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A scanning method for source visualization and transfer path analysis using a single probe

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There are several methods to capture and visualize the acoustic properties in the vicinity of an object. This article considers scanning PU probe based sound intensity and particle velocity measurements which capture both sound pressure and acoustic particle velocity.

The properties of the sound field are determined and visualized using the following routine: while the probe is moved slowly over the surface, the pressure and velocity are recorded and a video image is captured at the same time. Next, the data is processed. At each time interval, the video image is used to determine the location of the sensor. Then a color plot is generated. This method is called the Scan and Paint method.

Since only one probe is used to measure the sound field the spatial phase information is lost. It is also impossible to find out if sources are correlated or not. This information is necessary to determine the sound pressure some distance from the source, at the driver's ear for example.

In this paper, the method of Scan and Paint is enhanced in such way that it is possible to handle partial correlated sources. The key of the novel method is having a pressure microphone at the listener position which is used as a reference sensor. With all this data, it is possible to derive the spatial phase of the sources measured relative to the listening position.

1. INTRODUCTION

Novel scanning methods have been recently introduced to accurately map stationary sound fields in an efficient way [1-4]. In the previous literature, sound pressure, particle velocity, intensity, sound absorption or acoustic impedance have been measured with a new scanning method developed by Microflown Technologies called "Scan & Paint" [2,3]. The properties of the sound field are determined and visualized via the following routine: while the probe is moved slowly over the surface, pressure and velocity are recorded and, at the same time, a video image is captured. Next, all data is processed. At each time interval, the video image is used to determine the location of the sensor. Then, a color plot is generated.

Nonetheless, phase information has not been taken into account so far, only magnitudes of each measurable quantity have been characterized. Measuring this quantity implies a huge improvement for transfer path analysis problems, where the contribution of multiple correlated sources to a given position strongly depends on the phase characteristics of each one of them.

This paper introduces the measurement procedure and the implemented calculations so as to preserve the phase information of the sound field. Lab results are presented to validate the method experimentally. In addition, the method demonstrated in a car interior, giving accurate results.

2. THEORY

Current scanning methods have two main disadvantages: they are only able to characterise time stationary sound fields; and, they do not usually preserve phase information. The first disadvantage is an implicit feature of any scanning method due to the fact that different areas of a virtual plane scanned are not measured simultaneously. Nonetheless, relative phase of the sound field can be measured by using a microphone reference [4]. This information is necessary for transfer path problems. Hence, not only the theoretical considerations of preserving relative phase, but also, the derivation of transfer path analysis with a reference pressure is assessed.

2.1 Preserving relative phase information of the sound field

Ideally, if the phase response of an assessed sound field is periodic, absolute phase characterization could be undertaken with scanning methods. Taking into account the time instant when a measurement over a discrete area is undertaken, the corresponding delays could be subtracted for later events. Thus, the absolute phase response of the field could be found regarding one measured area as reference. However, this simplified approach only would hold for cases where the noise is made-up mainly by pure tones and when the accuracy of the measurements undertaken is extremely high. In most of real applications, it will be necessary to apply a more robust method to preserve phase information of the sound field.

As it is proven in [4], a reference microphone can be used to determine phase differences between measurements at two different positions. Consequently, relative phase information is acquired related to the reference microphone. It will give a good understanding of how sound generated by different sources are summing up at a given position. Thereby, this additional reference will be also very helpful for transfer path analysis problems which are discussed in the following sections.

2.2 Transfer path analysis

This section considers the theoretical framework for a Transfer Path Analysis method based on scanning measurements. The main challenge of this approach is the fact that the phase differences between the source points are necessary to compute the sound pressure at the human ear. If there are multiple partially correlated sources, the coherences between all points are also necessary. It has been shown that a reference microphone can be used to find the phase differences between the sources and also find a physically meaningful solution if there are multiple partially coherent sources [4].

Transfer Path Analysis consists of two measurements. The transfer functions from the source velocity to the reference pressure are measured in experiment 1. This measurement is performed assuming reciprocity, and the surface is scanned using the Scan & Paint approach [1-3]. In experiment 2, the sources at the interior of the car are measured. The pressure at the human ear at some frequency *f* is as follows [5]

$$p_2^{ear} = \int_{S_B} G_1(\vec{x}) u_2(\vec{x}) d\vec{x} \qquad (1)$$

where

$$G_1(\vec{x}) = -\frac{1}{A^{mon}} \cdot \frac{p_1(\vec{x})}{u_1^{ear}} \qquad (2)$$

where p_2^{ear} and u_2 denote the pressure at the human ear and the source velocity during experiment 2. G_1 denotes the transfer function during experiment 1, which implicitly depends on the area of the monopole source. Equation 1 cannot be used directly because the source velocities u_2 are measured one-by-one such that the phase differences between source velocities at different points are unknown. To solve this problem, we rewrite Equation 2 using the cross spectrum between the source velocity and the reference pressure. Noting that the reference pressure and the source velocity are random variables, we write

$$p_2^{ref}\overline{p_2^{ref}} = \int_{S_B} G_1(\vec{x}) u_2(\vec{x}) \overline{p_2^{ref}} d\vec{x} \qquad (3)$$

where $\bar{\cdot}$ denotes complex conjugate. Taking the expected value of Equation 3, we find

$$E\left(p_2^{ref}\overline{p_2^{ref}}\right) = \int_{S_B} G_1(\vec{x}) E\left(u_2(\vec{x})\overline{p_2^{ref}}\right) d\vec{x}$$

$$S_{p_2^{ref} p_2^{ref}} = \int_{S_B} G_1(\vec{x}) S_{u_2(\vec{x}) p_2^{ref}} d\vec{x} \qquad (4)$$

where the symbol S_{xy} denotes the cross spectrum between the signals x and y and S_{xx} means the autospectrum of the signal x. Note that no assumptions have been made about the correlation between the source spectra, and that signals which are uncorrelated to the reference pressure do not occur in Equation 4.

In conclusion, the pressure module can be estimated without losing the phase information of the field. As it has been pointed out above, the obtained phase is meaningful at the position where the reference microphone is located. This fact gives a good understanding of how the vibrations at a source cause a sound at a human ear.

3. EXPERIMENTAL VALIDATION

3.1 Approach and setup

Measurements were performed using a P-U probe and a mid to high frequency monopole manufactured by Microflown Technologies.

Four loudspeakers were used to generate a complex sound field (see Figure 1a). Loudspeakers 1 and 2 were driven with broadband non-white noise with a phase difference of 180 degrees between them. Loudspeakers 3 and 4 are also driven by non-white noise, but the two loudspeakers have the same phase. The noise from loudspeakers 1 and 2 is uncorrelated to the noise from loudspeakers 3 and 4. The spectra of the sources are depicted in Figure 2.

A laser sheet was used to visually determine the location of the measurement plane. Figure1b depicts the experimental setup used for the measurements performed in this article.

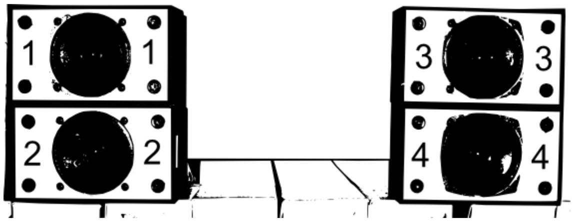

Figure 1a - Sketch of the setup (front view)

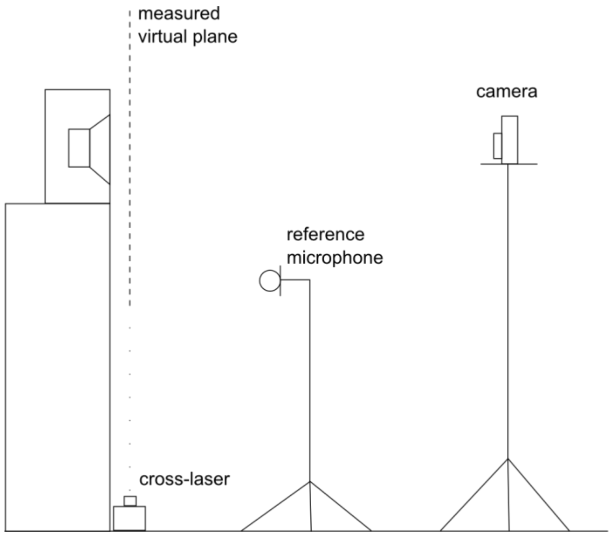

Figure 1b - Sketch of the setup (side view)

In the first step, the loudspeakers were switched off and a monopole source was placed at the reference position along with a particle velocity sensor. Then, pressure variations caused by the monopole source were measured at the virtual plane defined beforehand (see Figure 1b).

In the second step, the loudspeakers were turned on and the particle velocity normal to the measurement plane was measured.

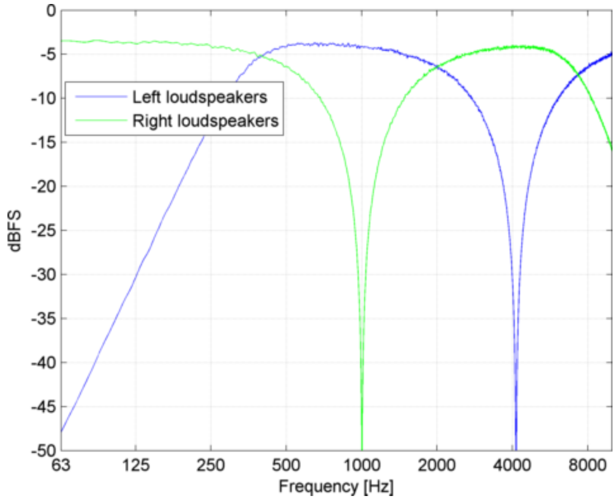

Figure 2 - Excitation signals used for the measurements

3.2 Experimental results

This section presents the experimental results. Amplitude and phase maps of the source are depicted as well as the contributions of transfer path analysis. Finally, the scanning method is validated by showing that the contributions of all source points sum up to the pressure at the human ear.

3.2.1 Sound source visualization

Sound source visualization is a powerful tool to gain understanding about the location and strength of noise sources. Sound pressure, particle velocity and intensity are the three most interesting magnitudes to characterise. The new adaptive algorithm implemented with the Scan & Paint technique allows seeing even small changes over the sound field. Furthermore, remarkable accuracy improvements have been achieved by averaging different sweeps.

Figure 3 shows the particle velocity map at a discrete frequency, 300 Hz. Sound velocity maps can be created for any frequency or even for frequency bands, which gives an intuitive feedback from the measurements.

As can be seen from this picture, sound levels increase in positions close to the loudspeaker, which fulfill the theoretical expectations. It is clear where the velocity maximums are, making very easy to localize noise sources across an unknown sound field.

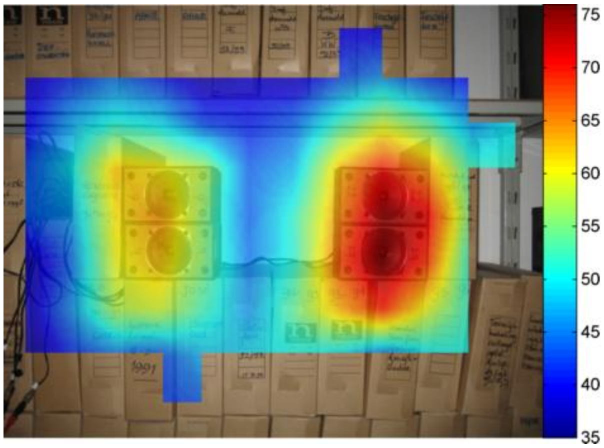

Figure 3 - Particle velocity map at 300 Hz [dB re 0.5 nm/s]

Apparently, regarding Figure 3, it could seem that the left loudspeakers are cancelling each other at low frequencies because they are out of phase; however, this statement is not true for particle velocity. The level difference appears because the left excitation signal was filtered at this frequency (see Figure 2). Cancellation effects could be seen in the pressure map but not in the velocity map. When one loudspeaker is moving forward, the other is moving backwards, pumping air from one to the other without compress the fluid, in this case, the room air; hence, loud pressure sound waves were not generated at lower frequencies.

3.2.2 Phase mapping

As has been explained in the previous sections, phase information between a pressure microphone and a Microflown or particle velocity sensor could be preserved by taking the cross-correlation between them (see Section 2.2).

It is well-known that phase changes more rapidly across the sound field than magnitude for higher frequencies, when wavelength becomes smaller. Consequently, unclear patterns are expected for high frequencies.

Figure 4 presents a phase maps where it is clear that the left loudspeakers are out of phase; whereas, the right loudspeakers are in phase.

3.2.3 Mixing plots: magnitude and phase mapping

Mix plots have been created so as to gather phase and magnitude information across the sound field, all at the same time. Subsequently, the particle velocity magnitude has been multiply by the signs of the phase matrix. Figure 5 provides a mixed picture of the graphs shown above. As can be seen, this intuitive picture provides a huge understand-ding of how the sound field is behaving.

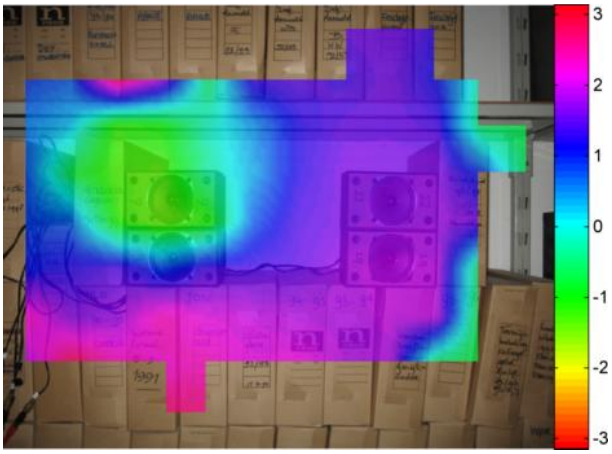

Figure 4 - Phase map at 300 Hz [radians]

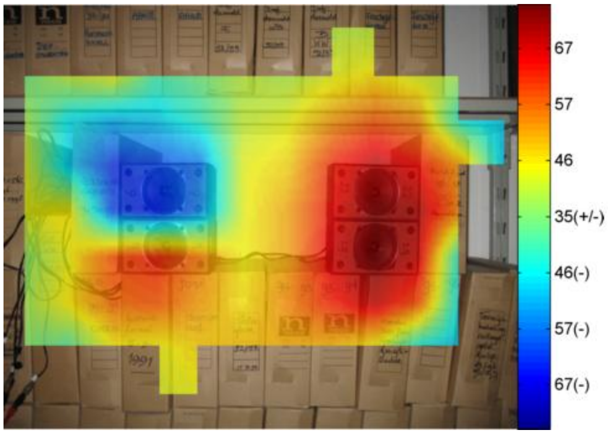

Figure 5 - Velocity and sign of the field at 300 Hz

[dB re 0.5 nm/s]

3.2.4 Transfer path analysis

The scanning transfer path analysis method derived in section 2 is applied to the current dataset. Figure 6 provides the pressure contributions of each point of the measured virtual plane at 300 Hz. This intuitive graph is very helpful to understand where the noisiest points are. As have been pointed out in Section 3.2.1, high particle velocity values close to the source surface will not directly imply generating high pressure sound waves. Therefore, as can be seen, the out of phase loudspeakers (left) are cancelling each other properly.

Furthermore, Figure 7 presents the results, where the pressure measured at the microphone position and its corresponding estimation have been plotted. As it is shown below, theoretical estimation matches the measurement from 250 Hz up to 10 kHz, even exciting the field with several correlated and uncorrelated noise sources.

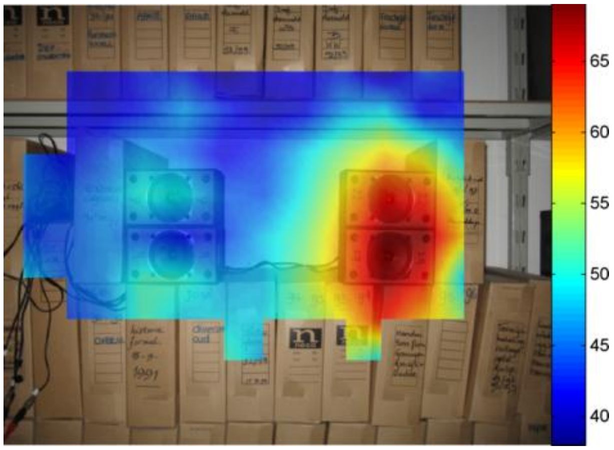

Figure 6 –Contributions to the pressure at the reference microphone at 300 Hz [dB re 20μPa]

The main limiting factor in the frequency range is the monopole source. Since it cannot generate sufficient power below 250Hz, the transfer path estimate is unreliable below that frequency. In future research, this problem will be addressed by using the low-frequency monopole source.

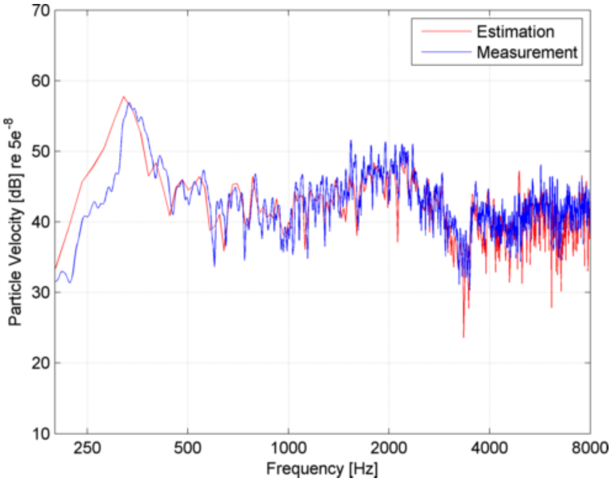

Figure 7 - Pressure estimation with four loudspeakers

It is important to highlight the assumption made on the derivation: noise sources were assumed to be rigid surfaces. In this case this statement is approximately true, fact which contributes to have the good matching found.

In summary, phase information of the field has been acquired accurately. It allows reaching good matching regarding problems which strongly rely on the phase content of the sound field. Further investigation has to be undertaken so as to assess problems without any constrain in order to enhance the results. However, it has been proven that time stationary transfer path analysis problems could be assessed using scanning methods.

4. Partial transfer path analysis in a car interior

This section demonstrates transfer path analysis in a car. Since the scanning method requires all of the identified to lie in the view of the camera, it is difficult, or even impossible, to cover all of the sources in a car. Hence, the method is applied to a small part of the car. It is possible to get accurate contributions for this area, but the contributions do no sum up to the pressure at the human ear because the sources outside of the view of the camera are not taken into account.

Two cases are studied. Firstly, transfer path analysis is performed with the engine running at 2000RPM. Secondly, the analysis is performed again at the same engine speed, with two loudspeakers placed on the dashboard.

In the high frequency range, the sound levels due to the engine are very low such that the loudspeakers are the dominant sources. Since these sources are characterized completely, the contributions of the source should add up to the pressure at the reference microphone. Figure 8 presents a comparison between the measured and estimated pressure. As can be seen, the high frequency range is matched fairly well. Furthermore, the trend of the low frequency range can be roughly predicted only covering a small part of the car.

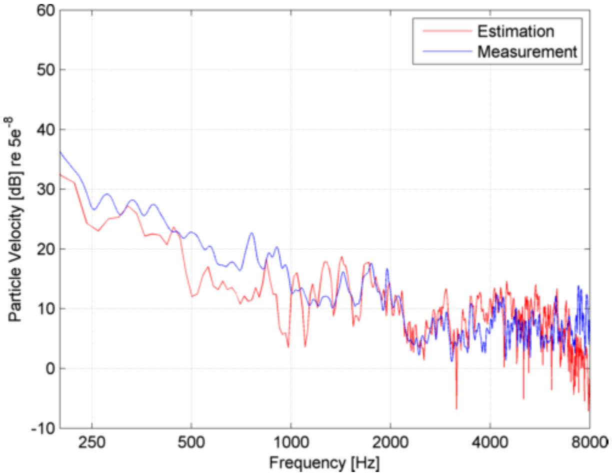

Figure 8 – Pressure estimation inside a car covering a small section of the source

Next, contributions to the pressure reference from each point of the sound field evaluated have been calculated for lower frequencies. As can be seen in Figure 9, there is almost no contribution from the loudspeakers to the reference microphone at this frequency, supporting again the statement made at the beginning of this section, the engine noise is dominant at low frequencies.

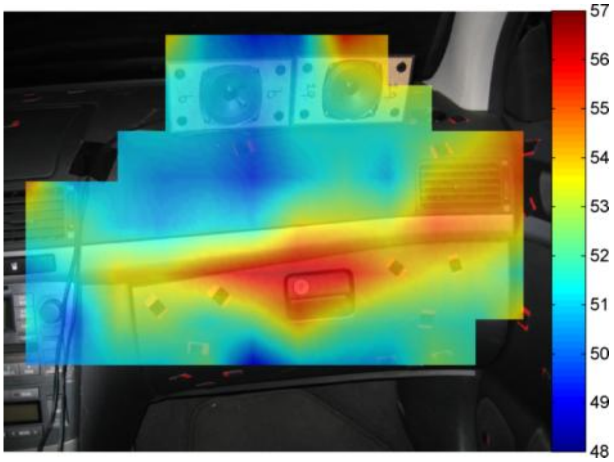

Figure 9 – Contributions to the pressure at the driver's ear at 250 Hz [dB re 20µPa]

Finally, Figure 10 is presented in order to show that phase information can be preserved even in a "hard" acoustic environment such as a car interior. A *mixed plot*[1] style has been chosen so as to be able to gain understanding of amplitude and phase at the same time. As it is shown, the two main sources at 1 kHz are the loudspeakers which are also out of phase (as it was expected).

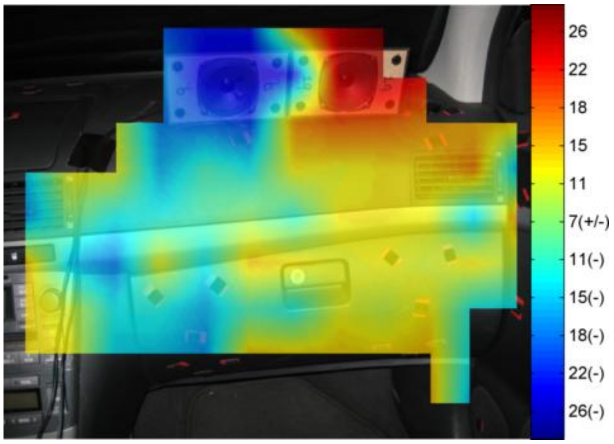

Figure 10 - Velocity mixed sound mapping at 1 kHz

[dB re 0.5 nm/s]

5. CONCLUSIONS

A scanning method to perform transfer path analysis in a car has been introduced, validated in a laboratory experiment and demonstrated in a car interior. For this purpose, a new method to preserve the relative phase information of a time stationary sound field has been introduced. Accurate results have been achieved.

6. REFERENCES

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[5] E. Tijs, J. Wind, D. Fernandez Comesana and H.-E. de Bree , "Ultra fast, high resolution panel noise contribution method," in *SAE 2011 Noise and Vibration*. Michigan, USA, 2011.

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[1] Procedure to generate this kind of plots has been explained in Section 3.2.3