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Low Frequency Amplitude Modulation related to Doppler frequency shift: an experimental study of a 101m diameter wind turbine in a swiss valley.

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Summary

An experimental characterization of the noise of a wind turbine in Switzerland is described with the aim to answer questions about the generation and collection of low-frequency noise of wind turbines. The secondary goal here is to determine to what extent the current Swiss rules allows to effectively assess this type of noise.

The equipped wind site is representative of an alpine Valley (villages, roads, highway, railways) and it allows studying the propagation of the sound for two opposite regimes of wind in a valley with a marked relief. The time dependent noise footprints of a 101-m diameter wind turbine are measured over three periods lasting 10 days for three seasons with collection of data from four sound level meters, one meteorological station, one LIDAR and an array of microphones. Turbine operations parameters are recorded with mean values (10 min.) for the entire campaign.

The time series and statistics of noise levels and amplitude modulations in the bands of third octave (50 Hz to 125 Hz) are presented and compared with Doppler frequency shift analyses of recorded sounds. Spectro-temporal sound analysis related to turbine operation parameters presents strong correlations validating the Doppler low-frequency shift hypothesis of three tonal acoustic sources located on the blades. This campaign characterizes the amplitude modulation depth of low-frequency of the wind turbine and it allows extracting a generic proposal for low-frequency noise mapping at different angular azimuthal locations around the wind turbine.

This study helps to deepen a methodology for campaigns of wind turbine noise measurements and analysis. At a longer term the obtained database will permit to study and to evaluate noise models against field measurements. It will give some recommendations on how to apply them to wind projects and to define the constraints of implementation of wind farms in Switzerland.

1. Introduction

1.1. A brief history of energy in Switzerland [1.1]

Following the Fukushima accident, the Swiss energy program has been reviewed with a view to reduce and close nuclear plants in Switzerland in the horizon 2050 ([1.5]). This strategy aims to reach a long term energetic supply, integrating first the use of existing resources such as hydraulic energy, which is wide spread in Switzerland, and renewable energy. The second phase would aim to replace the existing encouragement system by an incentive one.

In 2013, the yearly native energy production had a part of 60% of renewable energy, mainly produced by hydraulic energy dams. The energy supplied by solar energy, biomass, biogas waste and wind turbine only reached 3 % of the national production, against 37% for the nuclear plants, the rest being produced by classical thermal plants and long-distance heating. [1.1]

The energy potential for renewable energy has been estimated to 24,2 TWh at the horizon 2050, whose:

- 11,1 TWh for photovoltaic solar energy;
- 4,3 TWh for wind turbine energy;
- 1,2 TWh for biomass energy;
- 4,4 TWh for geothermal energy;
- 3,2 TWh for waste water, incinerators and biogas energy.

1.2. Wind turbines in Switzerland:

Nowadays, Switzerland has 55 wind turbines installed on 32 sites, providing a total of 93,9 GWh in 2014 for a total installed power of 60,3 MW, mainly consisting of individual wind turbines and few parks :

Site types	**Nb sites**	**Wind turb.**	**2014 prod.**
Individual wind turbines	26	26	19,1 GWh
Wind turbine park with 2 wind turbines	3	6	6,0 GWh
Wind turbine park with 3 wind turbines	1	3	12,9 GWh
Wind turbine park with 4 wind turbines	1	4	5,4 GWh
Wind turbine park with 16 wind turbines	1	16	50,5 GWh
Total	**32**	**55**	**93,9 GWh**

Table 1: Wind turbine sites in Switzerland.

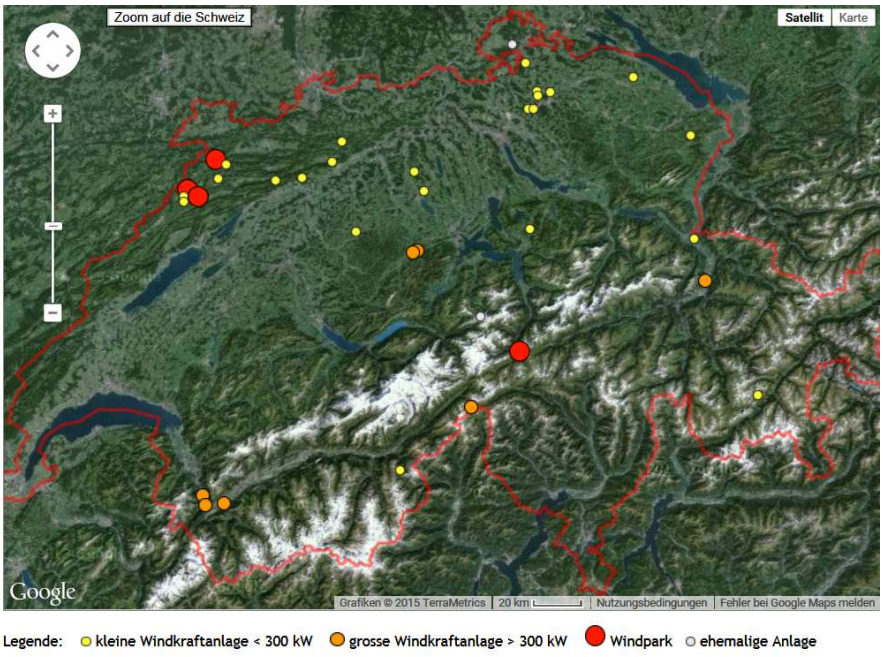

Figure 1 : Installed wind turbines in Switzerland [1.4]

The Swiss 2004 wind turbine energy concept gathers 128 potential planning sites with 12 prioritary sites. The average wind speed at 70m over ground level on these potential sites is around 5,6 m/s (min: 4,5 m/s; max: 8,4 m/s). These sites were identified regarding the wind turbine potential, as well as land planning and environmental exlusion criteria.

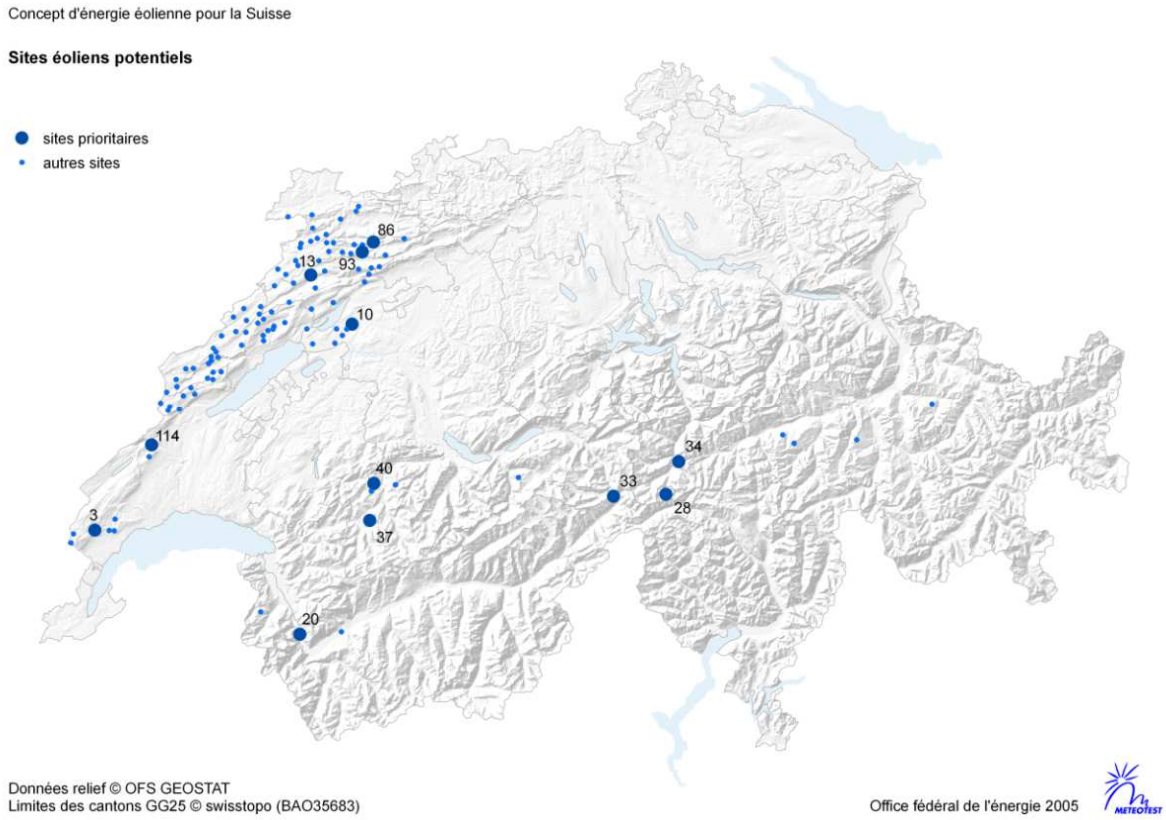

Figure 2 : Potential wind turbine sites [1.4]

1.3. Constraint, limits and the noise problem within legislation and population:

Facing many constraints as well on land planning as on environmental and social acceptance, the wind turbine planning is logically a matter of national planning in a Swiss context which has a strong decentralized planning philosophy. The national planning program and potential sites identification concept supports this fact. To be considered of general interest, hence have a chance of being realized, any wind turbine project needs to ensure in between 5 to 20 MW.

The Swiss democratic system opens possibilities for the population to react through legal procedure and form opposition to the project. Hence, the actual legislation on noise protection follows the precautionary and prevention principles and assimilates wind turbines to industrial noise [1.2]. That means wind turbine immission equivalent level (Leq) should be adapted by a temporal correction and three level correction factors. The main correction factor (K3 = 4) takes into account the impulsiveness components audibility at the immission place. This aspect is not only defined by the purely acoustic impulsiveness such as in typical industrial settings but integrates also well perceptible rhythmic-based discomforts (e.g. noise amplitude modulation).[1.3] Predicting the noise impact of a whole wind turbine project is nowadays one of the most challenging task for an acoustician: metrics, experience and some good understandings of physical phenomenon at stake miss.

1.4. Experimental characterization of the noise of a wind turbine

The primary objective is the experimental measurement of noise from a wind turbine ENERCON E-101 for the purpose of validating the usual acoustic models. The understanding of the noise generated by a wind turbine of this type and the knowledge of the performance of acoustic models should allow a controlled noise modeling of future wind farms.
In order to answer questions about the modeling and measurement methodology of noise from a wind turbine, the study is based on a detailed analysis of acoustic data collected for weather and wind different seasons of the year. The secondary objective is to determine to what extent the current Swiss rules effectively assess this type of noise.

The initial project is composed of two distinct parts:

- A series of seasonal measurements of an existing wind turbine.
- The analysis of experimental data and their comparison with modeling.

As part of the evaluation of noise emission, the study focus only with the following points in the order of importance:

1. The amplitude modulations and taking them into account in the evaluation
2. The low frequencies and their origins; taking them into account in the assessment

Starting from scratch, this study has been defined from state of the art related in [2] and observations of different federal and cantonal swiss offices that want to enhance their knowledge about amplitude modulation of low frequencies and want to develop know-how about the monitoring of this kind of noise sources.

2. Wind turbine site and descriptions

The equipped wind site is representative of an alpine Valley (villages, roads, highway and railways) and it allows studying the propagation of the sound for two opposite regimes of wind in a valley with a marked relief.

The time dependent noise footprints of a 101-m diameter wind turbine are measured over three periods lasting 10 days for three seasons with collection of data from four sound level meters, one meteorological station, one LIDAR and an array of microphones. Turbine operations parameters are recorded with mean values (10 min.) for the entire campaign.

The experimental data were collected for the following periods:

- From 16 to 28 May 2014,
- From 6 to 17 August 2014,
- From 9 to 22 December 2014.

Sound level meters are arranged on both sides of wind (two upstream, two downstream) as shown in yellow and blue in the following Figure 3; red place of the wind turbine. This minimum configuration is used to collect noise data in upwind and downwind for the two principal directions of wind. Sound level meters synchronized by the GPS clock, are programmed to collect noise data for the duration of the campaign; intermittent sound recordings complement noise data for subsequent acoustic analysis. The wind profiler is located upwind of the turbine for controlling the wind direction near the receiver DUO n°1 (sound level meter).

N° DUO 01dB	Distance	Wind reference
1*	150 m	Upwind
2	480 m	Upwind
3	270 m	Downwind
4	550 m	Downwind

Table 2: Location of sound level meters to the mast of the turbine.

Figure 3 : Location of wind turbine (red), soundlevel meters (upwind: yellow, downwind: blue). The mountain relief is on bottom side. (credit Google Earth)

3. Wind turbine operations parameters

Turbine operations parameters are recorded with mean values (10 min.) for the entire campaign and they are collected after each period of measurements.

Figure 4 illustrated the different characteristics of power delivered by the wind turbine in function of wind speed and wind direction. Operational data of the turbine are composed of:

- Wind speed at the nacelle (max, min, mean)
- Rotation speed of blades (max, min, mean)
- Power of the turbine (max, min, mean)
- Direction

As depicted in Figure 4, the wind turbine is operational for two major wind regimes delivering two regimes of power.

Turbine type	Enercon E-101
Number of turbines	1
Number of blades	3
Rotor diameter [m]	101
Hub height [m]	99
Cut-in speed [m/s]	2
Nominal wind speed [m/s]	13
Cut-off wind speed [m/s]	34
Capacity [kW]	3'000

Table 3: Wind turbine technical specifications

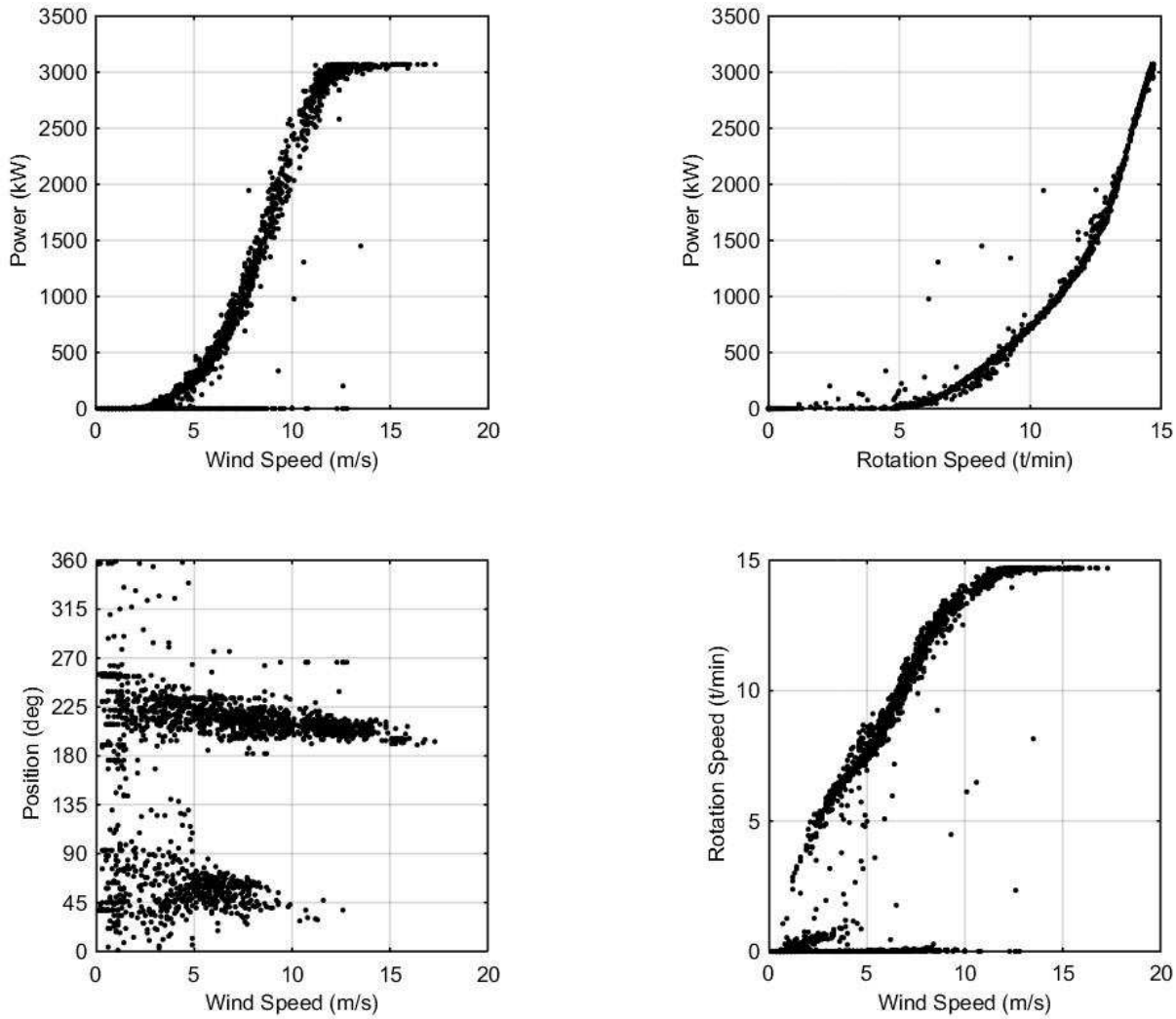

Figure 4: Wind Turbine statistics (12 days / May 2014)

4. Sound level and third octave spectral analysis related to wind turbine parameters

The whole data base covering the three periods of measurement imposed to develop an automation process based on synchronization of the different devices; this last authorizes to have a global control on quality and quantity of noise and wind data. Table 3 gives the time resolution of the listed devices used during the experiment.

4 sound level meters type DUO 01dB with audio recordings – GPS clock	LeqA, Leq 3rd octave Audio files	Leq T = 125 ms Audio Fs = 12800 Hz
1 wind profiler LIDAR ZephIR 300	Wind spec. 11 heights, meteo. Data @1m	T = 20 s approx.
1 Meteorological station VAISALA XT520	Meteo. Data @ 10 m	T = 1.25 s

Table 4 : Type of apparatus and time resolution of measured physical parameters

The noise data base is systematically analyzed in the third octave bands to assess the quality of the noise measurement but also to assess the presence of specific acoustic signatures related to the wind turbine and/or related to parasitic noise sources.

In addition, audio sequences are recorded every 30 minutes with one minute or ten minutes duration to process a precise spectral analysis so as to track spectral components with a higher time-frequency resolution based on a Short Time Frequency Transformation (STFT).

For each period of operation of the wind turbine, a report is delivered as depicted in Figure 5 and Figure 6. This report sheet contains time series (from top to bottom):

a) Wind speed measurements from the nacelle anemometer and from wind profiler (z = nacelle height)
b) The rotation speed of the blades (rotation per minute)
c) The third octave band spectrogram for the first audible frequencies (16 Hz to 125 Hz), colors are representative of the dB in the range [0 80].
d) The sound level Leq (dBA)

Nacelle anemometer delivers minima, maxima and mean values of wind direction and speed for duration of ten minutes while the wind profiler delivers data every 20 seconds approximately.

1.1 First Observations on these two periods

a) The rotation speed is correlated to the wind speed as depicted in Figure 4.
b) The LeqA time series is strongly correlated with the rotation speed of the WTN and the wind data.
c) The 3rd octave bands spectrogram figures out that some tonal components are dominant in the [50 Hz- 100 Hz] third octave bands and they seem to be related to the rotation speed of the turbine.

2.1.1 Observations on the 3rd octave spectrogram

For the both periods illustrated in Figure 5 and Figure 6 some tonal components are dominating the 50 Hz-125 Hz bands of frequencies.

In regards to time series of wind speed and rotation speed of the wind turbine, the energy is these 3rd octave bands seems to be directly correlated with the wind speed and the rotation

speed of the wind turbine. This phenomenon is observed for the three periods of measurements when the wind turbine is in operation and for the two major wind directions.

Since the study is interested in the understanding of LeqA modulation and low-frequency modulation, some detailed analysis of the whole data base is undertaken so as to model this kind of noise modulation.

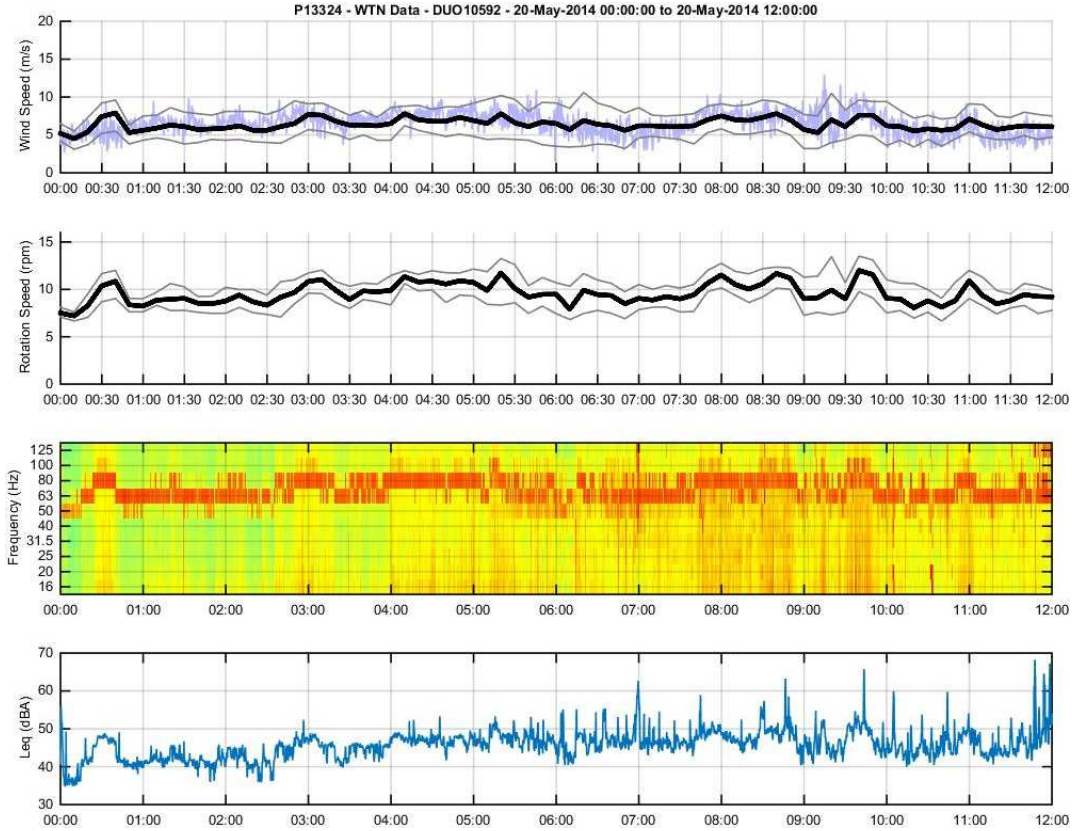

Figure 5 : Time series for the 60 degres wind direction.

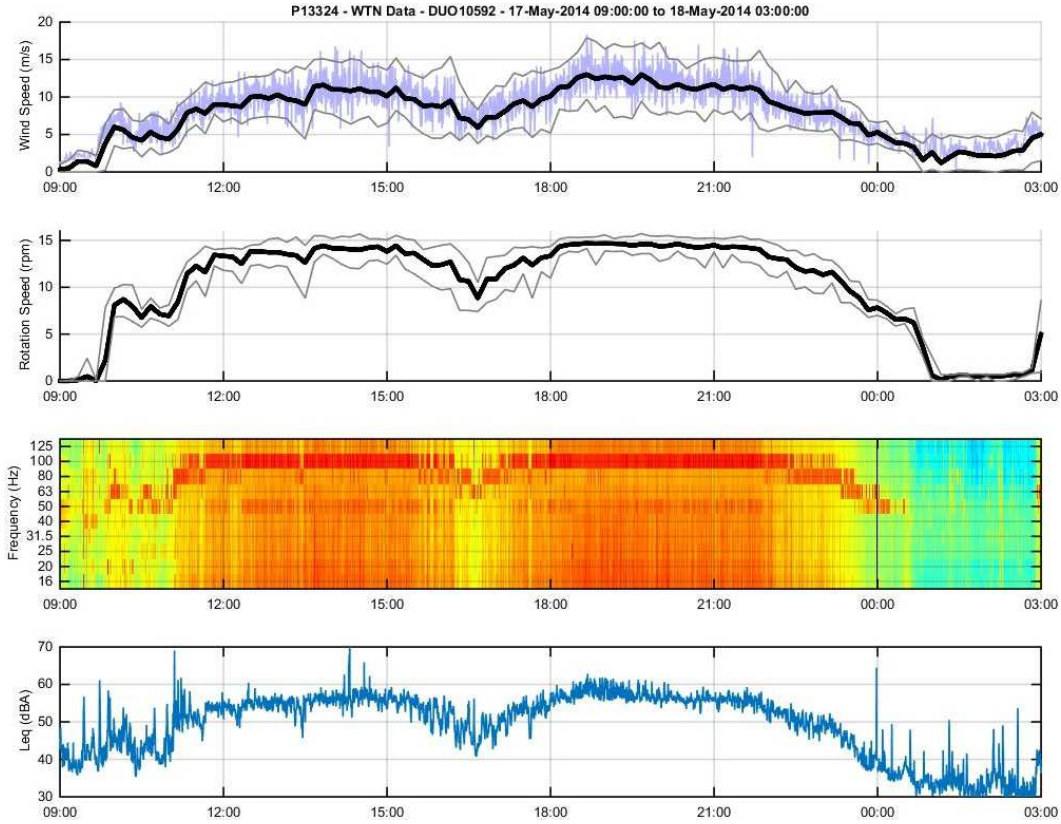

Figure 6 : Time series for the 220 degres wind direction

5. Leq (dBA) amplitude modulation and low-frequency tonal components amplitude modulation

The analysis of amplitude modulations of the overall sound level is separated into two parts:

- the first is interested in understanding the beats of the medium and high frequency significant of the LeqA amplitude modulations (AM);
- the second is the analysis of AM in the first bands in the third octave spectrum characterizing the modulation of low frequency tonal components.

Figure 7 illustrates sound level time series for a 30 seconds measurement. Amplitude modulation of 100 Hz and 125 Hz 3rd octave bands are of an order of two to three than those of Leq(A) and Leq 400 Hz.

Figure 8 illustrates the 3rd octave spectrum for a 10 minutes measurement indicating the emergence of tonal noise in the 100Hz and 125 Hz 3rd octave bands of frequency, emergences of 10 dB and 5 dB respectively for AM of 15 dB and 10 dB approx.

Since these amplitude modulations are pseudo-periodical and their periods are approximatively the one of the rotation speed of blades, the study has been oriented to the research of the source of these AM for the 3rd octave bands of frequencies related to the rotation speed of the wind turbine.

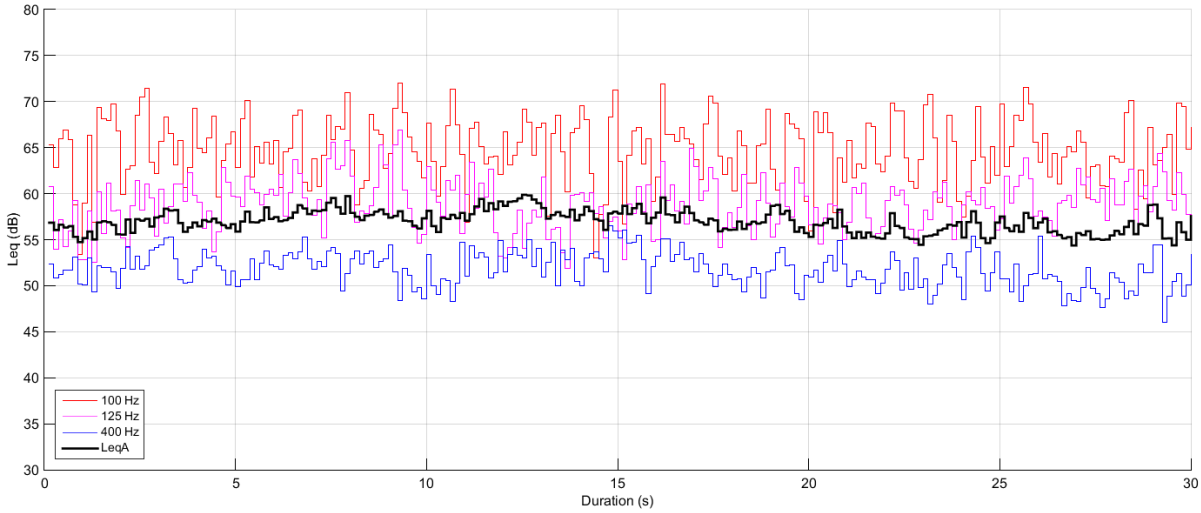

Figure 7 : Leq et Leq(A) time series of 30 seconds noise measurement (resolution 125 ms).

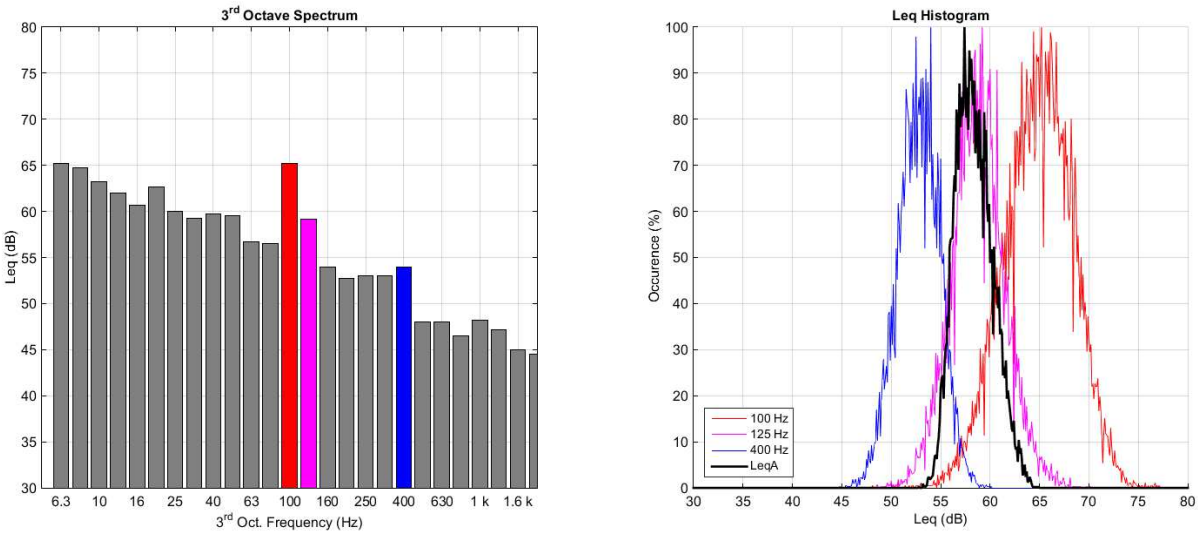

Figure 8 : Left, 3rd octave spectrum of 10 minutes of stationnary noise signal;

Right, histograms of Leq (100 Hz, 125 Hz, 800 Hz) and Leq(A)

6. Tracking tonal components in spectrograms

For purposes of understanding the origin of these amplitude modulations in the low frequencies, an acoustic analysis using Short Time Fourier Transform (STFT) spectrogram is applied on audio recordings [3].

Figure 9 illustrates the STFT spectrogram of one 10 minutes duration recordings and its associated 3rd octave spectrogram for the 20-120 Hz band of frequency. In regards to the 3rd octave analysis two tonal components at 50 Hz and 100 Hz dominates the spectrum with beating emergences of order ~6 dB and more than 10 dB respectively. The STFT decomposition permits to figure out that the 100 Hz 3rd octave band of frequency is composed of a central frequency shifting between 90 Hz and 110 Hz.

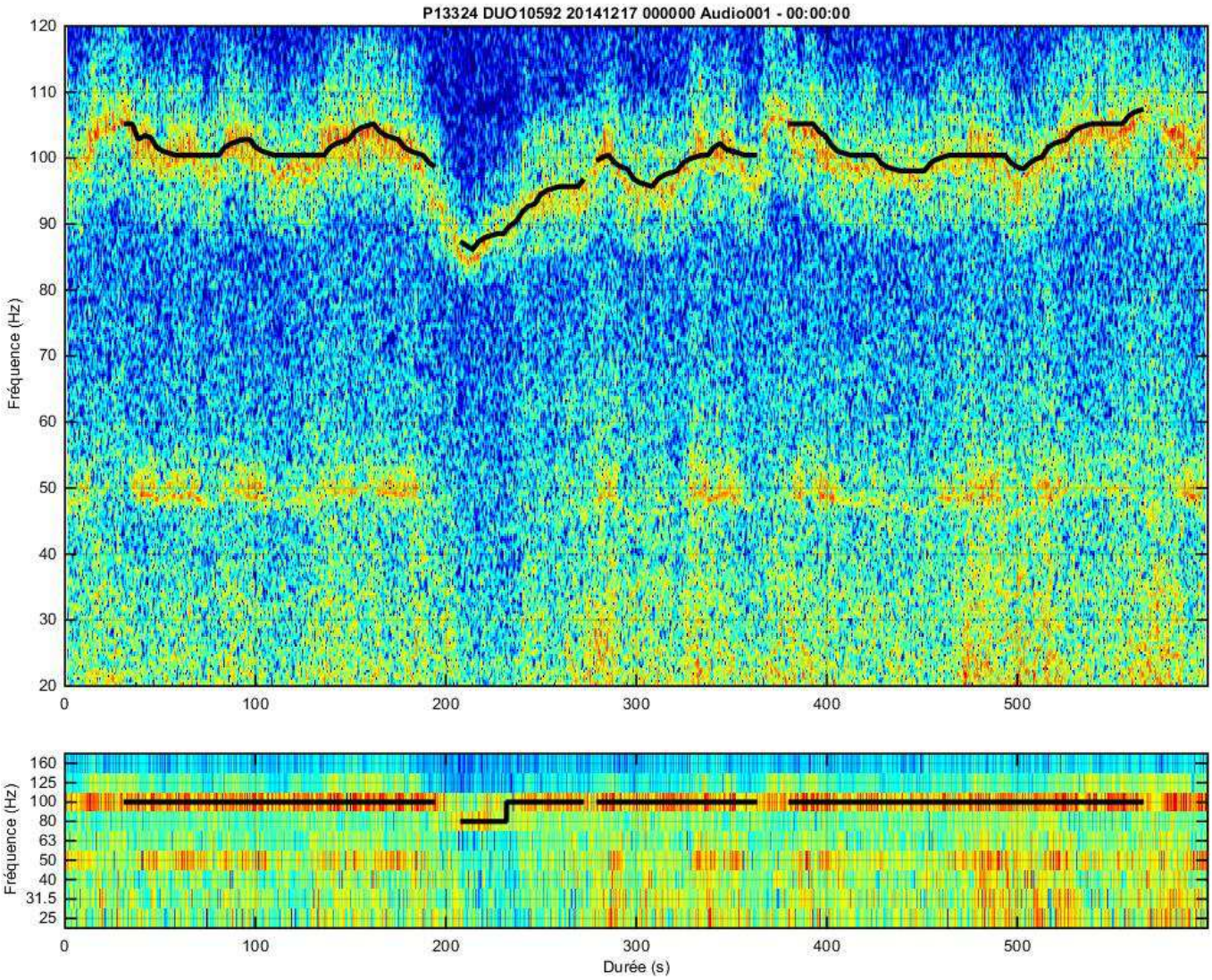

Figure 9 : Top: STFT spectrogram of one 10 minutes duration recording with the tracking of the central frequency. Bottom: 3rd Octave spectrogram of the recording

The analysis of the third octave time series for frequencies between 315 Hz and 800 Hz permits to estimate the rotation speed based on the calculation of the periodic emergence of the “swish” sound of rotating blades components. A direct relation is found between the central frequency and the rotation speed of the blades (figured in black on the figure). This frequency tracking permits to extract most of the dates for which the spectral components are to be evaluated in terms of sound levels and amplitude modulation; it gives also instantaneous information on operational parameters of the turbine.

7. Explaining amplitude modulation of low frequency tonal components

Using adequate parameters to process a tracking of the fluctuating central frequency dominating the sound signal, the STFT authorizes to figure out that the 3rd octave tonal component is composed of three tonal components.

Figure 10 shows that the three tonal components present the same central frequency which is shifted cyclically. In regards to the rotation speed of the blades it appears that the period of frequency modulation is the period of revolution of the blades.

Based on our observations and the detailed analysis of the recordings, we made the assumption that these mono-tonal sound sources are located on the blade. The cause of this frequency modulation is assumed to be the Doppler Effect. The simulation of three single-frequency point sources in revolution permit to assess the sound recorded at the receivers (sound level meters).

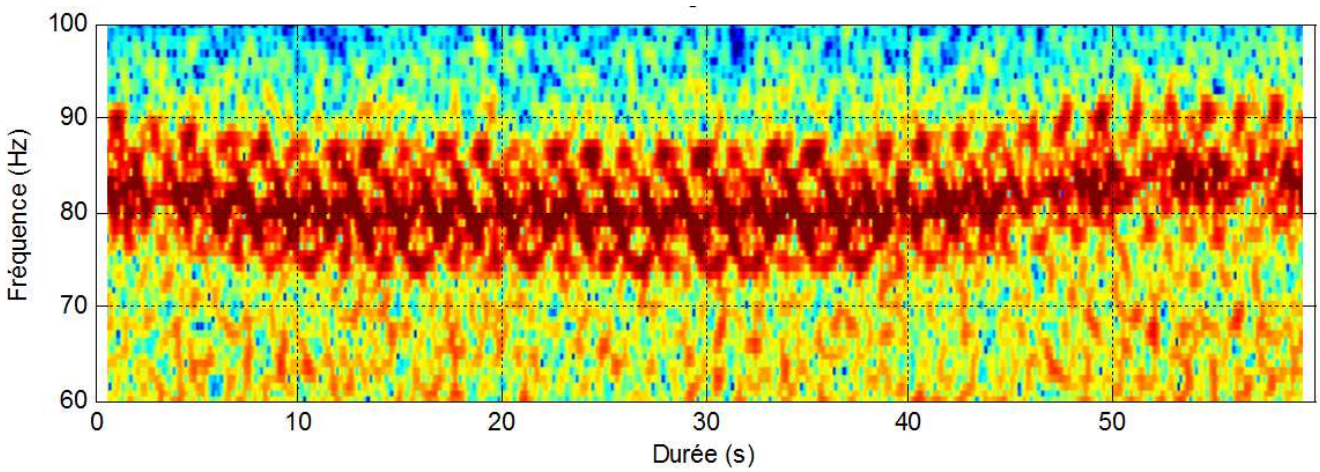

Figure 10: STFT spectrogram of a 60 seconds audio recording

The Doppler Effect may result from motion of the source, motion of the observer, or motion of the medium. So as to confirm this assumption, a simple model has been created based on experimental data (location of receiver and operational turbine parameters). The modelization of three sound sources located on blades is done by the calculations of the Doppler Effect with hypothesis on the following parameters:

a) Central Frequency calculated from the rotation speed of the blades
b) Range and azimuth of the receivers and the discrete positions of sources on blades
c) Period of revolution of the blades (rotation speed of the blades)
d) The medium is considered without motion at this first stage.

The result of this analysis can explain experimental observations; Doppler pattern of three single-frequency sources revolution movement to justify the frequency modulations observed. Figure 11 illustrates the spectrogram of a short sequence of a recording (left) and of the simulated (synthetized) sound signal extracted by real physical parameters:

a) Central Frequency is set to 80 Hz
b) Period of revolution is set to 5.35 seconds (11.2 rpm)
c) Location of the source is set to 41 m far from the nacelle
d) The medium is considered without motion first approx).
e) Sound sources are defined as monopoles with modulated amplitudes (first approx).

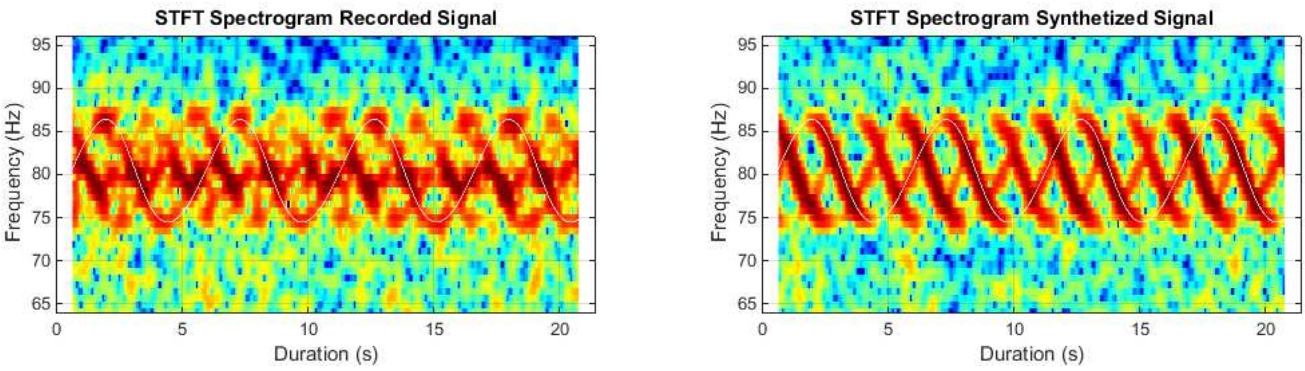

Figure 11: Left: STFT of a real signal; Right STFT of a synthetized signal. White lines are figuring the modelled instantaneous frequency of the sound source located on a blade for four complete revolutions.

Regarding the amplitude modulation of the 3rd octave band of the central frequency (80 Hz), Figure 12 illustrates that amplitude and their modulations of the real and the synthetized sound signals are of the same order and present similar temporal fluctuations.

The differences in their energy are explained by the assumptions on:

- sound radiation of sound sources located on the blades,
- propagating medium considered as homogeneous and static,
- background noise defined on a posteriori statistics.

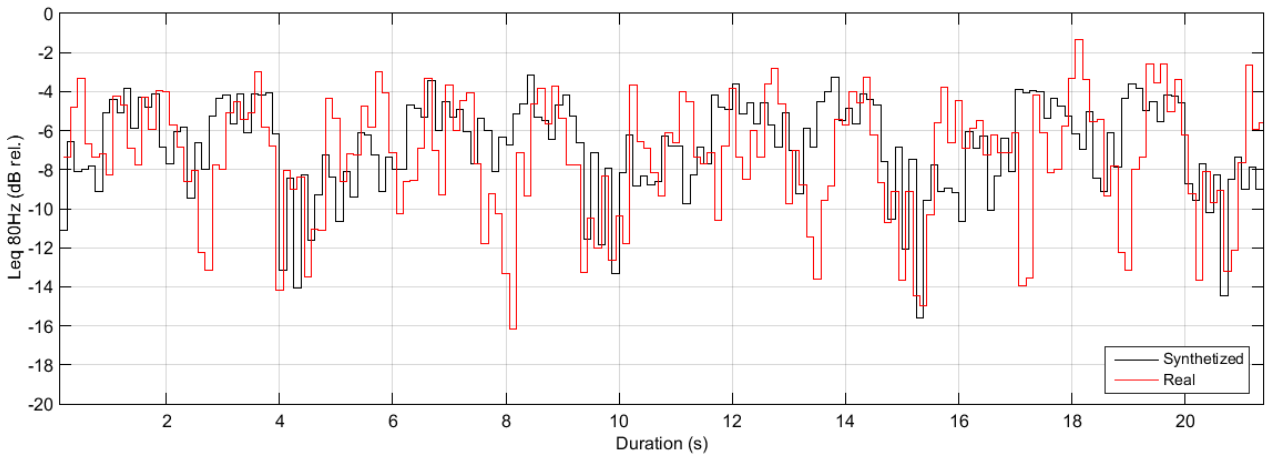

Figure 12: Time series of 3rd octave Leq (80Hz) for real (red) and synthetized (black) signals.

8. Doppler azimuthal mapping for AM and FM of low frequencies

A first validation of the Doppler Effect hypothesis consists in analyzing the STFT spectrogram of the signal recorded synchronously at two different locations (receivers are quasi in-line in the upwind).

Figure 13 illustrates that the Doppler Effect related to the modulation of frequency is attenuated for the receiver n°2 more distant to the wind turbine than the receiver n°1 as predicted by the theory. This specificity of the Doppler Effect will permit to fit the parameters of the physical parameters affecting the frequency shift by the analysis of noise monitoring using adequate locations of microphones around the wind turbine.

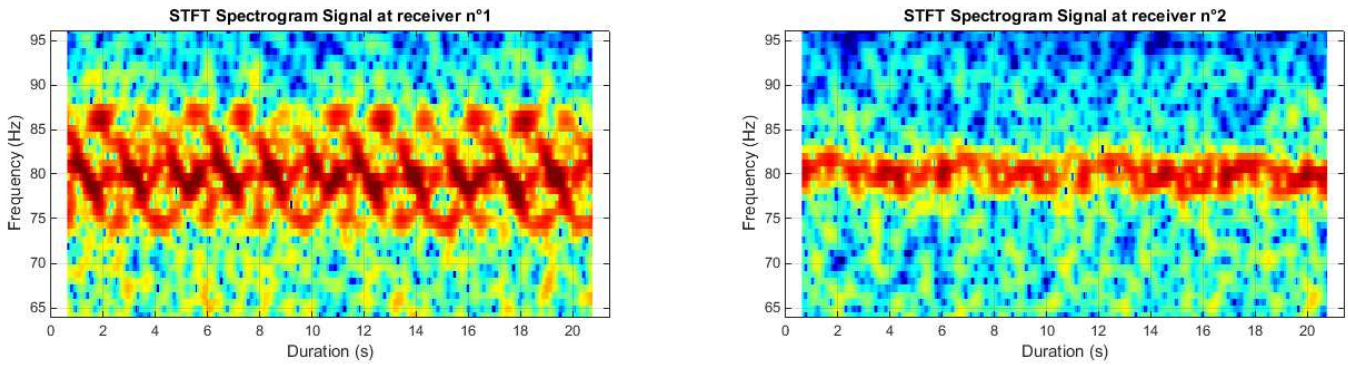

Figure 13: Left: STFT of a real signal at receiver n°1; Right of a real signal at receiver n°2.

Figure 14 illustrates the amplitude modulation of the 3rd octave central frequency at 80 Hz for both receivers. In contrary to the FM modulation, the receiver the farthest from the wind turbine presents higher amplitude modulation (AM1 = 14.5 dB, AM2 = 19.4 dB). It can be explained by the interference of the three dopplerized tonal frequencies which are dependent of the sound radiation of the acoustic source located on the blade and the position of the blade during one complete revolution.

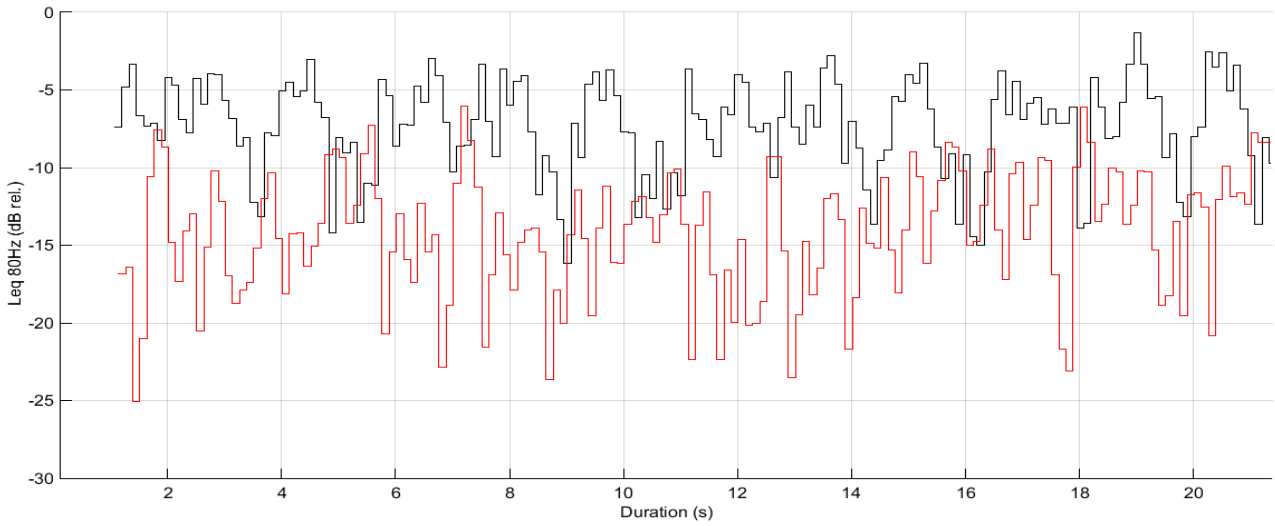

Figure 14: Time series of 3rd octave Leq (80Hz) for receiver n°1 (black) and n°2 (black).

This hypothesis of an acoustic source with a periodic movement of revolution allows thus to generate an azimuthal mapping around the turbine of the frequency dilatation coefficient due to the Doppler Effect and thus to understand the low frequency amplitude modulations for azimuthal distribution of receivers around the wind turbine.

This mapping depends on the position of the sound source on the blade and the emitted frequency; the latter depending on the period of revolution of the blades. For illustrative purposes, Figure 15 shows the range-azimuth dependency of the frequency dilatation coefficient for a static medium of propagation around the turbine for different azimuths and different distances of the location of the receiver given one location of the sound source on the blade. This mapping could be enhanced by considering the vertical sound speed profile affected by wind, pressure and temperature.

However it indicates that the frequency dilatation coefficient is:

- Reduced at large range in the wind direction,
- Maximized in plane of blades.

This type of azimuthal mapping gives first explanation on observed low frequency amplitude modulations with hypothesis on sound radiation of sources located on blades. Following the

literature, these acoustic sources could be modeled as dipole under some assumptions given in airfoil noise research.

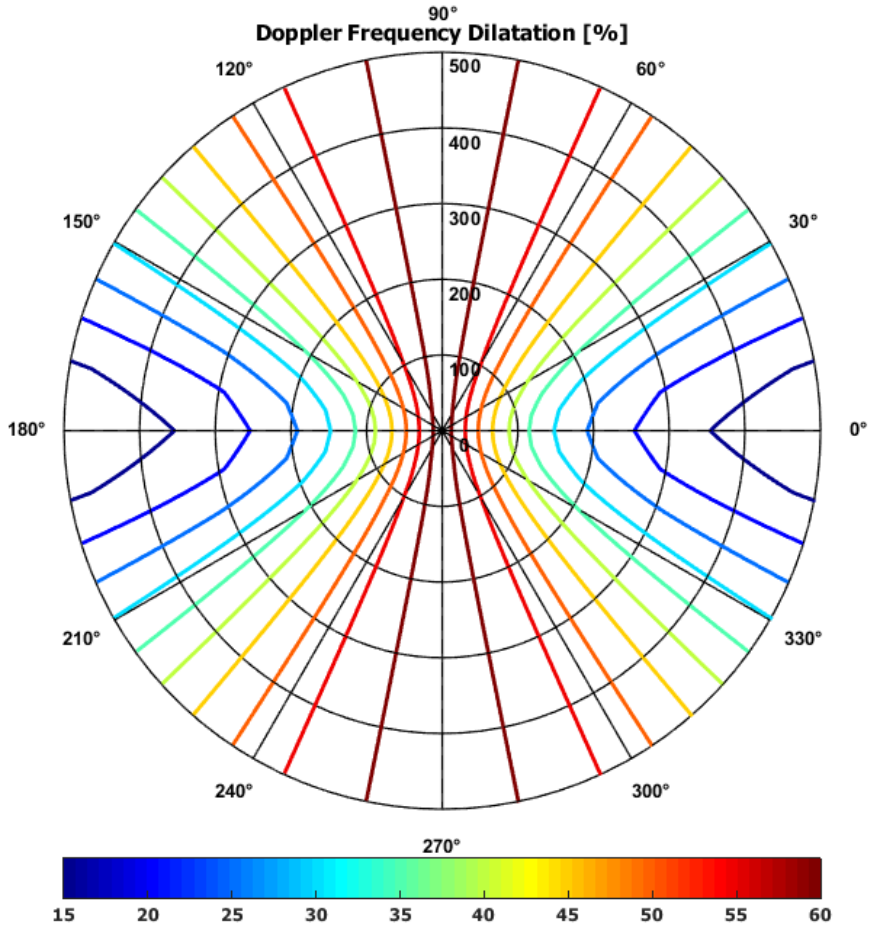

Figure 15: Example of an azimuthal mapping of the frequency dilatation coefficient due to the Doppler Effect for different ranges and and angles of the receiver around the turbine. The plane of the turbine is on the 90°-270° axis.

9. Ongoing work on this experiment data base

In order to answer questions about the modelling and measurement methodology of noise from a wind turbine, the study is based on a detailed analysis of acoustic data collected for weather and wind different seasons of the year. The secondary objective is to determine to what extent the current Swiss rules effectively assess this type of noise. This projects benefits of several identified acoustic signatures which could be useful for a deeper understanding of their generation and useful to evaluate their consideration by the Swiss rules.

The whole noise data base presents different operational parameters of the wind turbine for different climatic conditions when the blades radiate dopplerized frequencies. The undertaken work has permit to identify and to locate tonal noises components in low frequencies between 50 Hz and 125 Hz affected by the Doppler Effect due to the revolution of the blades. These tonal components can now be tracked from wind speed data collected from the wind profiler and/or from the spectral decomposition of the noise collected with one to few sound level meters.

The location of the low frequency tonal sound sources is actually studied considering the climatic effects affecting the Doppler shift. At mid-term it can be envisaged to locate precisely theses low frequency sound sources for the different regimes of the wind i.e. for different power of the wind turbine. By considering the sound radiation of located sound sources on blades and the wind speed data, it can be envisaged in the near future to have a sound synthesis of wind farms equipped with this type of wind turbine.

The statistical analysis of the different period and regime of operation of the wind turbine will then permit to address some reference noise scenarios to be compared with acoustic modelization in regards to wind profiles and meteorological parameters.

10. Conclusions

An experimental characterization of the noise of a wind turbine in Switzerland is described with the aim to answer questions about the generation and collection of low-frequency noise of wind turbines. The time series of noise levels and amplitude modulations in the bands of third octave (50 Hz to 125 Hz) are presented and compared with Doppler frequency shift analyses of recorded sounds. Spectro-temporal sound analysis related to turbine operation parameters presents strong correlations validating the Doppler low-frequency shift hypothesis of three tonal acoustic sources located on the blades.

This campaign characterizes the amplitude modulation depth of low-frequency of the wind turbine and it allows extracting a generic proposal for low-frequency noise mapping at different angular azimuthal locations around the wind turbine.

This study helps to deepen a methodology for campaigns of wind turbine noise measurements and analysis. At a longer term the obtained database will permit to study and to evaluate noise models against field measurements. It will give some recommendations on how to apply them to wind projects and to define the constraints of implementation of wind farms in Switzerland.

11. Acknowledgements

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