inter noise
2013 | INNSBRUCK | AUSTRIA
15.-18. SEPTEMBER 2013
NOISE CONTROL FOR QUALITY OF LIFE

Visualization of acoustic intensity vector fields using scanning measurement techniques

Daniel Fernández Comesaña[1,2], Emiel Tijs[1], Peter Cats[1] and Douglas Cook[3]

[1] Microflown Technologies,

Tivolilaan 205, Arnhem 6824 BV, the Netherlands

Email: fernandez@microflown.com

[2] Institute of Sound and Vibration Research

University of Southampton, Southampton SO17 1BJ, UK

[3] New York University of Abu Dhabi,

Sama Tower, Abu Dhabi, United Arab Emirates

ABSTRACT

Sound propagation paths are not always well understood mainly because of the complex nature of the source or the environment. A direct method to capture the sound energy flow throughout a room is to measure the three-dimensional sound intensity distribution across space. In the past years, several studies have been carried out using step by step measurements with a three-dimensional intensity probe consisting of a sound pressure transducer and three orthogonal particle velocity sensors. The probe's ability to measure even in highly reverberant environments and its small size are key features required for numerous applications. However, punctual measurements are time-consuming, especially when a large number of measurement positions are evaluated. The use of advanced scanning measurement techniques, such Scan & Paint, allows for the gathering of data across a time stationary sound field in a fast and efficient way, using a single sensor and webcam only. The acoustic signals are acquired manually by moving a probe across a measurement plane whilst filming the event with a camera. In the post-processing stage, the sensor position is extracted and then used for linking a segment of the signal acquired to a certain position of the space. In this manner, the overall measurement time is reduced from hours to minutes. In this paper, the acoustic intensity vector fields of several complex examples are investigated; revealing the acoustic energy flow of several vehicles, a loudspeaker in a room, and also the interaction between an absorbing sample and a reverberant sound field.

Keywords: Sound intensity, scanning measurements, sound visualization.

1. INTRODUCTION

Acoustic energy maps combined with images of the energy flow (derived from direct measurements) are uncommon in acoustic metrology [1]. Traditionally, the analysis of acoustic fields concerns only the distribution of pressure levels (scalar variable). The ability to measure sound intensity has revolutionized the approach to examining many acoustic phenomena. This technique has been applied to various studies, greatly simplifying the research methods.

Visualization of sound intensity may involve depicting various acoustic phenomena, depending on the area of interest. In sound engineering, it may be an acoustic wave power density distribution in space, the wave dissipations or the evaluation of its motion within the medium. For technical acoustics, directional characteristics of industrial sources and the variables connected with reflection, scattering and diffractions on obstacles could prove interesting, which are used to draw maps of the noise levels and to evaluate the effectiveness of anti-noise monitors in industrial premises.

The Scan & Paint scanning methodology has been adapted to be used with a three dimensional sound probe which incorporates three orthogonal particle velocity sensors and a pressure microphone. By scanning the probe across a plane, and by keeping its orientation fixed, the intensity vector field of the evaluated scenario can be acquired.

2. THEORY

A three-dimensional P-U sound intensity probe comprises two fundamentally different transducers: a pressure microphone and particle velocity sensors, also called Microflowns. In the near field there is, by definition, a phase difference between both physical quantities ($\theta_p - \theta_u \neq 0$) [2]. This implies that the instantaneous products of the sound pressure and each orthogonal particle velocity yields to a complex vector: the complex acoustic intensity $\vec{C}$. The imaginary part of this quantity is known as the reactive intensity $\vec{J}$, which is the non-propagating energy. It is hence more common to study acoustic sound fields in terms of the active, or propagating, part of the complex intensity [3], i.e.

$$\vec{I} = \{I_x, I_y, I_z\} = < p\vec{u} >_T = \frac{1}{2}\, Re\{p\vec{u}\} \qquad (1)$$

where $<.>_T$ indicates time averaging, and the latter expression is based on the complex representation of harmonic variables. Since all quantities are measured simultaneously, the calculation of the three dimensional acoustic intensity can be performed directly, without any approximation. This quantity provides directional information about the flow of acoustic energy. In addition, a scalar term can be extracted for visualization purposes by taking the module of the intensity vector, hence

$$|\vec{I}| = \sqrt{\frac{1}{2}\left(Re\{pu_x\}^2 + Re\{pu_y\}^2 + Re\{pu_z\}^2\right)} \qquad (2)$$

Figure 1 shows a schematic representation of the complex and also three dimensional acoustic intensity mentioned above.

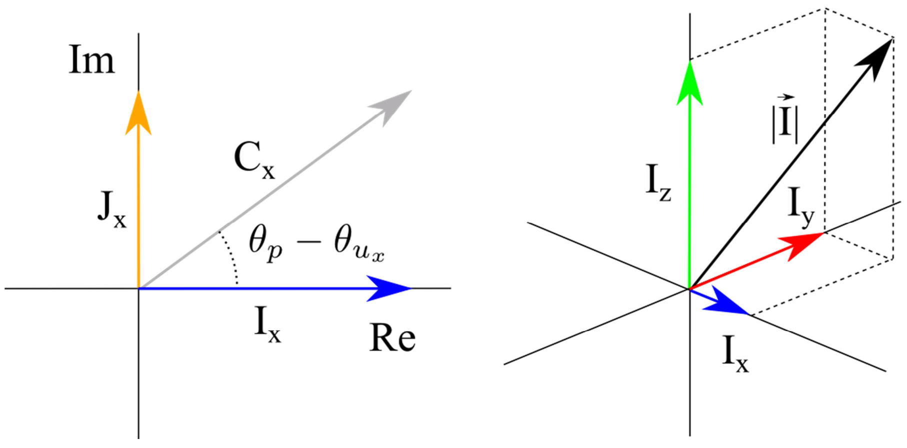

Figure 1 – Schematic representation of the complex acoustic energy in one dimension (left) and the three-dimensional active intensity (right).

Whereas pressure-based measurement methods cannot be used in environments with high levels of background noise or reflections, direct intensity measurements with PU probes are unaffected by the pressure-intensity index (the ratio of sound pressure squared to active intensity) [4,5]. On the other hand, the error of the intensity estimation using PU probes mainly depends upon the reactivity of the sound field (the ratio of reactive to active intensity J/I). If the reactivity is high, as for example in the near field of a source, a small phase mismatch in the transducer's calibration may lead to a considerable error in the intensity estimate. In [6] it was stated that in practical situations the reactive intensity should not exceed the active intensity with more than 5 dB, which correspond to a ±72 degrees phase difference between sound pressure and particle velocity. Although active intensity may be biased in a highly reactive field, the phase difference between pressure and particle velocity can be measured accurately. Therefore, it is still possible to detect which measurement positions are exposed to a high reactivity.

3. MEASUREMENT METHODOLOGY: SCAN & PAINT

A method called 'Scan & Paint' is used to quickly visualize a slice of a sound field with a high spatial resolution. A detailed description of the method can be found in [7,8]. The acoustic signals of the sound field are acquired by manually moving a single transducer across a measurement plane whilst filming the event with a camera. In the post-processing stage, the sensor position is extracted by applying automatic color detection to each frame of the video. The recording can then be split into multiple segments by applying a spatial grid algorithm [9]. Each signal fragment will be linked to a grid cell, depending upon the position of the probe at that particular time. Spectral variations across the space are computed by analyzing the signal segments of each grid section.

In this paper, the Scan & Paint method is used for the first time to acquire 3D intensity measurements of several noise sources. The results of these tests are visualized with normalized intensity vectors (Equation 1) and color maps of the active intensity level (Equation 2).

4. EXPERIMENTAL EVALUATION

In this section, several experimental cases are evaluated with the proposed technique. A picture of the setup is overlaid with both measured vector field and colormap of the acoustic intensity norm. As mentioned above, an intensity measurement is only valid if the reactivity is not too high. Therefore, all results from positions where the measured phase exceeds ±72 degrees are omitted.

4.1 Loudspeaker in a conventional room

The radiation from a loudspeaker cabinet in a normal room was investigated. The display of acoustic intensity allows us to understand how the acoustic field is excited, potentially helping to improve the source design or positioning. Figure 3 presents the experimental result obtained at a third octave frequency band of 4 kHz.

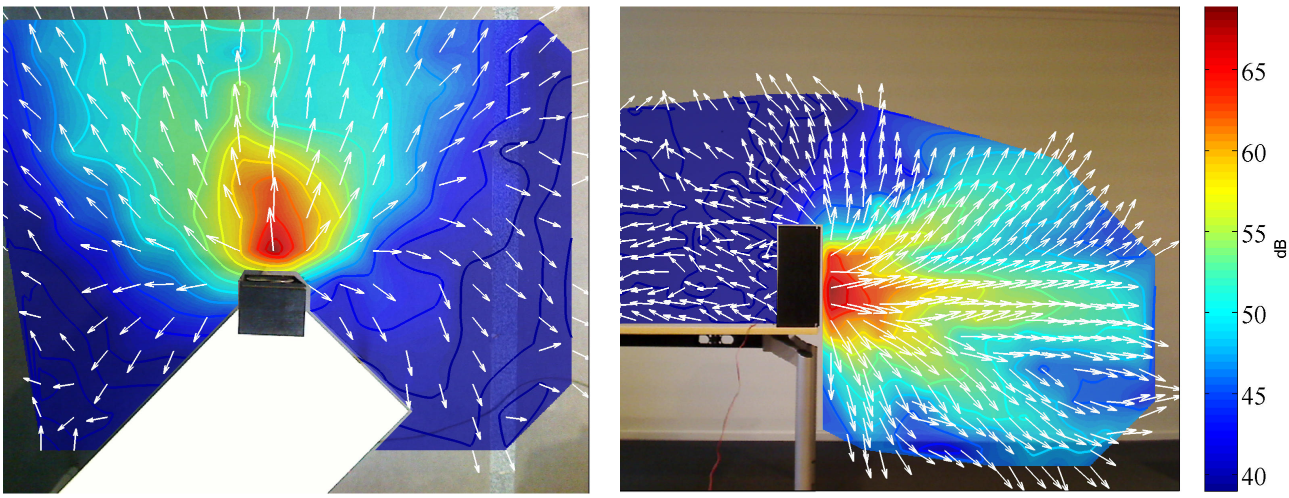

Figure 2 – Acoustic intensity vector field of a loudspeaker at 4 kHz. Top view (left), and side view (right).

4.2 Vehicle exterior noise

Standardized exterior noise tests are commonly used to determine the quality of vehicles being developed. The combination of static tests and on-road measurements provides an essential key to undertaking a successful refinement process. Beamforming techniques, using phased microphone arrays, are one of the most common tools for localizing and quantifying noise sources across the vehicle body. However, the use of such devices can result in a series of well-known disadvantages regarding, for instance, their very high cost or transducer calibration problems. The direct sound field mapping using sound intensity techniques offers an alternative approach to assess vehicle exterior noise in an efficient way.

With the latter technique, the sound field produced by a static Nissan 350Z has been evaluated in an outdoors open area. The noise radiation from the front and the back of the vehicle was mapped by re-positioning the camera twice. The camera itself was positioned at a height of 3 meters. Figure 3 presents the results obtained at 250 Hz and 1260 Hz. As shown, the intake and exhaust systems are the main noise sources at lower frequencies, situated on the left side of the vehicle body. Furthermore, a symmetric pattern can be seen at the front of the vehicle at higher frequencies; the ventilation areas of the engine bay act as the main radiation sources.

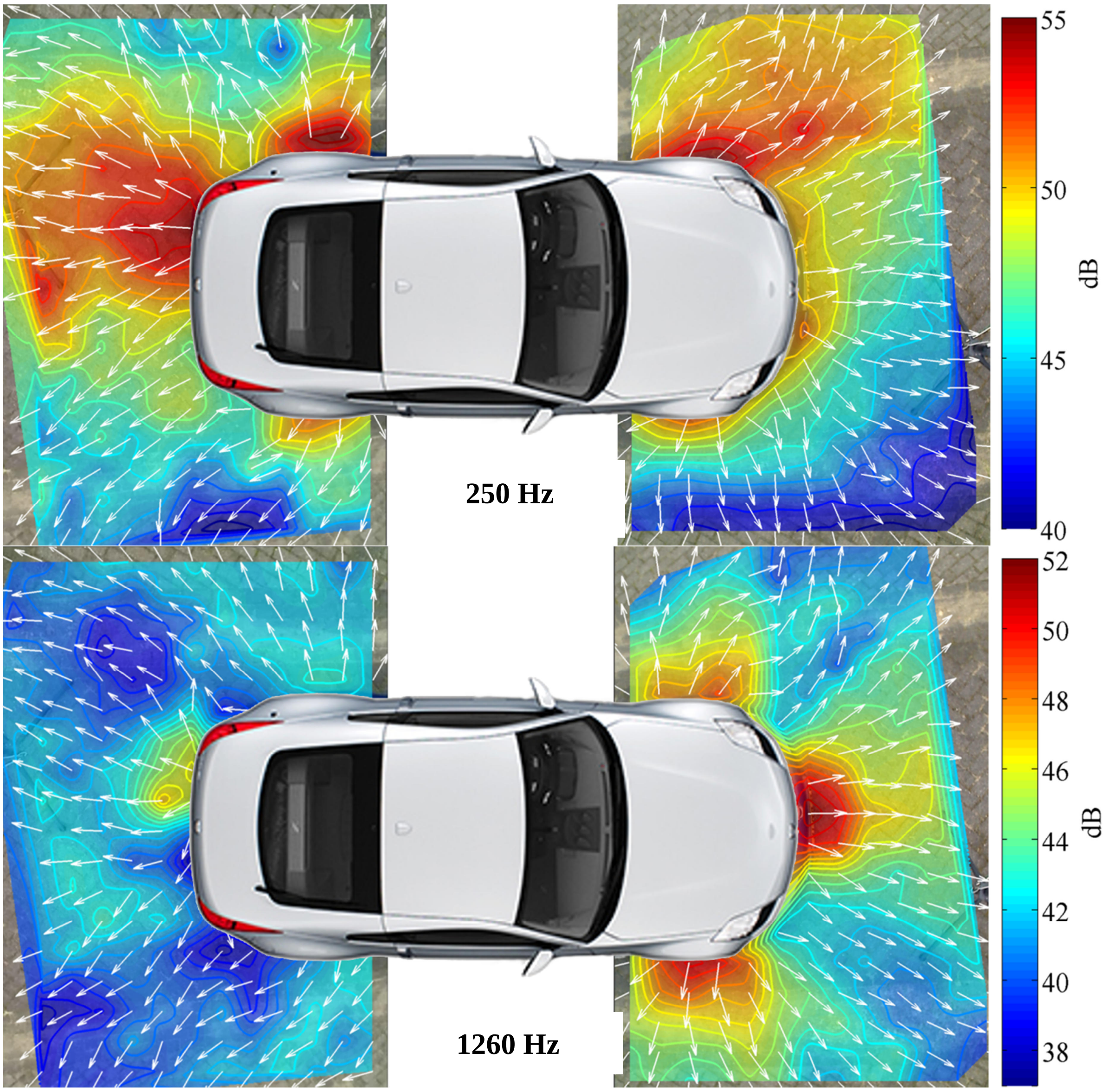

Figure 3 - Acoustic intensity vector field at 250 Hz (top) and 1260 Hz (bottom) of a static Nissan 350Z with an engine rotational speed fixed at 3000 RPM.

4.3 Unmanned Aerial Vehicle

The interest in developing Unmanned Aerial Vehicles (UAV's) has rapidly increased in the latest years. The idea of using a vehicle controlled remotely or even automatically has experienced a rapid rise in popularity. One of the current topics of discussion is the reduction of the acoustic signature of the UAVs, ideally to achieve acoustic stealth.

The sound field produced by the jet engine of a radio-controlled plane has been measured on land in a fixed position with idle engine conditions. Figure 4 presents the test results. As can be seen, the intake noise is the dominant noise source at 5 kHz. In contrast, at other frequencies, the maximum noise is radiated at 45 degrees with respect to the exhaust, as expected for most jet engines.

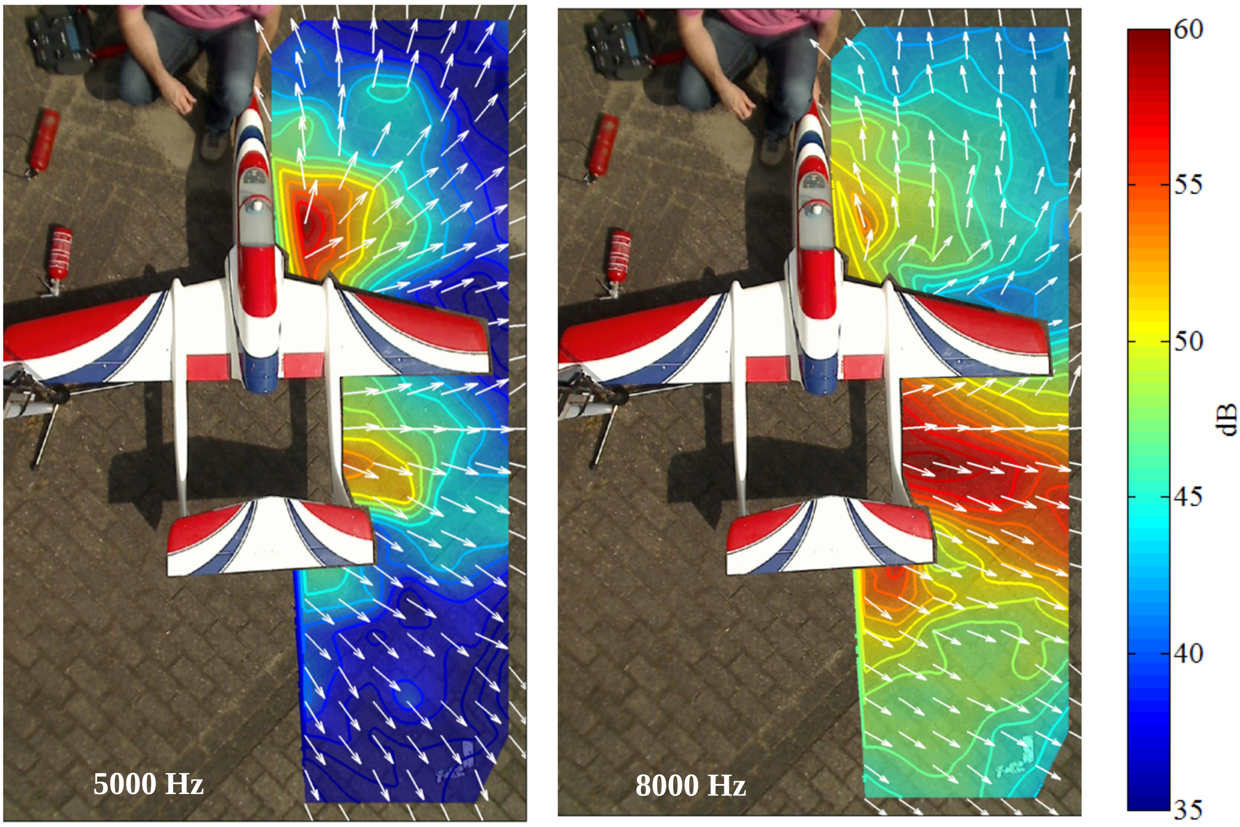

Figure 4 - Acoustic intensity vector field of a radio control airplane at 5 kHz (left) and 8 kHz (right).

4.4 Sound absorbing material

An $11.5m^2$ slab of Flamex 25N was installed on the floor of a reverberant room. Around the perimeter edge of the sample steel borders were placed that were flush with its surface. 3D intensity measurements were performed by a test engineer that manually scanned with the USP probe through the measurement planes, while the sound source of the room was excited. Two measurements were performed; i.e. one in a horizontal plane 5 cm above the sample surface and also a vertical plane at 40 cm from the edges of the sample. Each of the planes was measured in approximately 5 minutes.

Figure 5 shows some results from the intensity measurements for the horizontal plane and a vertical plane. The intensity vectors in these figures are normalized so they all have the same length. This figures show that there are no noticeable complex diffractions around the edge of this sample. Additional results of this test can be found in [10]. At most frequencies the intensity vectors clearly point towards the sound absorbing sample. At high frequencies the interferes of the incoming- and reflected sound waves are clearly visible, and in some cases the intensity vectors point away from the sample.

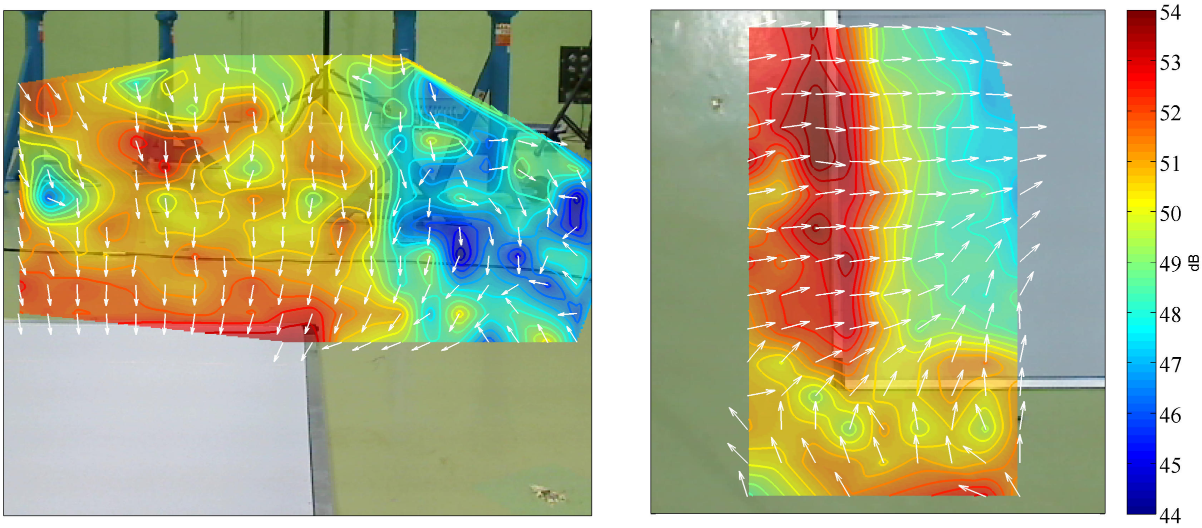

Figure 5 - Normalized intensity vector field with a color map of the intensity level at the 1250 Hz third octave band. Left: front view. Right: top view.

5. CONCLUSIONS

The visualization of acoustic intensity fields enable to display energy wave phenomena around complex (radiating) structures. The use of a vector quantity directly acquired with a three dimensional sound intensity P-U probe contributes to a more comprehensive interpretation of acoustic radiation mechanisms, in contrast to scalar sound pressure based methods. The method can potentially be used for machine diagnostics, vibroacoustic characterization and sound radiation assessment in real-life conditions. In addition, the interaction between a reverberant sound field and an absorbing material has been studied, revealing that the net acoustic energy tends to impinge the surface material in the normal direction. The Scan & Paint scanning measurement technique allows the acquisition of acoustic data across large areas in a fast and efficient way. The measurement time is reduced from hours to minutes. The acoustic intensity vector fields of several complex examples have provided strong experimental evidence of the capabilities of the proposed technique.

REFERENCES

[1] S. Weyna, “Acoustic flow visualization based on the particle velocity measurements”. In proceedings of Forum Acousticum (2005).
[2] L. Kinsler, A. Frey, A. Coppens, and J. Sanders, “Fundamentals of Acoustics”. Spon Press, (1982).
[3] F. J. Fahy, “Sound Intensity”. E & FN Spon, 2nd edition, London (1995).
[4] E. Druyvesteyn and H-E. de Bree, “A new sound intensity probe: comparison to the “pair of pressure microphone” intensity probe”. Journal of Audio Engineering Society, 48 , Issue 1/2 (2000).
[5] F. Jacobsen and H-E. de Bree, “A comparison of two different sound intensity measurement principles”. Journal of the Acoustical Society of America. 118 (3). pp. 1510-1517 (2005).
[6] F. Jacobsen and H-E. de Bree, “Measurement of sound intensity: P-U probes versus P-P probes. In proceedings of NOVEM, Noise and Vibration: Emerging Methods. Saint-Raphael. France (2005).
[7] E. Tijs, H-E. de Bree and S. Steltenpool, “A novel acoustic pressure-velocity based method to access acoustic leakages of an acoustic enclosure in non-anechoic conditions”. In proceedings of Euronoise, the 8th European Conference on Noise Control, Edinburgh, Scotland (2009).
[8] H-E. de Bree, A. Grosso, J. Wind and E. Tijs, “Scan&Paint, a new fast tool for sound source localization and quantification of machinery in reverberant conditions”. VDI conference, Schwingungsanalyse und Identifikation. Leonberg. Germany (2010).
[9] D. Fernandez Comesana, “Mapping stationary sound fields”, Master's thesis, Institute of Sound and Vibration Research (2010).
[10] P. Cats, E. Tijs and D. Fernandez Comesana, “Exploration of the differences between a pressure-velocity based in situ absorption measurement method and the standardized reverberant room method.” In Proceedings of ICA, Montreal, Canada (2013).