



Auralization of outdoor fan noise in shielded areas

Ignacio GARCÍA MERINO¹; Krister LARSSON²

SP Technical Research Institute of Sweden

ABSTRACT

In a situation where traffic, railway or aircraft noise sources are not present, as it happens in shielded areas, other sources might become relevant in terms of annoyance. This is the case of typical turbomachinery elements, such as fans, compressors or turbines, where sound is generated aerodynamically. As a part of the Sonorus project, where all noise sources in urban environments are considered, the goal of this research is to develop an auralization tool that generates a time domain signal depending on the fan working conditions and the propagation scenario. In this paper, a computational aero-acoustics solver is used to simulate the flow field generated by an axial fan, and the acoustic field is calculated using the Ffowcs-Williams and Hawkings method. The information contained in this acoustic field is used to generate an audio signal for auralization purposes. The model results are evaluated by comparisons with recordings and measurements.

Keywords: Auralization, fan noise, quiet areas, aero-acoustics, sound synthesis.

1. INTRODUCTION

The Directive 2002/49/EC for the assessment and management of environmental noise (1) seeks, among other objectives, to preserve the sound quality in the different areas of human activity. This document also classifies the different kinds of sources which can affect humans into four categories: road traffic, aircraft, railway and industrial, dedicating specific Directives (2, 3, 4, 5) to each of them.

Following this classification, the multidisciplinary project Sonorus studies the generation and propagation of the noise generated by these sources in urban environments by means of auralization, as it is a more complete way to evaluate noise perception and annoyance. The outcome is a time domain signal that simulates how a receiver would actually hear a certain sound generated in a given scenario.

Such scenarios are, in this case, quiet urban areas, which use building orientation, closed housing blocks or any other kind of shield to protect spaces where human exposure to noise should be especially avoided (6). Hence, these areas are less exposed to traffic road, railway and aircraft noise, and this is the situation where aerodynamically generated noise sources like the previously mentioned ones, might become annoying.

This paper shows the comparison between the spectra of recorded sounds from a real axial fan under laboratory conditions and the calculated spectrum of a model of the same fan, obtained through a hybrid approach of computational fluid dynamics (CFD) and computational aero-acoustics (CAA). Design, meshing and solving tasks were carried out with the commercial software package Ansys Fluent, while the frequency and time domain signals were analyzed and synthesized with Matlab.

2. ACOUSTIC FIELD PREDICTION

2.1 Aero-acoustics

2.1.1 Noise generation mechanisms

Aerodynamic noise is generated when turbomachinery elements produce air or any other fluid circulation by means of rotating solid surfaces. Typical examples of these noise sources are fans, compressors, turbines or rotors, but this paper will focus the attention on the particular case of an axial fan.

Several physical phenomena are involved in the process of turbomachinery noise generation: blade thickness noise generated when the blade displaces fluid mass, blade loading causes steady and

¹ ignacio.garciamerino@sp.se

² krister.larsson@sp.se

unsteady external forces, and unsteady shear stresses result into turbulent noise. These three cases can be classified, respectively into three of the elementary sound source configurations (7), monopole, dipole and quadrupole, whose relevance is discussed in the next section.

2.1.2 Acoustic analogies

The aero-acoustics theory starts with Lighthill's analogy (8), where he assumes two different regions of space: a flow field contained in a region where the sound is generated and a stationary fluid volume where the sound propagates. The flow field is characterized by rewriting the mass and momentum conservation equations into an inhomogeneous wave equation with Lighthill's stress tensor present in the source term (Equation 1) representing quadrupoles associated to momentum transport.

$$\frac{1}{c_0^2} \frac{\partial^2 p'}{\partial t^2} - \frac{\partial^2 p'}{\partial x_i^2} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \quad (1)$$

Where p' is the pressure fluctuation, T_{ij} is Lighthill's stress tensor, an c_0 is the sound speed for the medium.

However, Lighthill's analogy can't be directly applied to a real case of turbomachinery noise generation, as it doesn't consider the surfaces present in the fluid domain. It was first Curle who included the effect of solid boundaries in Lighthill's equation (9), and later Ffowcs-Williams and Hawkings who generalized Curle's method for moving surfaces (10), making thus the aero-acoustics theory applicable to any element that produces sound by blade rotation, like fans or turbines. The Ffowcs-Williams and Hawkings analogy (FW-H hereafter), shown in Equation 2 will be the basis of the calculations performed for this work.

$$\frac{1}{c_0^2} \frac{\partial^2 p'}{\partial t^2} - \frac{\partial^2 p'}{\partial x_i^2} = \frac{\partial^2}{\partial x_i \partial x_j} [T_{ij} H(f)] - \frac{\partial}{\partial x_i} \{ [P_{ij} n_j + \rho u_i (u_n - v_n)] \delta(f) \} - \frac{\partial}{\partial t} \{ [\rho_0 v_n + \rho (u_n - v_n)] \delta(f) \} \quad (2)$$

FW-H adds two new source terms to Lighthill's inhomogeneous wave equation, a monopole and a dipole term, as a consequence of pulsating flow and varying loading forces, respectively, of the surface sources presents in the fluid. The first term in equation 2 is Lighthill's stress tensor, which can be neglected if assuming a rigid body. $H(f)$ is the Heaviside function, P_{ij} is the compressive stress tensor, n_j is the normal unit vector, u_i and v_i are fluid and surface, respectively, velocity components in x_i direction, u_n and v_n are fluid and surface, respectively, velocity components normal to the surface and $\delta(f)$ is the Dirac delta function. f is a mathematical function that represents the rigid body where $f=0$ on the surface and $f>0$ in the exterior flow region.

The analytical integration of equation 2 under the assumption of free field results in a solution, which will consist of a contribution of monopole and dipole acoustic sources. For calculations of complex geometries, a CFD solver is required.

2.2 Ansys Fluent

The direct calculation of sound pressures in the time domain by solving the Navier-Stokes equations is a complex and computationally expensive task, as it involves the modelling of viscous and turbulence effects. The alternative is to use a hybrid method that combines the computation of surface and fluid velocities from turbulence models and the acoustic analogy concepts described in the previous section. In this way, the near-field flow is calculated and the obtained flow variables are used to evaluate the corresponding surface integrals at the receiver positions, following the FW-H formulation.

This process can be fully implemented with Ansys Fluent, a CFD solver based on the finite volume method which offers dedicated modules for the design, meshing and calculation tasks. Once the physical parameters are set as an input to Ansys Fluent, the outcome is a short sound pressure signal in the time domain whose spectral information will be extracted for synthesis purposes.

2.2.1 Setup

The design of the fan included in the CFD model is the same as the test candidate described in section 4. A five-blade axial fan with a low Mach number, whose dimensions and physical parameters are used as input to Ansys to create a 3D structure. Since Ansys Fluent is a finite volume solver, this structure must be meshed in order to proceed to the solution. Rotational symmetry is assumed and only one blade was designed and meshed, although the whole fan can be displayed, as shown in Figure 1. The number of elements in the mesh was 472.000.

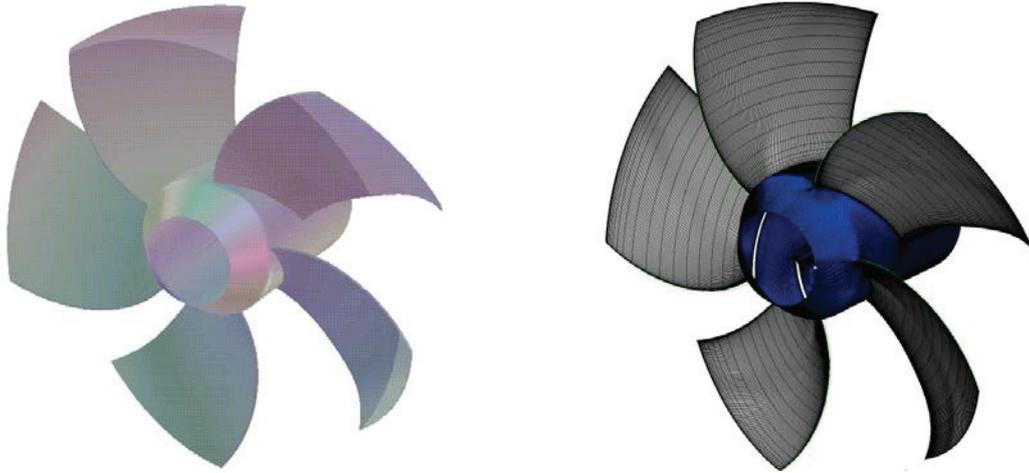


Figure 1 – Fan design and mesh

As mentioned above, the hybrid method requires a turbulence model to generate the flow field values. There are several models available, k-omega, k-epsilon or Shear Stress Transport (SST), although particular cases like acoustics or combustion require higher-end models like Large Eddy Simulation (LES) or Detached Eddy Simulation (DES). These last two were used, choosing eventually LES due to a faster and more stable convergence when calculating transient solutions.

The desired output of Ansys Fluent is a short sound pressure signal containing information in the audible spectrum, that is, up to 22 kHz. which involves a 44.1 kHz. sampling frequency and a 2.267e-5 s. time step size. Such a small value would imply an unaffordable amount of time steps in order to generate one single complete revolution, so an alternative approach is needed.

The relevant spectral content is found in the low frequency part of the spectrum, where the first harmonics and the turbulent broadband noise are located, and where the higher accuracy is required. Three different simulations with different time step sizes were performed: Simulation 1 with a short time step which covers the audible spectrum with a very low frequency resolution; simulation 2, covering up to 5 kHz and a finer frequency resolution, and simulation 3, with the highest frequency resolution to detect accurately the spectral content up to 1 kHz. The parameters of the three calculations are displayed in Table 1 in an increasing order of accuracy.

Table 1 – Calculation parameters

Simulation	Sampling frequency, kHz	Time step size, s	Bandwidth, kHz	Time steps number	Simulated time, s
1	44.1	2.267e-5	22.05	500	0.001133
2	10	0.0001	5	500	0.05
3	2	0.0005	1	500	0.25

2.2.2 Numerical results

Due to the limited number of time steps, a small time step size results in low frequency resolution. This is the reason why Simulation 1 is not useful to extract tonal components. Simulation 2 calculates the spectral content up to 5 kHz, shown in Figure 2, where four sound pressure signals are calculated for four microphone positions 5 m from the fan, but at four different angles: 30, 45, 60 and 75 degrees from the axis of flow.

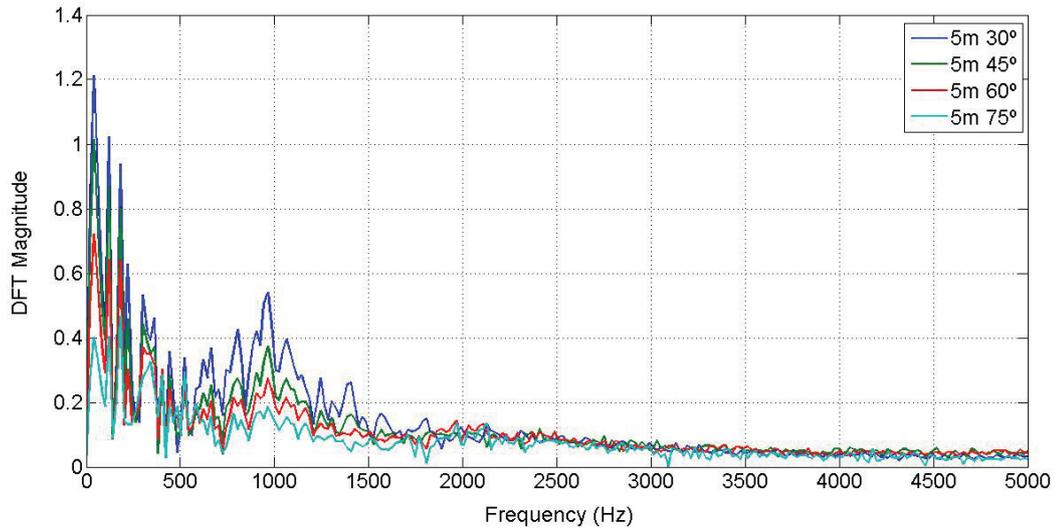


Figure 2 – Spectra of acoustic predictions up to 5 kHz

In this case the relevant spectral content is located under 1500 Hz, where the frequency resolution is not fine enough to extract reliable information. Simulation 3 calculates the spectral content up to 1 kHz, as shown in Figure 3.

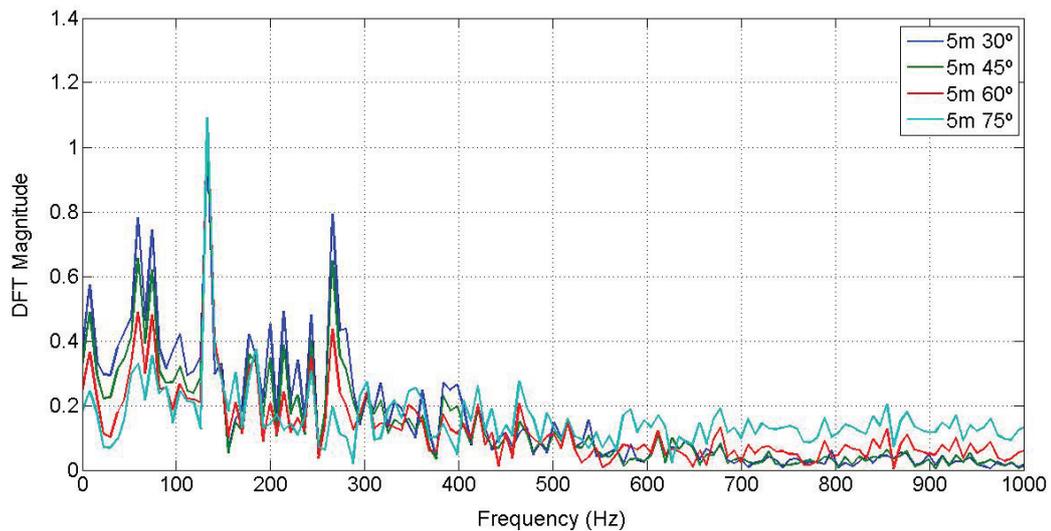


Figure 3 – Spectra of acoustic predictions up to 1 kHz

In this simulation, the frequency resolution is fine enough to capture the first two harmonics located at 132 Hz and 264 Hz for three of the four simulated angles. Since the highest values are obtained in this part of the spectrum, this is the set of data which will be used for the synthesis in the next section.

3. SYNTHESIS MODEL

The acoustic field prediction provided by Ansys Fluent needs to be analyzed and re-synthesized, since the generated sound pressure signal is just a few revolutions long, due to computational costs. In order to achieve that, a spectral model based on the separate generation of tonal and broadband components is used (11).

The calculated sound pressures already calculated correspond to the steady-state working conditions of the axial fan. This type of signals shows a strong tonal behavior at the blade passing frequency and its harmonics, and also stochastic noise spread over a broad frequency range, especially relevant at low frequencies.

Due to this separation between sinusoidal and broadband components, the Spectral Modelling Synthesis technique (12) is an appropriate tool to synthesize this kind of sounds.

$$s(t) = \sum_{i=1}^K A_i(t) \sin(2\pi f_i t + \varphi_i) + w(t) \quad (3)$$

Equation 3 shows the different components of the synthesized signal: K different tones with a time-varying amplitude, located at the integer multiples of the blade passing frequency, plus a stochastic signal representing the broadband noise. These two different components will be synthesized separately, considering only frequency and a constant-over-time amplitude for the sinusoids generation.

3.1.1 Broadband noise

This component depends on the turbulent flow generated by the fan rotation, depending thus on its physical parameters (dimensions, rotational speed, mass flow, etc.). The spectral shape is assumed constant over time when the fan reaches the steady-state working conditions, so the Fourier transform of the short time domain signal calculated by Ansys Fluent is used to estimate the shape of the broadband noise spectrum.

The technique chosen to split the broadband noise from the tonal components is the Two-Pass Split Window (TPSW). This method was developed to remove background noise from frequency domain signals, but it can work in the other direction and remove peaky components from a given spectrum. It consists of a gapped window, a smooth filter and a non-linear modification in between them (13). Once applied, it provides with a spectrum free of high level narrow components, as shown in Figure 4, where only the signal obtained at 30° is displayed.

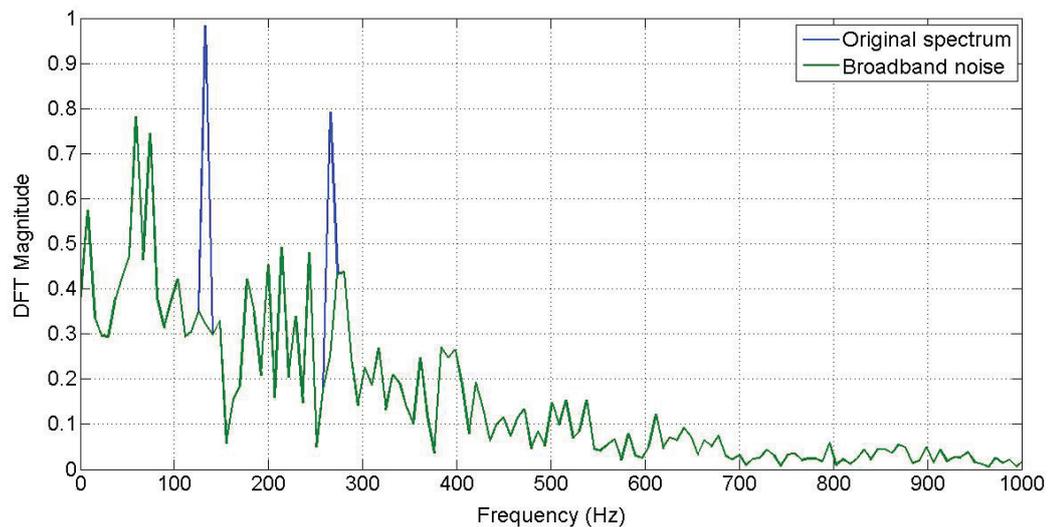


Figure 4 – Broadband noise spectrum for the 30° case

The output of the TPSW filter is a frequency domain signal with the same bandwidth as the input, and with no presence of peaky components. The spectrum has a low frequency resolution due to the limited time steps calculated by Ansys, hence the number of elements shall be increased in order to generate an audio signal with a desired length.

3.1.2 Tonal components

The pure tones removed in the previous step can be obtained by subtracting the broadband noise estimation from the spectrum of Ansys Fluent output. This subtraction results in a frequency domain signal consisting ideally of pure tones located at the multiples of the blade passage frequency, as shown in Figure 5 for the signal obtained at 30°.

The peak removal/detection algorithm can detect narrow peaks as long as their value is higher than the adjacent ones. The algorithm detects the first two harmonics (132 Hz and 264 Hz) for the 30°, 45° and 60°, but the second harmonic is not detected at the 75° position.

The magnitudes and positions of these peaks will be used as input parameters in the sinusoid generator that will synthesize the tonal components.

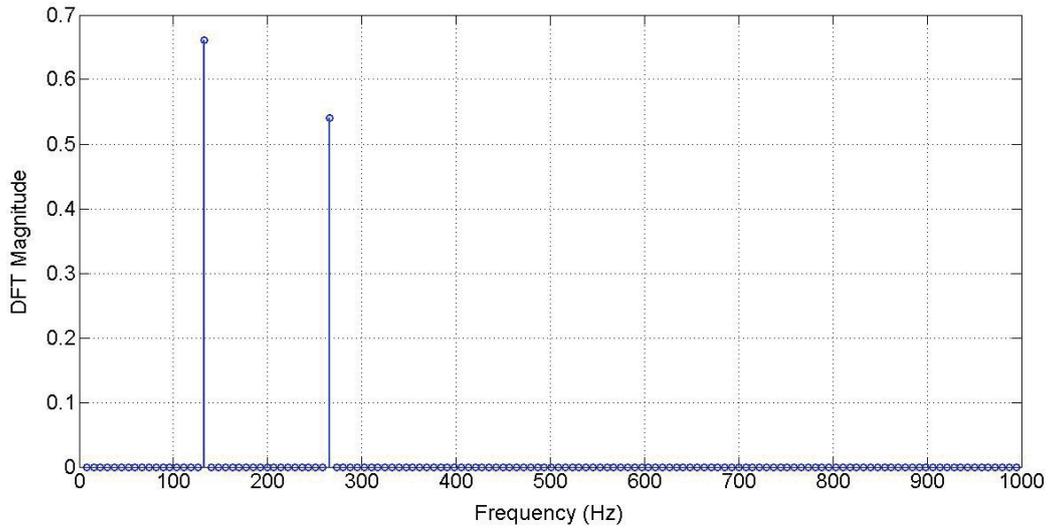


Figure 5 – Tonal components for the 30° case

3.2 Results

The synthesized signal is the result of the superposition of sinusoids and noise, and its spectrum is shown in Figure 3 together with the Fourier transform of the time domain signal computed by Ansys Fluent. The re-synthesized signal is 10 seconds long.

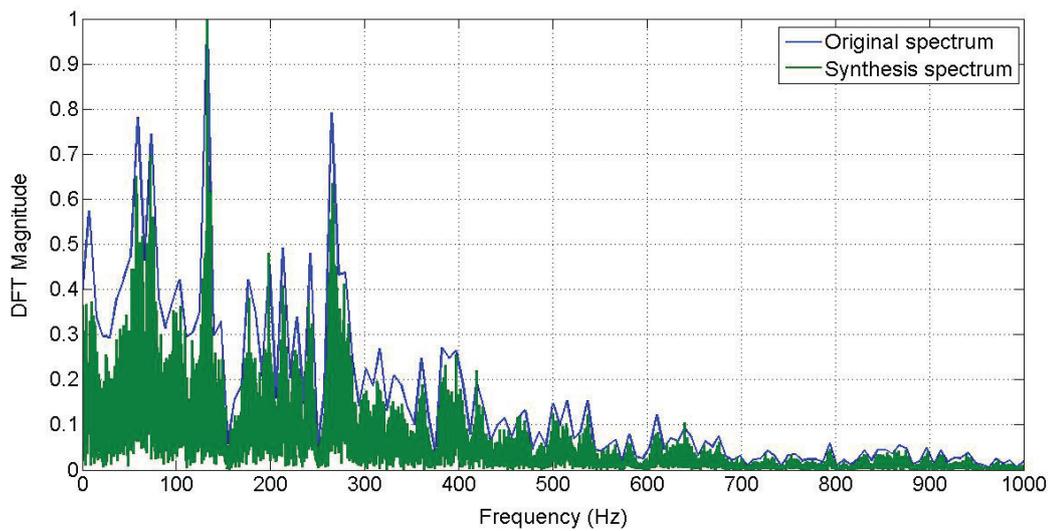


Figure 6 – Comparison of prediction and re-synthesis spectra for the 30° case

4. RECORDINGS

The design included in the acoustic prediction model corresponds to a real fan used as a test object to be compared with numerical results. It is an axial cooling fan with five blades and 0.65 kg/s. air flow rate when rotating at 1584 rpm. The tip diameter is 30 cm. and the fan is covered with a grid basket in the flow direction, as seen in Figure 7.

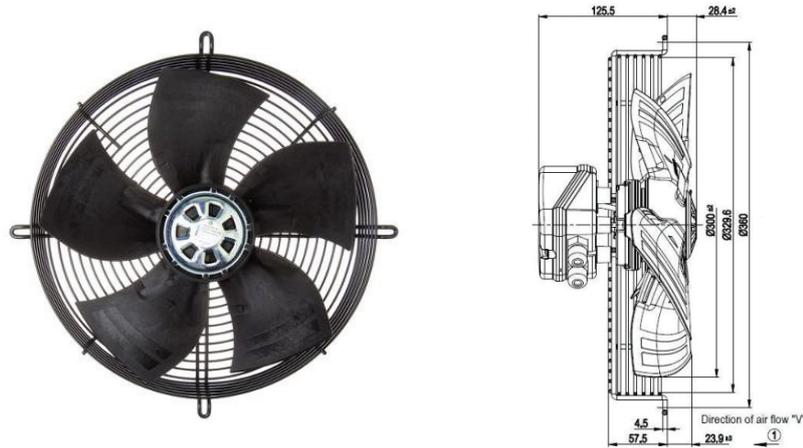


Figure 7 – Fan design and dimensions

4.1 Setup

The sound generated by the fan when rotating at 1584 rpm was recorded in the anechoic room of Chalmers University of Technology in Gothenburg, Sweden. This way, the assumption of free field mentioned in section 2 is fulfilled.

Another assumption was the calculation of sound pressure values for mid and far field receiver positions, hence the microphone was located at the maximum distance allowed by the room, that is, 5 meters. Four different angles from the flow axial direction were used, 30, 45, 60 and 75 degrees in the horizontal plane of the fan, and the sound recordings were 10 seconds long.

Figure 8 shows the mounting of the fan in the anechoic room and the microphone positions. It was hung from wires to prevent a rigid supporting structure from vibrating due to the rotor excitation.

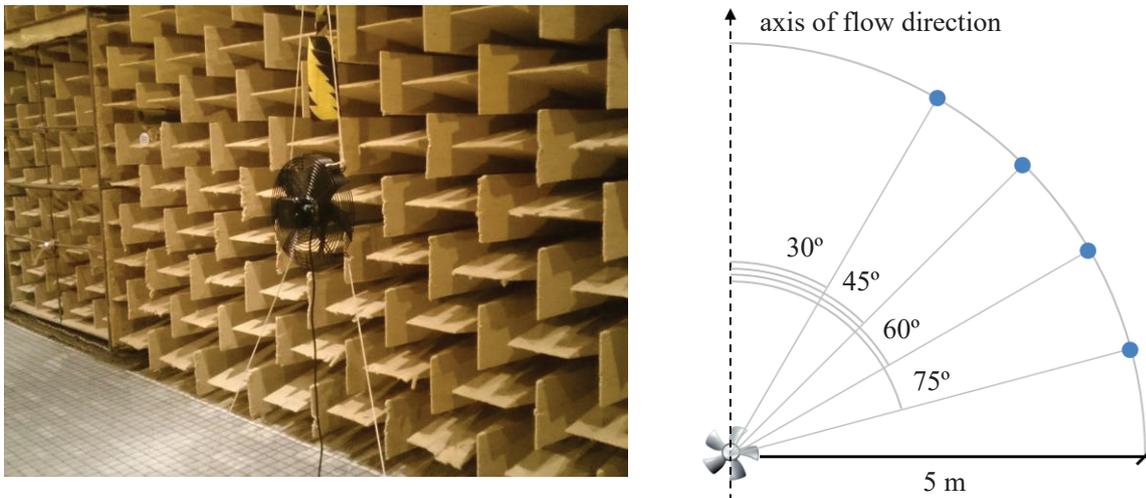


Figure 8 – Mounting and microphone positions

4.2 Experimental results

The spectrum of the recordings is calculated in order to compare the recorded audio signal to the calculated sound pressure signal. Figures 9 and 10 show the spectral content of the signals obtained at the four different microphone positions until 5 kHz and 1 kHz, respectively.

The graphics show how the signal is composed of a broadband component, which decays as the frequency increases, and pure tones located at the integer multiples of the blade passing frequency, being relevant in this case the first three harmonics, 132 Hz, 264 Hz and 396 Hz. There are other tonal components in the low frequency range, being relevant for the peak around 50 Hz, which is a sub-harmonic tone caused by backflow vortices (14).

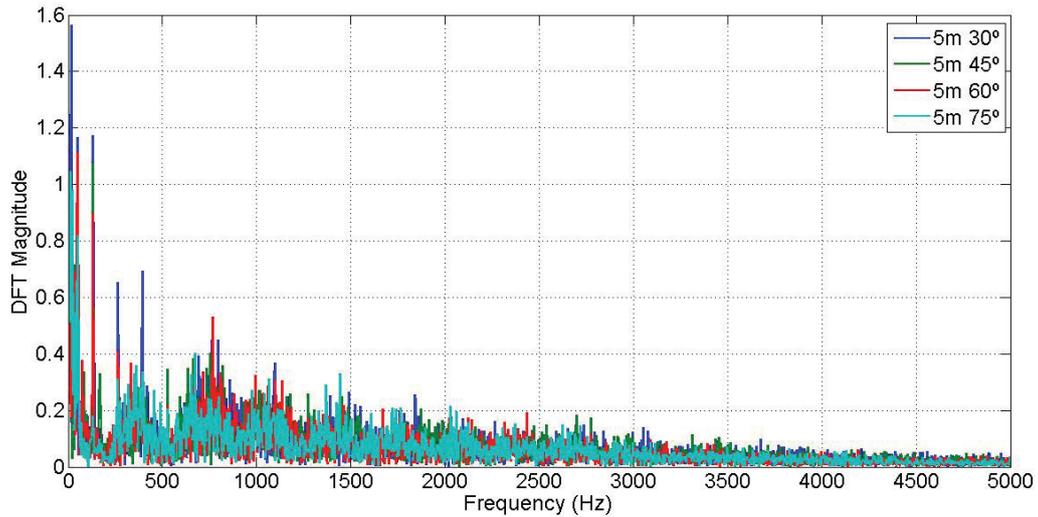


Figure 9 – Spectra up to 5 kHz of the four microphone positions

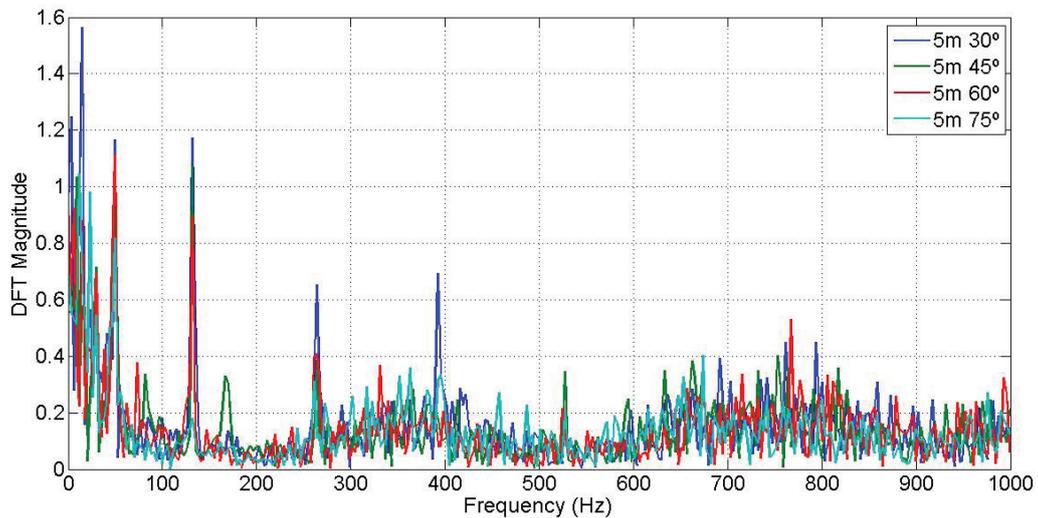


Figure 10 – Spectra up to 1 kHz of the four microphone positions

5. DISCUSSION

The comparison between recorded and synthesized sound is displayed in Figures 11 to 14, where the spectra for the different positions is shown up to 1 kHz. The synthesis model provides similar acoustic predictions for the 30°, 45° and 60° microphone positions, especially when estimating position and magnitude of the harmonics and detecting low frequency components in the audible range, given the short length of the generated signals.

According to the predicted values for the 75° position, the model doesn't generate accurate solutions for positions away from the flow axis. There are also broadband noise components in the 600 to 1000 Hz range not detected in the simulation.

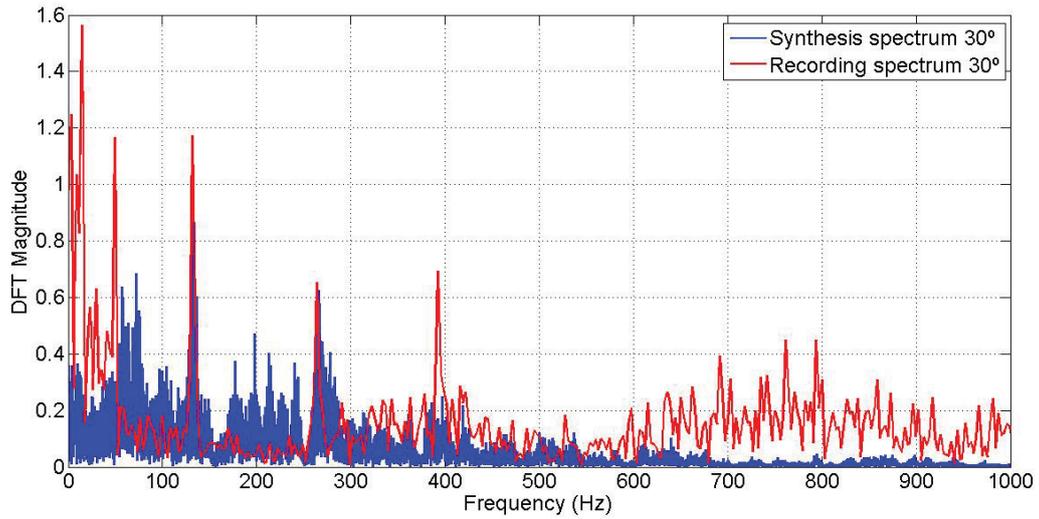


Figure 11 – Spectra comparison for the 30° position

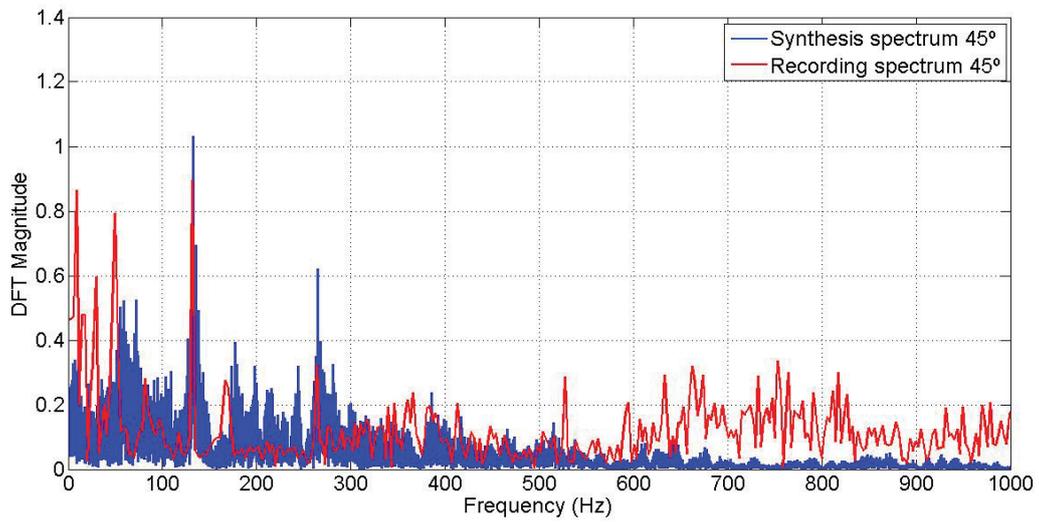


Figure 12 – Spectra comparison for the 45° position

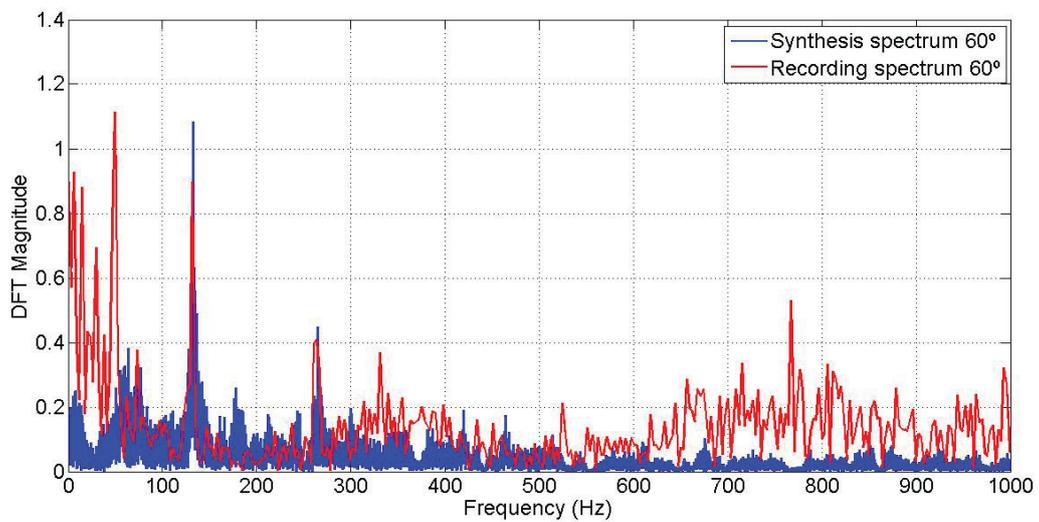


Figure 13 – Spectra comparison for the 60° position

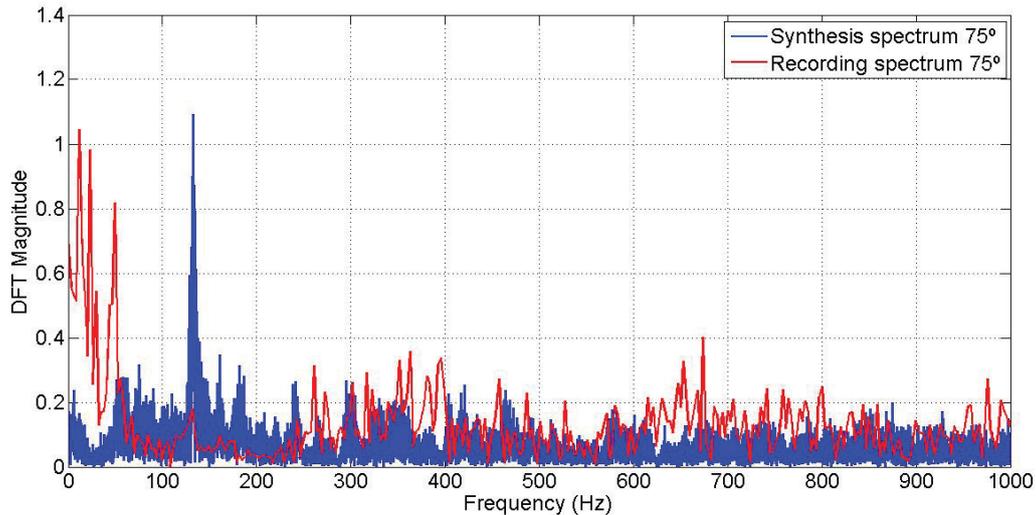


Figure 14 – Spectra comparison for the 75° position

6. CONCLUSIONS

The Ffowcs-Williams & Hawkins analogy is a powerful tool to predict turbomachinery sound. Combined with a CFD solver, it can produce sound pressure signals which contain reliable information about the spectral content of the flow induced noise, which can be manipulated later with a spectral synthesis model to generate an audio file.

However, this process can be improved through finer and optimized meshes and the calculation of a higher number of flow field values. The next steps towards a complete auralization tool include these tasks, and others like directivity analysis, the inclusion of reflecting surfaces in the model, the combination with propagation models, and listening tests.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013 under REA grant agreement number 290110, SONORUS "Urban Sound Planner".

REFERENCES

1. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. Official Journal of the European Communities L 189/12, 18.7.2002.
2. Regulation (EU) No 540/2014 of the European Parliament and of the Council of 16 April 2014 on the sound level of motor vehicles and of replacement silencing systems. Official Journal of the European Union L 158/131, 27.5.2014.
3. Regulation (EU) No 216/2008 of the European Parliament and of the Council of 20 February 2008 on common rules in the field of civil aviation. Official Journal of the European Union L 79/1, 19.3.2008.
4. Directive 2008/57/EC of the European Parliament and of the Council of 17 June 2008 on the interoperability of the rail system within the Community. Official Journal of the European Union L 191/1, 18.7.2008.
5. Directive 2000/14/EC of the European Parliament and of the Council of May 2000 on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors. Official Journal of the European Union L 162, 03.07.2000.
6. Qside project. Good practice guide on quiet areas. EEA Technical report No 4/2014. p. 7-11.
7. Neise W, Michel U. Aerodynamic Noise of Turbomachines. DLR Internal Report 22314-94/B5; 1994. p. 81-103
8. Lighthill, M. J. On sound generated aerodynamically, I General theory. Proceedings of the Royal

- Society of London. Vol. A211, No 1107; 1952. p. 564-587.
9. Curle, N. The influence of solid boundaries upon Aerodynamic Sound. Proceedings of the Royal Society of London. Vol. A231; 1955. p. 505-514.
 10. Ffowcs Williams J.E, Hawkings D.L. Sound generated by turbulence and surfaces in arbitrary motion. Philosophical Transaction of the Royal Society, A 264, No 1151; 1969. p. 321-342.
 11. I. García Merino, K. Larsson: Auralization of Non-traffic Sources in Protected Areas. Forum Acusticum 2014, Krakow
 12. Serra X, Smith J. Spectral modelling synthesis: A sound synthesis/analysis technique based on deterministic and stochastic decomposition. Computer Music Journal, Vol. 14. No. 4; 1990.
 13. Struzinski W.A. A new normalization algorithm for detection systems. Journal of the Acoustical Society of America, 76(6), 1738-1742
 14. Magne S, Moreau S, Berry A. Subharmonic tonal noise from backflow vortices radiated by a low-speed ring fan in uniform inlet flow. The Journal of the Acoustic Society of America, 2015 January 137(1). p. 228-37.