of the Butterworth and Chebyshev filters at the high cutoff frequency.

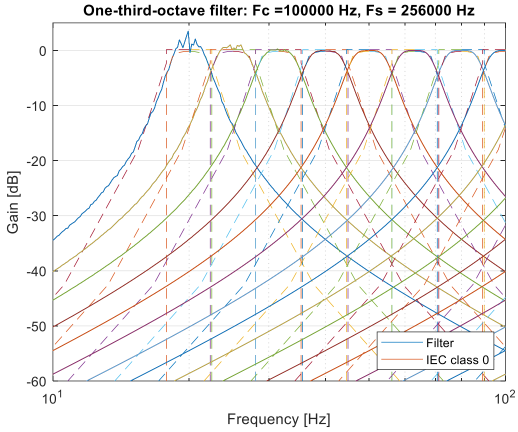

Figure 3. Magnitude response of the one-third-octave band Butterworth filters at low frequencies.

The two Butterworth filters took 0,472 ms to filter the signal, while the Chebyshev filter took 0.241 ms, this is, the Chebyshev filter employed 51.1 % of the time of the two Butterworth filters, reducing the computational time to almost one half while removing the instability.
Figure 3 shows the magnitude response of the one-third-octave band filters at low frequencies. The continuous lines represent the magnitude response of the filters and the dotted lines represent the one-third octave band specifications as given by the IEC 61260 standard[16]. The specifications of the Butterworth filters were:

- Type: Bandpass
- Mid-band center frequencies from 20 Hz to 20 KHz
- Design method: transfer function
- Order = 2

From figure 3 we notice that the first two filters on the left present instability in the bandpass, and that the filter attenuation does not meet the IEC standard, thus, not providing proper filtering. Also, increasing the order of the filters increased the filter instability. The solution was found by replacing these filters with Chebyshev type 1 bandpass filters with the following specifications:

Figure 4 shows that the Chebyshev filters meet the IEC 61260-1 specifications and are also stable. Using the same test file, the filtering process took 6,838 ms using the Butterworth filters and 5,957 ms for the Chebyshev type 1 filter.

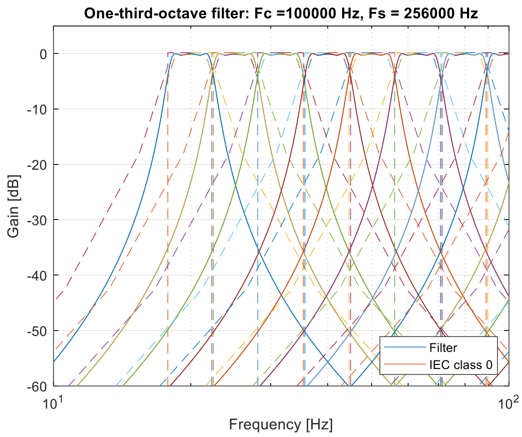

Figure 4. Magnitude response of the one-third-octave band Chebyshev type 1 filters at low frequencies.

3.4 Reading the .wav files

It was observed that in the original script, the wave file was read from the hard disk in segments. Every time a new segment was about to be analyzed, the script read the segment from the hard disk. This action takes more time than that if the file is already loaded in memory. Therefore, the script was modified to load the entire file in memory, and then, the needed segment is selected for processing. Both methods were tested using the test file. In the first case, where the file is loaded by segments, it took 0,556 ms in total to load the segments. In the second case, it took 0,318 ms to load the entire sample and select the desired segments, reducing the processing time to 57,2 % of the original time. This processing time will vary depending on the amount of RAM and the type of hard disk of the computer used.

3.5 Calculation of the Sound Pressure Level (SPL)

The SPL is given by the following formula[12]:

$$L_p = 10log_{10}\left(\overline{p^2}/p_0^2\right) dB \tag{1}$$

Where:
L_P = Sound Pressure Level in dB
p = underwater sound pressure
p_0 = reference sound pressure

Since the reference pressure p_0 is 1 µPa in water, the formula becomes:

$$L_p = 10log_{10}\left(\overline{p^2}\right) dB \tag{2}$$

Equation 2 was implemented in the original software as:

$$L_p = 20log_{10}\left(\sqrt{\overline{p^2}}\right) dB \tag{3}$$

Equation 3 involves the calculation of the square root of the mean square pressure, this operation is computationally intensive and can be avoided implementing equation 2. A test of both implementations showed that for the test file, the original software took 1,399 ms and the new implementation took 0,361 ms, which represents only 25.8% of the original processing time.

3.6 Calculation of the Kth percentile

The first step in calculating the Kth percentile requires sorting the values of the variable under study (sound pressure in our case). Since the pressure (*p)* takes negative values, it is required to calculate the absolute value before sorting. We also need to square the pressure to calculate the SPL (see equation 2), since the signal is real, the square pressure will be real and positive, therefore we can sort the square pressure (instead of *p*), and avoid taking the absolute value of *p,* making the code simpler. Using a test file, the process of sorting the three pressure signals (full-band, filtered and one-third-octave band) took 20,395 ms, when taking the absolute value of *p*, and took 19,811 ms without taking the absolute value, this is, a reduction of 0,584 ms. The improvement in processing time might not look significant when compared to sorting, but if we compare this value (0,584 ms) with the time needed for reading the wave files (0,318 ms) and calculating the SPL value (0,361 ms) in the new implementation, we notice that this value is significant.

3.7 Saving the results

The original Matlab script saved the results in the .mat file format, which is proprietary. Instead, it was decided to use the hdf5 file format, which is open and widely used by the scientific community. Therefore, the script was modified in such a way that all the metrics described in section 3.1, for the full-band, filtered and one-third-octave band signals, are saved in a single .hdf5 file per recording. Also, the following metadata is saved in each .hdf5 file:

- Raw data type
- File name
- Sampling frequency
- Number of bits
- Temporal resolution
- Target recording
- Distance from the target
- Duty cycle
- L_{eq} averaging time

4. OVERALL PERFORMANCE

The total execution time of the original script and the new one were measured using the test file in order to obtain and compare the overall performance. To make a meaningful comparison, both scripts were modified to calculate the same metrics. Using our test file, the original script took 24,16 s to process to whole sample and the optimized script took 21,58 s, this is 2,58 s less or 10,68 % less time.

5. CONCLUSIONS

In this work, an optimized Matlab software was created that can process .wav files of underwater acoustic recordings, generate 9 different metrics, and save the results in the .hdf5 file format. This software was based on a script provided by one of the authors. The development process required knowledge in different disciplines like: Underwater acoustics, digital and analog signal processing including filtering, programming, computer architecture, and statistics. A detailed analysis of the original script revealed that: 1- the filters needed to be modified or changed. 2- The code could be modified to improve performance. These observations led to the modifications of the original script described in this paper.

There are dozens of metrics described in the literature in underwater acoustics, therefore, it is important to make a careful selection of them, in order to avoid generating a vast number of results that might be difficult to analyze and not lead to conclusions.

The high bandwidth of the signals under study (128 KHz) hinders the creation of the filters, especially at low frequencies (see Figures 1 and 3). A high-resolution plot of the filter frequency response at low frequencies is needed to detect filter instability.

The creation of the one-third-octave band filters required a lot of experimentation, due to the low bandwidth and closeness of the filters. The Chebyshev type 1 filters proved to be well suited to fulfill the IEC 6126-1 standard, but it was necessary to use the second order section method to remove the instabilities (see Figure 4).

When analyzing large files (~1 GB), in order to load the entire .wav file in memory, the computer in use should have enough RAM (32 GB recommended), otherwise, you might not be able to benefit from the improved performance.

The implementation of the SPL using equation 3 is facilitated by the use of the Matlab rms function, which calculates the root-mean-square of p in one step. Even though this makes the code more compact, implementing equation 2 is much more efficient in terms of execution speed.

The performance results shown here will vary depending on the type of hardware used and the signal analyzed, but in any case, the optimized software outperforms the original script.

When analyzing large datasets (for example, 30 days of continuous recordings), a 10 % improvement in performance will result in a significant saving of processing time (approximately 24 hours).

6. ACKNOWLEDGMENTS

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