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# Perceptual Evaluation of Sound Synthesis of Wind Turbine Noise

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## ABSTRACT

*This study brings together several laboratories with the aim of assessing the health effects of "audible" noise (> 20 Hz) and infrasound (< 20 Hz) emitted by wind turbines. To study loudness and annoyance due to this noise, perceptual tests are planned at the LMA, where a restitution cabin has been developed, specifically designed to diffuse very low frequencies and infrasound. As recording wind turbine noise is only possible at low wind speeds for a good quality sound reproduction, it would be interesting to be able to use sound synthesis of wind turbine noise. From sounds recorded in a wind farm for different meteorological conditions, the corresponding sounds have been synthesized. A physical model synthesis was performed, based on an extended-source aeroacoustic model taking into account propagation over flat ground. Dissimilarity tests including recorded and synthesized sounds enabled a 2D perceptual space to be built. Synthesized and the corresponding recorded sounds are closed together in the perceptual space, but some differences can be perceived, mainly due to difference in amplitude of fluctuation and spectral balance. The analysis of the perceptual space opens up interesting prospects for improving the sound synthesis and its use for future perceptual tests.*

### 1. INTRODUCTION

Precise rules govern the design and the conception of wind turbines to limit their impact on the population, particularly concerning noise exposure. Acoustic pressure is classically measured in the octave bands from 125 to 4 000 Hz. Low-frequency sounds (SBF, 20 to 200 Hz, audible) and infrasound (IF, < 20 Hz, considered inaudible), which are difficult to measure, are not taken into account. Some people complain about annoyance that is sometimes more severe than acoustic measurements would suggest. This annoyance is often described as coming from infrasound (IF), even though the acoustic pressure of the IF emitted is below perception thresholds. However, the inaudibility of infrasound does not rule out an effect on the inner ear or central nervous system.

The present study is part of a larger project (RIBEoIH, Research on the Impacts of Wind Turbine Noise on Humans) whose objectives are to evaluate the health effects of noise, particularly SBFs and IFs, emitted by wind turbines, to gain a better understanding of the auditory mechanisms associated with the perception of IFs and SBFs and their link with annoyance, and to gain a better understanding of the effects of IFs on the inner ear or central nervous system, which may explain certain symptoms sometimes described by subjects exposed to IFs and who complain about them.

In the RIBEoIH project, it is planned to measure annoyance due to wind turbine noise using perceptual tests run into the laboratory. These perceptual tests will be carried out at the LMA, where a booth has been developed specifically to reproduce very low frequencies and infrasounds. Since the recording of wind turbine noise is only possible at low wind speeds at the microphone (in order to avoid wind noise on the microphone), we would like to use sound synthesis of wind turbine noise to design signals that reproduce different conditions of interest (weather and turbine operating regime).

Synthesis of wind turbine noise has been developed by the laboratory IMSIA [1], but before to use these sounds in a test dealing with annoyance assessment, it is essential to evaluate the synthesis to determine whether the sounds actually represent the recorded sounds.

The objective of our study was to reveal perceptual space of wind turbine noise, synthesized and recorded, in order to explore the perceptual dimensions of wind turbine

noise, to highlight the (dis)similarity between synthesis and recorded sounds, and to explain any eventual dissimilarities found.

## 2. SOUNDS AND REPRODUCING SYSTEM

### 2.1. Recordings

Recordings were extracted from a data base from the PIBE project ([2], <https://www.anr-pibe.com/>). The wind farm was composed of 8 wind turbines of 3 MW each. The campaign consisted in storing 100ms sound pressure levels and acoustic spectra, as well as 2 min audio samples periodically recorded. In the present work, we will be focused on one point of recording (out of 5), at 677m from the closest wind turbine. Recordings were extracted from a period from June to July 2020.

### 2.2. Synthesis

The physics-based synthesis of wind turbine is described in [1]. It is based on an extended-source aeroacoustic model taking into account propagation on flat ground. Tonal noise and background noise are not currently considered in the model.

### 2.3. Reproducing system

The sounds were played on a special system built to reproduce spectra from infrasonic frequencies up to 3 kHz.

The system is composed of 32 subwoofers Electrovoice ELX 118 of 18" modified in enclosed loudspeakers (for frequencies below 30 Hz), 40 bass loudspeakers Beyma 10G40 of 10" mounted in a homemade enclosure (for frequencies between 30 Hz and 3 kHz). This set of loudspeakers was mounted in an enclosed, insulated and leakproof 23.8 m<sup>3</sup> (effective volume, 40 m<sup>3</sup> empty) concrete cabin (see *Figure 1*). The high cut-off frequency of the system is high enough to reproduce wind turbine noise spectra which decrease abruptly above 2 kHz (see *Figure 2*). The 32 subwoofers are driven by 8 Lab Gruppen IPD 1200 2-channel amplifiers (for a total of 16 independent channels). The 40 bass loudspeakers are driven by 10 QSC PLX 2502 2-channel amplifiers (for a total of 20 independent channels). Each channel drives a pair of loudspeakers. A PCI express RME HDSPe MADI card connected to a RME ADI 648 multichannel interface permits to control, with an ADAT protocol, a ferrofissh A16 MKII AD/DA which converts the digital signal into an analog signal (and vice-versa) sent to the Lab Gruppen amplifiers and a RME M-32 DA AD/DA which converts the digital signal into an analog signal (and vice-versa) sent to the QSC amplifiers. An ANTELOPE OCX HD clock synchronizes all this equipment.



Figure 1: Room for IS and LF sound restitution

### 3. PERCEPTUAL EXPERIMENTS

#### 3.1. Stimuli

We selected 8-second excerpts from the recordings. Eight seconds were chosen in order to have several period of amplitude modulation in the signal (the modulation frequency varies from about 1 Hz up to a few Hz, depending on wind speed). Four wind conditions were available in the recordings, there are presented in Table 1. For each condition, different excerpts were cut at different time periods, and 2 were selected. The synthesis spectrum lacks frequencies below 20 Hz compared to the recorded sound (see *Figure 2*). Thus, one of the 2 excerpts selected before was low-pass filtered in order to look like the synthesized sound as much as possible in the frequencies below 20 Hz. This was done to check, using the dissimilarity test, whether the lower energy below 20 Hz gives rise to perceptible differences. In total, 16 excerpts were used in the experiment. The naming of the sound files is presented in Table 1.

Table 1: Sounds used in the experiment. The original recorded sounds are named  $C_i S_x \text{Ref}$  and the synthesized sound are named  $\text{ref}C_i$  where  $i$  refers to a wind condition and  $x$  to the number of the selected excerpt.

Stimulus		Wind speed	Wind direction	Wind shear exponent
C4_S2_Ref	recording	10 m/s	67° (upwind)	0.29
C4_S3_Ref	recording	10 m/s	67° (upwind)	0.29
C4_S3_LM	recording	10 m/s	67° (upwind)	0.29
refC4	synthesis	10 m/s	67° (upwind)	0.29
C7_S1_Ref	recording	7 m/s	72° (upwind)	0.38
C7_S2_Ref	recording	7 m/s	72° (upwind)	0.38
C7_S1_LM	recording	7 m/s	72° (upwind)	0.38
refC7	synthesis	7 m/s	72°(upwind)	0.38
C9_S1_Ref	recording	8 m/s	131° (downwind)	0.34
C9_S2_Ref	recording	8 m/s	131° (downwind)	0.34
C9_S1_LM	recording	8 m/s	131° (downwind)	0.34
refC9	synthesis	8 m/s	131° (downwind)	0.34
C11_S1_Ref	recording	7 m/s	161° (downwind)	0.32
C11_S2_Ref	recording	7 m/s	161° (downwind)	0.32
C11_S1_LM	recording	7 m/s	161° (downwind)	0.32
refC11	synthesis	7 m/s	161° (downwind)	0.32

The stimuli were coded on 24 bits and sampled at 48 kHz. They were played at their actual level: level during the recording and level given by the synthesis. The reproducing system was calibrated with a GRAS 46AN microphone ( $\pm 1$  dB from 1 Hz to 10 kHz) placed at the position of the center of the head of the listener without him/her and a pistonphone Brüel&Kjaer 4231. The levels were also checked at the position of each ear with the same microphone. The differences between the two ears were less than 1dB and the levels corresponded to the actual levels observed during the recording period.

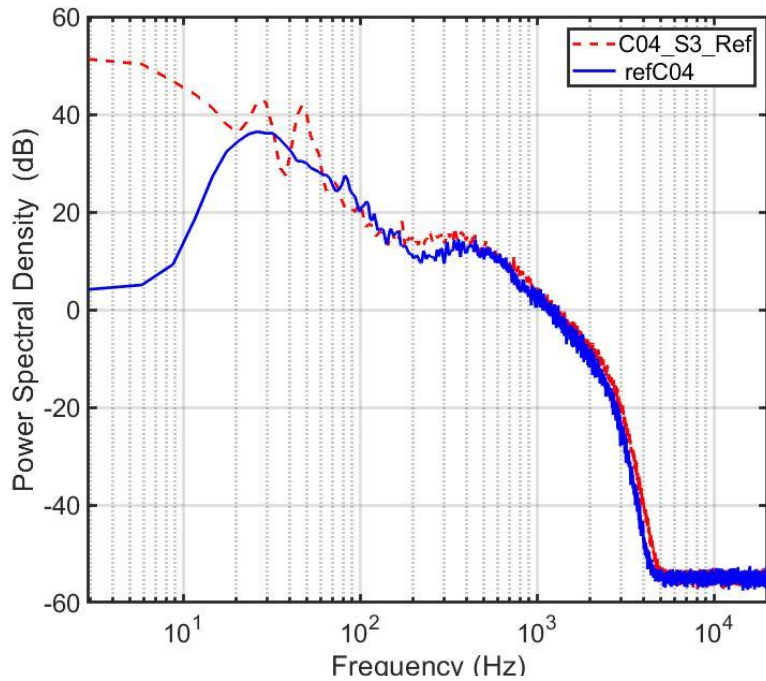


Figure 2: Spectra of the recorded sound C04\_S3\_Ref compared to the corresponding synthesis refC04 (cf. Table 1)

### 3.2. Method

The 16 stimuli were compared in pairs. The task of the listener was to evaluate the dissimilarity between the 2 sounds of the pair on a continuous scale from 0 (very similar) to 10 (very dissimilar). The experiment began by listening to all the sounds. Sixteen buttons were displayed on a screen in front of the listener. Clicking on a button caused a sound to be played. The sounds were randomly assigned to each button. The participant had to listen to each sound at least once before starting the main test. The aim of this preliminary experiment was to give the participants an idea of the extent of the differences between the sounds of the corpus, so that they could use the dissimilarity scale in its entirety during the main test. In the main test, 120 pairs of sounds ( $16 \cdot 15 / 2$ ) were presented randomly. The order of the sounds in the pair was also chosen at random. Only one order was presented, but it differed from one participant to the next one. A trial started by playing the pair, the participant had to listen to both sounds, then they could evaluate the dissimilarity or listen again to one or both sounds of the pair. The experiment lasted about one hour.

Twenty-one participants (7 women), from 22 to 60 years old (mean  $\sim 35$  years), took part in the experiment. They all had a normal hearing (audiometric threshold  $< 20$  dB HL from 125 Hz to 8 kHz). Fourteen participants had a profession related to acoustics. Participants were paid for their participation.

### 3.3. Results

The experiment makes it possible to build a dissimilarity matrix for each participant. An INDSCAL multidimension analysis was done on the dissimilarity matrices. A two-dimension solution was found to be most appropriate after analysis of stress-screw elbow and confidence ellipsoids (ellipses representing the 95% confidence intervals for stimuli coordinates [3]). *Figure 3* shows the relative location of the sounds in this two-dimension space with the corresponding confidence ellipsoids.

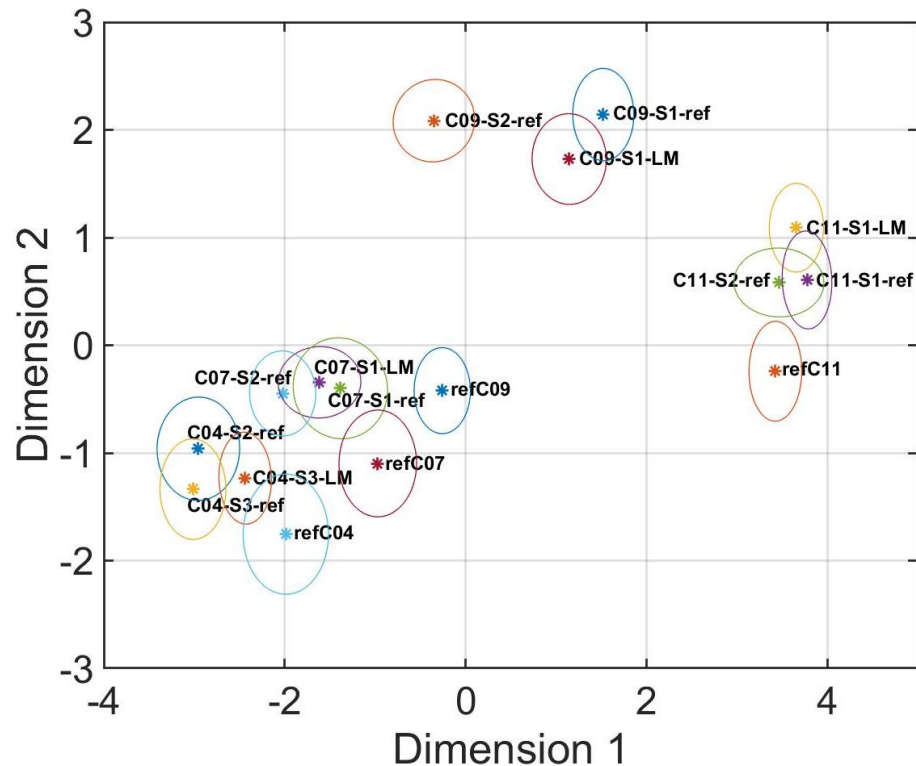


Figure 3: Perceptual space of wind turbine noises (recorded and synthesized), with ellipses representing the 95% confidence intervals for stimuli coordinates.

Listening to the sounds on each dimension allowed us to interpret the dimensions from a perceptual point of view.

Dimension 1 is related to loudness, with loud sounds on the left of the dimension and soft sounds on the right. Surprisingly, dimension 1 is also associated with two other percepts: modulation amplitude and spectral balance. From the left to the right of the dimension, modulation goes from deep to flat and spectral balance from bass to treble.

Dimension 2 is also associated to a percept related to spectrum. As the dimension increases, sounds lose very low frequencies, especially to the left of the figure. In addition, a frequency emergence appears at high frequency and is strongest at the top of the dimension.

We also looked for correlation between the dimension and acoustical/psychoacoustical indices. The indices were calculated using Artemis software (Head Acoustics). Correlations are reported in *Table 2*.

Dimension 1 is highly correlated (negatively) with Sound Pressure Level and loudness. It is also correlated with SCG, sharpness and to fluctuation strength. These correlations confirm the previous auditory analyses of dimension 1. Surprisingly, it is also negatively correlated with tonal component in Bark 1 (frequencies lower than 100 Hz) and energy in Barks 8 to 10 (770 to 1300 Hz).

Dimension 2 is negatively correlated with tonal component in Bark 1 (TETC\_1-1), confirming the previous auditory analyses. It is also negatively correlated with energy in Barks 8 to 10 (TETC\_8-10), with level and loudness indices and with sharpness which was not obvious when listening to dimension 2. Dimension 2 is also correlated with level and loudness, which was also not obvious when listening to dimension 2.

It should be noted that dimensions are correlated together ( $r=0.62$ ;  $p<0.05$ ), due to level (and loudness). Using partial correlations with a control of level (or loudness), the two dimensions are not significantly correlated. With the partial correlation analysis, it was observed that dimension 1 remains significantly correlated with sharpness and CGS, and dimension 2 with TETC\_1-1 and TETC\_8-10, which is more in line with what observed when listening to the sounds.

Table 2: Coefficient of correlation between dimensions and acoustical/psychoacoustical indices. LAmean: mean Sound Pressure Level in dBA; Log10(Nmean): logarithm of the mean Loudness; Smean: mean of the sharpness; Fmean: mean Fluctuation Strength; Rmean: mean Roughness; SCG : Spectral Center of Gravity; TETC\_1-1: tonal component in Bark 1; TETC\_8-10: energy in Barks 8 to 10.  $P < 0.05$  are indicated by \*.

	Dimension 1	Dimension 2
LAmean	-,99 *	-,65 *
Log10(Nmean)	-,996 *	-,59 *
Smean	,996 *	,60 *
Fmean	-,50 *	-,36
Rmean	,1	-,10
SCG	,92 *	,46
TETC_1-1	-0.96*	-0.54*
TETC_8-10	-0.97*	-0.51*

We will now focus our result analysis on the differences between synthesized and recorded sounds. All synthesized sounds are perceived differently from the corresponding recorded sounds, as shown in Figure 3 with a poor overlap of ellipsoids. But we can also see clusters around each condition: the synthesis is always closer to the corresponding recordings than to those of the other conditions, except for condition C09, where the synthesized sound, refC09, is quite far from the recordings. As indicated by its position on dimension 2, it differs from the recorded ones in having more pronounced low frequencies.

In all conditions, the synthesized sounds are less modulated than the recordings. This is in line with their positions on dimension 1 for C04 and C07, but not for C09 and C11. A specific listening of condition C04 revealed also that a low frequency component is missing compared to the recordings. This is not consistent with our analysis of dimension 2. In condition C11, a specific listening revealed that the synthesis has a low frequency component not present in the recordings, but is also higher-pitched and louder. This is also not in line with our analysis of dimension 2, in which the synthesized sound is different from the recorded sounds.

#### 4. CONCLUSIONS AND PERSPECTIVES

The purpose of this study was to evaluate wind turbine noise synthesis from a perceptual point of view. The method, which uses multidimensional scaling on dissimilarity matrices, allowed us to build a perceptual space of recorded and synthesized wind turbine sounds. We found that, for 3 out of 4 conditions, the syntheses are closed to the recordings, but they can be differentiated. In one condition, the synthesized sound is quite far from the recordings.

Synthesized and recorded sound are differentiated mainly by modulation and spectral balance. Yet, the fact that a given dimension is linked to several elementary sensations is surprising and may hint towards a perceptual space that has more than 2 dimensions. However, to highlight more dimensions the number of stimuli should be increased but given the pairwise comparison method used this would have led to even longer experiment duration.

The pairwise comparison method might also be the very reason why listeners were able to detect dissimilarities between recording and synthesis as this method leads listeners to perform a very precise comparison of the stimuli present in a pair. Together with the fact that 14 out of 21 listeners were sound specialists brings the question of the precision we are looking for. The aim for the RIBEoIH project is to figure out whether the synthesis can be used



in placed of recordings to assess annoyance in laboratory conditions in such a way we are not restricted by weather conditions preventing good quality recordings. Even though the results presented here show there is perceived differences between them, syntheses and recordings are still clustered together highlighting they do sound alike.

To further asses if we could use synthesis as attended, another measure of dissimilarity involving more stimuli and a majority of non-expert listeners is planned.

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