MAPPING STATIONARY SOUND FIELDS USING SCANNING TECHNIQUES: THE FUNDAMENTALS OF "SCAN&PAINT"

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Scanning measurement techniques such as "Scan & Paint" have been shown to improve upon the performance of traditional methods in terms of flexibility, measurement time and cost as long as the sound field can be assumed time stationary. The method is based on the acquisition of sound pressure and particle velocity by manually moving a PU probe across a sound field while filming the event with a camera. The sensor position is extracted by applying automatic color tracking to each frame of the recorded video. It is then possible to visualize sound variations across the space in terms of pressure, particle velocity or sound intensity. Several algorithms can be applied for mixing spatial information with the acoustic signals. This paper introduces the two main algorithms developed: the point method and the grid method. For this purpose, not only the theoretical foundations of both methods are explored but also their practical implications as efficient sound visualization techniques.

1. Introduction

In the development of acoustics, sound representations have been thought of as a key to aid in its understanding. The necessity to represent sound and vibration information visually triggered many investigations with a common goal: to create tools to build intuition and understanding upon specific problems.

Many alternative methods and apparatus have been proposed over time [1] as is addressed in the following section. Nevertheless, the current measurement procedures for characterizing sound fields can be classified by three major categories, regardless of the post-processing techniques applied: step-by-step, simultaneous and scanning measurements. Each of these techniques can be evaluated simply using three main features: measurement time, flexibility and total cost of the equipment.

Step-by-step is the most common technique to create spatial representations of stationary sound fields. It is based upon the acquisition of data at a set of discrete positions. The flexibility of this method is one of its main advantages since the number of transducers and their spatial distribution is completely customizable. The number of sensors used is directly related to the cost of the equipment but inversely proportional to the time needed to undertake the experiments. In the case that all measurement positions of interest are characterized simultaneously, it is be necessary to use of a large multichannel system.

Measurement solutions based upon sensor arrays conventionally imply a large cost and low flexibility derived from their complexity. An intermediate solution, able to reduce the measurement time without increasing the equipment cost can be found by using scanning methods. Scan-based techniques have a fundamental difference to the previously cited procedures: data is no longer acquired at discrete spatial positions since the sensor, or set of sensors, are moved continuously during the acquisition stage. This fact implies that the recorded acoustic signal will have an associated tracking path. Thus, evaluation of the time interval when the sensor is passing over the area of interest is required in order to estimate the spectral content at any point.

Far too little attention has been paid to scan-based measurement techniques despite the capabilities they offer. Several attempts have been made to incorporate scanning microphone arrays in combination with acoustic holography algorithms [2-4]. However, the high cost of the tracking systems used and the complex setup needed for carrying out the experiments has limited the growth in popularity of this powerful measurement technique. The scan-based method introduced in this paper, Scan & Paint, is rather different from the previously proposed methods: instead of using a moving frame array, a single probe is utilized; furthermore, the standard complex tracking system is replaced by a simple manual movement of the sensor, tracked using video processing. These two key features maximize flexibility whilst minimizing the cost of the measurement procedure.

In the following sections the theoretical foundations of the novel scanning measurement technique Scan & Paint are presented along with the evaluation of a measurement example.

2. Scan & Paint

The sound visualization technique proposed as an alternative sound visualization method is called “Scan & Paint” [5, 6]. 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 colour detection to each frame of the video. It is then possible to split the long recording into multiple segments by applying a spatial discretization via a point method [6] or a grid algorithm [7]. Each fragment of the signal will be linked to a spatial position, depending upon the location of the probe during the measurement.

Only the 2D location relative to the background image is computed at this point so it is later required to define the relation between 2D coordinates and 3D coordinates, to establish a relationship between pixels and meters in the measured plane. The camera should be placed perpendicular to the measurement area so as to avoid any visual errors caused by the camera projection.

Additionally, a fixed reference pressure microphone can be used to preserve the relative phase information across the sound field at the different grid positions. The location of this common ground has to be assigned to a position which has a high degree of linearity with the measurement area covered, hence obtaining high coherence values.

3. Mathematical Formulation

3.1 Spatial Grid Method

We begin by defining a continuous 2D dimensional spatial domain with an additional time dimension associated to it. If we discretize the spatial domain and define the limits of time between 0 and certain time length T, then

$$\Omega_{\mathrm{T}} = \Omega_{\mathrm{h}} \times [0, T] \in \mathbb{R}^3 \tag{1}$$

where Ω_{h} is the union of M by N subspaces $\Omega_{\mathrm{h}}^{\mathrm{m,n}}$ non-overlapped, i.e.

$$\Omega_h = \bigcup_{m=1}^{M} \left(\bigcup_{n=1}^{N} \Omega_h^{m,n} \right) \tag{2}$$

where $\bigcup_{m=1}^{M}$ denotes the union operator of the elements m=1 to M. The area covered by each block $\Omega_h^{m,n}$ can be delimited using a regular spatial grid of cell size Δ_X by Δ_y. We can then describe the center of each grid cell $\Omega_h^{m,n}$ depending on the starting point of the discretization grid (x_0, y_0), the cell size (Δ_X, Δ_y) and their row and column index (m, n)

$$\vec{Y}_{m,n} = (x_m, y_n) \;/\; \vec{Y}_{m,n} \in \Omega_h^{m,n} \tag{3}$$

with

$$x_m = x_0 + \Delta_x \,(m - 1/2) \tag{4}$$

$$y_n = y_0 + \Delta_y \,(n - 1/2) \tag{5}$$

$$m = 0,1, \dots M \quad \text{and} \quad n = 0,1, \dots N \tag{6}$$

where M and N are the total number of rows and columns of the spatial grid. Therefore, each cell will be defined spatially such as

$$\Omega_h^{m,n} = \left(x_m - \frac{\Delta_x}{2}, x_m + \frac{\Delta_x}{2} \right) \times \left(y_n - \frac{\Delta_y}{2}, y_n + \frac{\Delta_y}{2} \right) =$$

$$= \left\{ (x, y) \in \mathbb{R}^2 \;/\; x_m - \frac{\Delta_x}{2} < x < x_m + \frac{\Delta_x}{2}, y_n - \frac{\Delta_y}{2} < y < y_n + \frac{\Delta_y}{2} \right\} \tag{7}$$

Figure 1 illustrates the studied scenario.

Once the spatial domain of interest has been discretized we can then establish a link between measurement data acquired with a moving transducer and the grid defined above. Denoting the path followed by the sensor by $\vec{r}(t)$, it is possible to fragment the continuous route into several segments, using the grid structure contained in Ω_h as a tool to divide the original signal and associate each segment to a spatial position. As a result, each grid cell will have associated a list of uneven segments such as

$$\xi_{m,n} = \vec{r}(t) \cap \Omega_h^{m,n} = \left\{ \vec{r}\left(\tau_{m,n}^{(1)}\right), \vec{r}\left(\tau_{m,n}^{(2)}\right), \dots \vec{r}\left(\tau_{m,n}^{(L)}\right) \right\} \tag{8}$$

where $\tau_{m,n}^{(l)}$ is a time interval which links a section of the original time signal to a certain spatial area of the grid $\Omega_h^{m,n}$; and L is the number of sweeps within the cell. Each of these time intervals within a cell can be defined as delimited by certain boundaries $a_{m,n}^{(l)}, b_{m,n}^{(l)}$, i.e.

$$\tau_{m,n}^{(l)} = \left[a_{m,n}^{(l)}, b_{m,n}^{(l)} \right] \;/\; a_{m,n}^{(l)}, b_{m,n}^{(l)} \in [0, T] \tag{9}$$

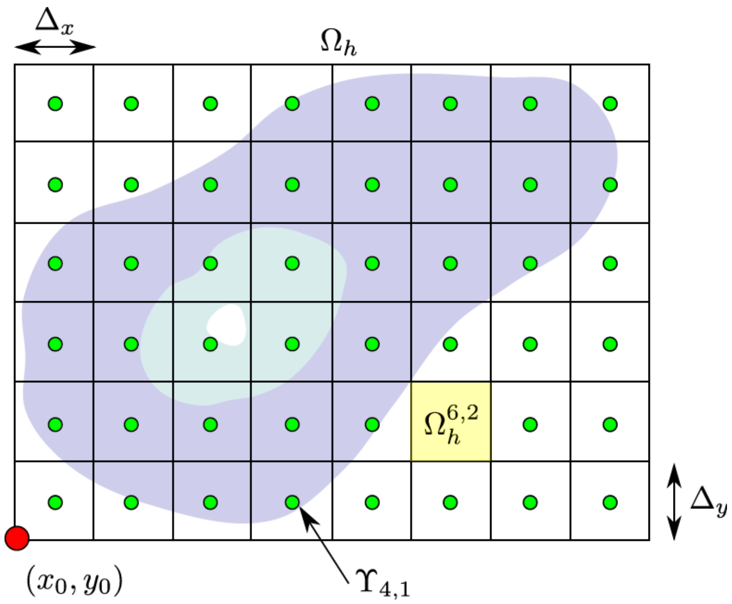

Figure 1. Sketch of the spatial domain evaluated

By definition (Equation 8), one grid cell can have multiple associated sections of the original signal if the sensor passes across to the same area several times. The use of a sound probe which combines a sound pressure microphone along with a particle velocity sensor (a P-U probe) enables the gathering of information for both acoustic quantities across the space. Consequently, if a P-U probe is moved along a measurement plane recording its instantaneous position, applying the grid method proposed will lead to the association of measured time data to the different grid cells. As a result, we can define an array of sound pressure signals $\mathbb{P} \in \Omega_\mathrm{T}$, and another of particle velocity $\mathbb{U} \in \Omega_\mathrm{T}$ such as

$$\mathbb{P}(\vec{\Upsilon}_{\mathrm{m,n}}) = \left\{p\left(\tau_{\mathrm{m,n}}^{(1)}\right), p\left(\tau_{\mathrm{m,n}}^{(2)}\right), \dots p\left(\tau_{\mathrm{m,n}}^{(L)}\right)\right\} \tag{10}$$

$$\mathbb{U}(\vec{\Upsilon}_{\mathrm{m,n}}) = \left\{u_n\left(\tau_{\mathrm{m,n}}^{(1)}\right), u_n\left(\tau_{\mathrm{m,n}}^{(2)}\right), \dots u_n\left(\tau_{\mathrm{m,n}}^{(L)}\right)\right\} \tag{11}$$

where p and u_n are the recorded sound pressure and particle velocity signals, respectively. The route followed by the probe will determine which grid cells have data assigned to them and which, if any, will be empty. Averaging will be therefore needed for the case of multiple time signals being associated to a single cell. Since data is acquired asynchronously at the different cells, the averaging process must be applied in the frequency domain, thus

$$P_{m,n}(f) = \frac{1}{L}\sum_{l=1}^{L} \widehat{Sp}_{m,n}^{(l)}(f) \tag{12}$$

$$U_{m,n}(f) = \frac{1}{L}\sum_{l=1}^{L} \widehat{Su}_{m,n}^{(l)}(f) \tag{13}$$

where each $\widehat{Sp}_{m,n}^{(l)}(f)$ and $\widehat{Su}_{m,n}^{(l)}(f)$ denote the power spectral density estimation of a given segment of the sound pressure and particle velocity signals, respectively, i.e.

$$\widehat{Sp}_{m,n}^{(l)}(f) = \frac{1}{B_e T_l} \int_0^{T_l} p\left(\tau_{\mathrm{m,n}}^{(l)}, B_e, t\right) \tag{14}$$

$$\widehat{Su}_{m,n}^{(l)}(f) = \frac{1}{B_e T_l} \int_0^{T_l} u\left(\tau_{\mathrm{m,n}}^{(l)}, B_e, t\right) \tag{15}$$

where $p\left(\tau_{\mathrm{m,n}}^{(l)}, B_e, t\right)$ is a portion of $p(\tau_{\mathrm{m,n}}^{(l)})$ passed by an ideal rectangular band-pass filter with a bandwidth of B_e centred at frequency f [8].

3.2 Spatial Point Method

An alternative spatial discretization process can be also introduced based upon the tracking data available from scanning measurements. Since we deal with a finite number of localized positions, it is then possible to define a series of spatial positions associated to the audio signal acquired, such as

$$\vec{\Gamma}_{\mathrm{i}} = (x_i, y_i) \;\; / \;\; \vec{\Gamma}_{\mathrm{i}} \in \Omega_{\mathrm{h}} \tag{16}$$

with $i \in \mathbb{N}$ indicates the position index. Each of the tracking samples or spatial points $\vec{\Gamma}_{\mathrm{i}}$ has a time interval τ_i associated to it. With the spatial point method the discretization process is performed along the scanning route $\vec{\mathrm{r}}(\mathrm{t})$ depending on three main parameters inputted by the user: number of averages (n_d), sample block width (B) and overlap ratio between sample blocks (o_d). Therefore, each time interval is defined as

$$\tau_i = \left[\frac{i}{f_v} - \frac{n_d B o_d + o_d}{2 f_s}, \frac{i}{f_v} + \frac{n_d B o_d + o_d}{2 f_s}\right] \tag{17}$$

where f_v and f_s denote the video and audio sampling frequencies, respectively. The pressure and particle velocity levels representative of each spatial position $\vec{\Gamma}_{\mathrm{i}}$ are then obtained by Evaluating the full length audio signal in the time interval assigned, i.e.

$$\mathbb{P}(\vec{\Gamma}_{\mathrm{i}}) = p(\tau_i) \tag{18}$$

$$\mathbb{U}\left(\vec{\Gamma}_{\mathrm{i}}\right) = u_n(\tau_i) \tag{19}$$

Finally, the spectral analysis presented above can be also applied to each signal segment $p(\tau_i)$ in order to obtain an acoustic map of the local variations of sound pressure, particle velocity or sound intensity across the measurement plane.

4. Experimental results

In this section both Scan & Paint processing methods are assessed with a complex noise source. A Nissan 350z was measured while running the engine in stationary conditions of 3000 RPM. A measurement of four minutes was performed by scanning over the open engine bay with a Microflown PU probe. Figure 1 shows the tracking data calculated using automatic color tracking of the probe (left); and the virtual measurement points $\vec{\Upsilon}_{\mathrm{m,n}}$ obtained after applying a regular discretization grid (right).

Figure 1. Measurement tracking (left) and data points of the grid method (right)

Sound pressure, particle velocity or sound intensity colourmaps can be produced by applying the methods presented above. Figure 2 shows a comparison of the results obtained with the grid method (left) and point method (right). As is shown, dynamic range and noise source positions are very similar in both maps. However, the point method has a higher spatial resolution with a higher variance error. On the other hand, the grid method leads to smoother results, converging to an optimal answer when performing longer scans and sweeping several times over the same area. Ultimately, the resolution of the grid method can become comparable to the point method if the area of each grid cell is reduced, but consequently decreasing the data within a cell and thus the accuracy.

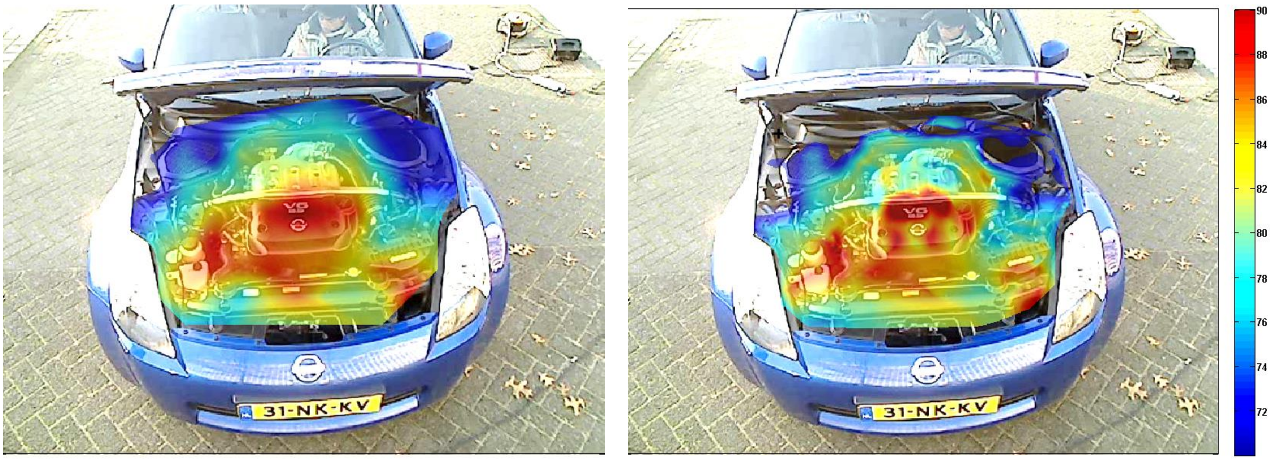

Figure 2. Particle velocity mapping with grid method (left) and point method (right) at 150 Hz.

The use of a scanning P-U intensity probe provides a fast and efficient way to characterize the overall sound power output of a noise source. It is therefore essential to guarantee an accurate and stable result when either of the Scan & Paint processing methods is applied. Figure 3 presents a comparison of the sound power estimation of the example shown above. As it can be seen, both methods yield to almost identical results, proving the validity of the signal processing techniques introduced.

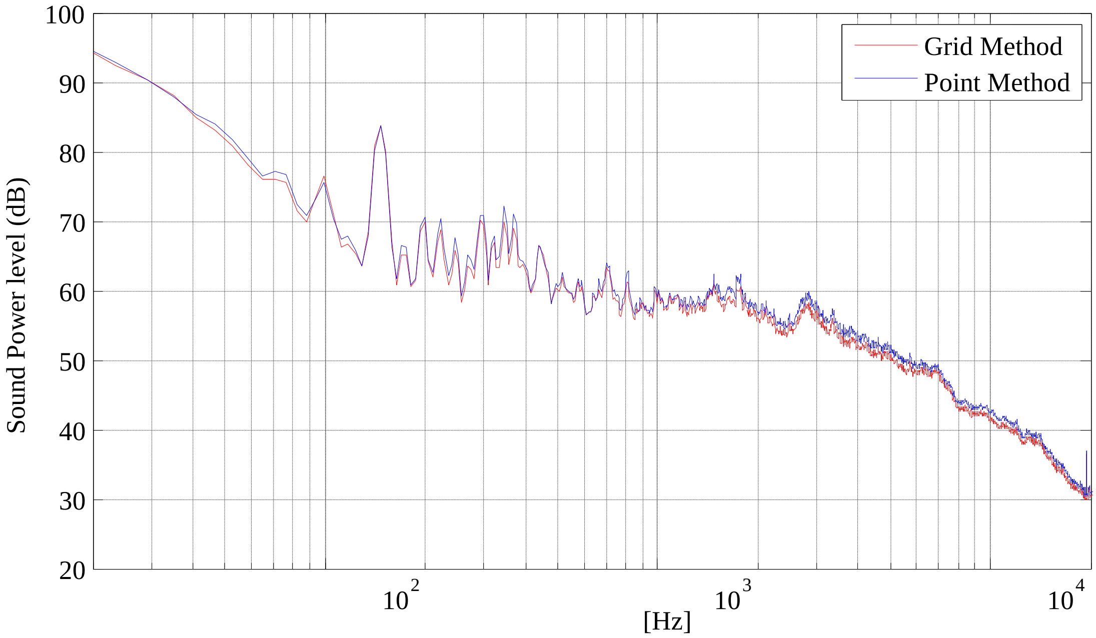

Figure 3. Sound power estimation using grid method (red) and point method (blue).

5. Conclusions

The theoretical foundations of two different sound visualization techniques based upon scanning measurements have been presented. Both, the spatial grid method and the point method have been evaluated with an experimental measurement case. Results presented along this paper prove the strong agreement between the two methods. Sound power calculations have also been performed with both methods with almost identical results. It has also been found that the point method yields to higher spatial resolution colourmaps whereas the grid method converges to a more accurate answer, mainly due to the spatial averaging applied. Ultimately, both methods become equivalent if the grid method is evaluated with small spatial grid areas.

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