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MEASURING UNDER NON STATIONARY CONDITIONS WITH SCANNING TECHNIQUES

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ABSTRACT

By using scanning techniques is it possible to reduce significantly the number of sensors required to characterize a sound field. Thereby, by moving any sensor and tracking its position along the measurement, it is possible to produce colorful sound maps. The use of such techniques normally implies that the sound field has to be assumed time-stationary, because any change during the measurement would be not taken into account. However, this paper aims to present a new scanning method which is able to be used for assessing non-stationary sound fields. This technique is based on taking transfer functions between the scanning transducer and a reference sensor. Then, the number of positions measured is limited for each frequency evaluating the dynamic range acquired. As an example, some experimental results of mapping sound radiation of musical instruments are presented along with a discussion focused on the advantages and disadvantages of the method.

1 INTRODUCTION

Human understanding is mainly based on seeing; leading people to create many visual representations to help understanding what is going on when things cannot be seen. Sound representations have been key aids for understanding practical problems regarding noise issues. Many different techniques have been implemented over years for charting sound fields and noise sources but always with a trade-off between cost, time and accuracy.

Already from the late 1980's scan-based methods have been introduced for mapping stationary sound fields [1]. Recent works have introduced a novel scanning method called Scan & Paint [2–4] for measuring sound pressure, particle velocity, intensity, sound absorption and acoustic impedance in an efficient way. 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. The absolute position of the probe is unknown, only the 2D coordinates relative to the background image are computed. Then, an acoustic color plot is generated.

Scanning methods are proven to minimize the measurement time and cost, but conventionally constrained to mapping stationary sound fields. In the literature of Near field Acoustic Holography (NAH), several signal processing techniques have been proposed to overcome some problems derived from the degree of time stationary of the source [5–7]. However, these techniques require using multiple references along with scanning microphone arrays. In contrast, this paper is focused on presenting an effective method for directly visualizing sound radiation patterns without back-propagating the sound field to the source and using only one fixed and one moving sensor.

The sound radiation patterns of a musical instrument is a classic example of non-stationary sound source. There are no standard regulations regarding the measurement procedure required for characterizing their directivity patterns due to its practical difficulties. Directivity patters play an important role on virtual acoustics, specially when computing room auralizations [8]. Therefore, finding a measurement technique which allows to characterize the sound radiated of a non-stationary source in a fast and efficient way will simplify the process remarkably.

The following sections will present the theory and methodology required to implement the proposed measurement technique. Furthermore, an experimental case is presented an example of musical instrument sound radiation maps. Next, advantages and disadvantages of the novel technique are discussed.

2 THEORY

Lets start assuming that the sound field is generated by a plane circular piston of radius a mounted on a flat rigid baffle of infinite extent. For far field conditions, the complex pressure produced at a distance r and at a certain angle θ can be defined as [9]

$$p(r,\theta,t) = \frac{A}{r}D(\theta)e^{j(\omega t - kr)} \tag{1}$$

where A is a time independent term which relates source characteristics such as the piston size, velocity, specific acoustic impedance and wavenumber; ω is the angular frequency; and $D(\theta)$ is a directivity term which can be expressed in terms of a Bessel function J_1, such as

$$D(\theta) = \frac{2J_1(ka\sin(\theta))}{ka\sin(\theta)} \tag{2}$$

Radiation patterns of sound sources are useful to assess how much energy is emitted from different directions. Conventionally, the power distribution of a source can be estimated by calculating its power spectral density (PSD) at different spatial positions. The PSD of a pressure time signal p of length T is given by [10]

$$S_{pp} = \lim_{T\to\infty} \frac{E\left[|P(f)|^2\right]}{T} \tag{3}$$

where $P(f)$ is the Fourier transform of p, and $E[...]$ denotes the expected value. By definition the PSD of a non-stationary source will change along time. This fact implies that multiple channels would be required for tracking sound power changes across space and time. Therefore, it is necessary to implement another approach in order to measure sound radiation under non stationary conditions. By assessing the theoretical definition given in Equation (1) can be inferred that taking a ratio between two positions (r_1, θ_1 and r_2, θ_2) allows to get an expression which is time independent and provides a way of measuring the relative radiation changes, i.e.

$$\frac{p(r2,\theta_2,t)}{p(r1,\theta_1,t)} = \frac{r_1 D(\theta_2)}{r_2 D(\theta_1)}e^{jk(r_1-r_2)} \tag{4}$$

The term presented in Equation (4) can be seen as a transfer function between two microphone positions. Fixing one of the sensor gives a static reference useful for linking the measurements performed with the moving transducer in a relative sense. Tracking the position of the moving sensor across time make possible to represent transfer function variations across space, which are directly related with the radiation patterns of a sound source. For practical applications the transfer functions have to be estimated. Several methods can be implemented depending on the signal which is likely to have undesired noise. In the case described above, the moving sensor is exposed to manipulation noise and the signal to noise ratio between direct and reverberant field will be smaller. Consequently, the estimator H_1 has been implemented because it is unbiased with respect to the presence of output noise. The transfer function estimator H_1 is defined as

$$H_1(f) = \frac{S_{p_s p_r}(f)}{S_{p_r p_r}(f)} \tag{5}$$

where, similarly to the PSD, the term $S_{p_s p_r}$ represents the cross power spectral density (CPSD) between two finite time signals p_s (scanning pressure) and p_r (reference pressure) of length T, i.e.

$$S_{p_s p_r} = \lim_{T \to \infty} \frac{E\left[P_s(f) P_r^*(f)\right]}{T} \tag{6}$$

where $P_r^*(f)$ is the complex conjugate Fourier transform of p_r. In addition, it is important to highlight that evaluating Equation (5) for a baffled circular piston in far field conditions would lead to the same expression presented in Equation (4). Consequently, it has been shown analytically that the transfer functions between a fixed and a moving transducer directly gives a time independent ratio which carries information about the relative signal between the two sensors.

This method can also be extended for more complex noise source due to all the source features cancel out when evaluating a ratio between two positions. Nevertheless, errors could appear if not only the absolute level varies but also the spectral content changes along time. An algorithm for limiting the spatial positions depending on the dynamic range of the assessed frequency is presented in the next section in order to overcome this potential problem.

3 POSITIONAL DISCRIMINATION ALGORITHM

So far it has been pointed out that taking transfer functions between a fixed and a moving transducer allows to characterize time independent relative variations across a sound field. Nonetheless, a detailed description of the measurement scenario is required to understand how to apply a positional discrimination algorithm. Figure 1 shows a schematic view of a generic experimental setup.

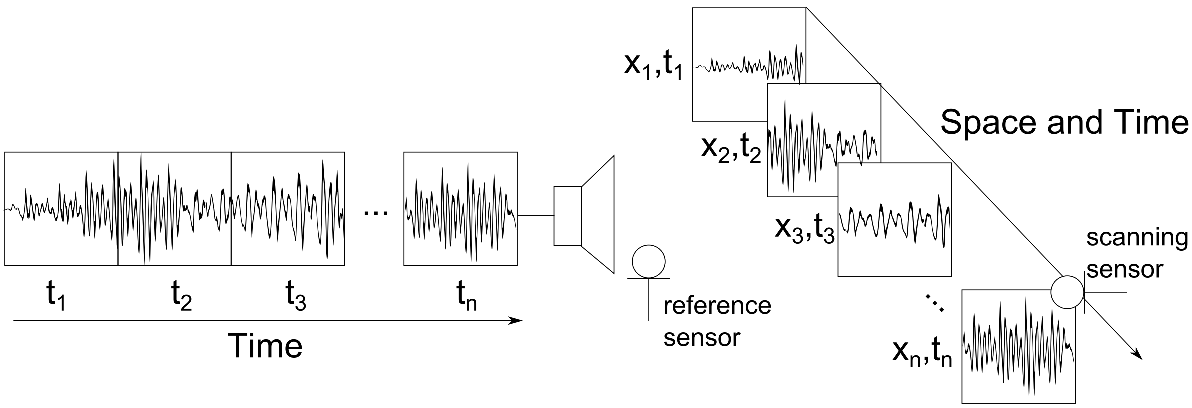

Figure 1. Schematic view of the measurement scenario

Figure 1 illustrates how a continuous time signal is driving the sound source while the scanning microphone is moving across the sound field. A finite grid of positions can be created relative to the location of the moving transducer. Then the time intervals series $(t_1, t_2, ..., t_n)$ can be linked with their corresponding measurement positions $(x_1, x_2, ..., x_n)$.

Next, the time sequences measured with the moving and static sensors are combined by computing the transfer function estimator H_1 (see Equation (5)). This allows to assess how the sound radiation changes across the space. Nevertheless, it is required to have sufficient spectral excitation at the source so as to evaluate this power spatial changes. Hence, the PSD (see Equation (3)) of the fixed transducer can be studied for different time intervals so as to neglect transfer functions with poor signal to noise ratio.

Depending on the frequency aimed to analyze, a maximum dynamic range has been establish depending on the maximum transfer function found. Consequently, any position with insufficient signal excitation for a given frequency has been disregarded. This leads to have an irregular spatial grid which size changes across the frequency domain. Figure 2 shows a representation of the procedure.

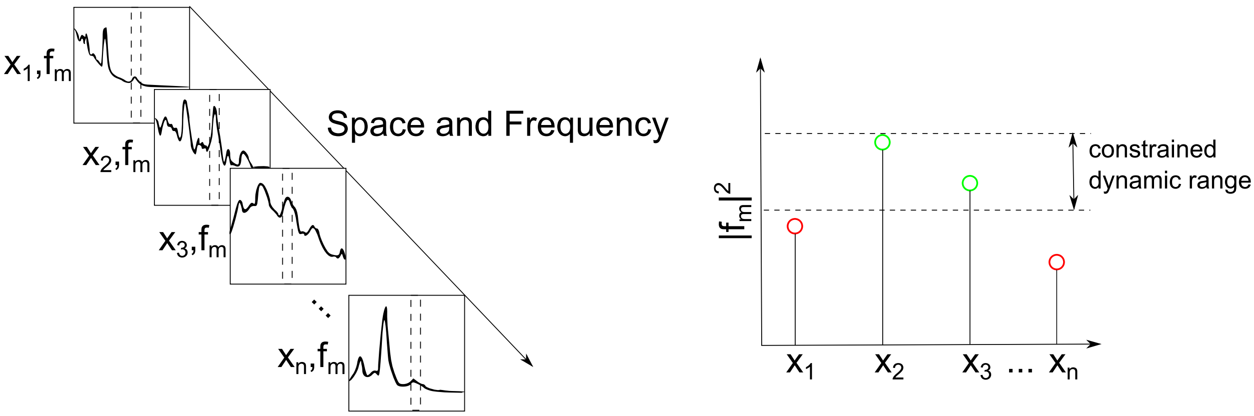

Figure 2. Diagram of the positional discrimination procedure

4 INSTRUMENTATION AND EXPERIMENTAL SETUP

Scanning measurements were carried out using a Microflown PU probe which contains a pressure microphone along with a particle velocity sensor. The reference pressure at a fixed position was measured using a supercardioid goose-neck microphone DPA 4099. In addition, a camera "Logitech Webcam Pro 9000" was required for recording a video of the measurements.

Measurements were performed in the large anechoic chamber of the ISVR (Southampton, UK) for achieving free-field conditions.

The sound radiation of a cello was measured carrying out two sweeps one meter away from the musical instrument along a surface of two meters by two meters. The cello played a chromatic scale during the measurements. The time expended in each scanning was about 4 minutes.

5 RESULTS: SOUND RADIATION MEASUREMENTS

This section present an example of how the measurement procedure presented can be used in challenging scenarios such as musical instrument measurements. Figure 3 illustrates how the excitation signal changes in amplitude (left) and frequency content (right) across the time. As can be seen, the sound field produced by the source is not time stationary at all. Since the cello is playing a continuous chromatic scale the excitation completely changes from one position to another.

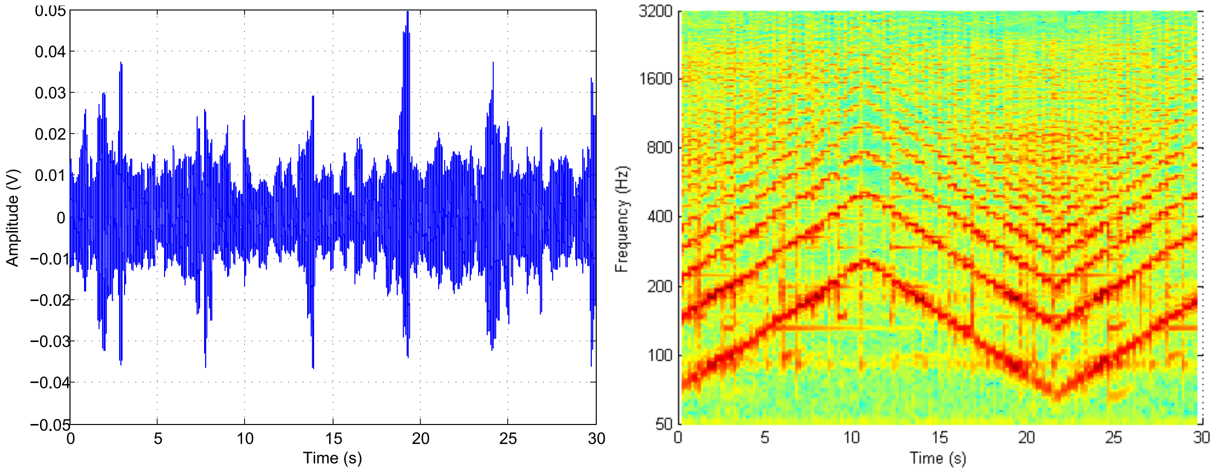

Figure 3: Time history segment of the fixed transducer during a cello measurement (left) and its corresponding spectrogram (right)

Next, Figure 4 presents the left side radiation pattern of a cello. The continuously changing sound field (see Figure 3) can be assessed as if it was stationary by calculating the transfer functions across the measurement plane and applying the positional discrimination algorithm. Then, sound pressure level of any position which has been neglected due to poor signal to noise ratio is calculated by interpolating the closest grid points. As a result, smooth directivity patterns can be measured in a fast and efficient way.

The scale bars of Figure 4 have been adjusted because the excitation level varies between the two frequency maps assessed. However, the dynamic range (15 dB) have been maintained in order to compare both graphs.

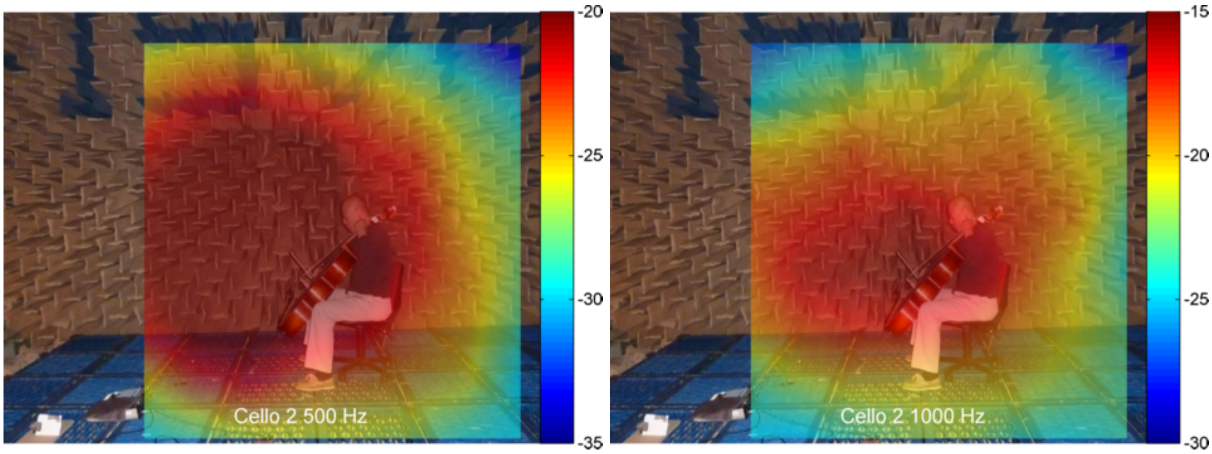

Figure 4. Radiation pattern of a cello at 500 Hz (left) and 1 kHz (right)

6 ADVANTAGES AND DISADVANTAGES OF THE MEASUREMENT PROCEDURE

Current methods for measuring non-time stationary sound field rely on using large sensor arrays. The most common solution uses one sensor for each measurement position. Alternatively, methods based on NAH can reconstruct the entire sound field by placing multiple reference transducers and then scanning an area with a large array [5]. The novel technique proposed in this paper only requires two sensors: one static while the other is manually moved. Time, cost, simplicity, flexibility and accuracy are the main issues evaluated in this section which determine the advantages and disadvantages of choosing a measurement technique.

Time required for setting up the instrumentation and performing the measurement is always a big issue. Manual sweeps of a single probe are a fast procedure for directly obtaining information about a sound field. The radiation measurement presented in this paper was undertaken in less than 4 minutes, which can be seen as a reasonable amount of time for characterizing the sound field produced by a non-stationary sound source such as cello.

One of the main problems of most conventional array measurement systems is the cost of the equipment. Not only the number of transducer required for performing the measurements but also the multichannel acquisition system rise the price strongly. The proposed two-sensor solution has far less requirements than most of the current large multichannel applications.

The measurement protocol and the post processing stage should be fairly intuitive. The use of a camera makes sure that all the measurement process is filmed . This has been proved to be helpful with trouble shooting. Color maps overlaid on pictures give a direct feedback that is easy to understand.

The flexibility of the proposed method is one of its stronger advantages against array-based solutions. The novel technique allows to setup all instrumentation and resize the measurement plane just by moving the camera. Furthermore, the spatial resolution of the measurement is selected after performing the measurement allowing to assess several spatial distribution a posteriori. The criteria for selecting the blocks size of the grid depends on the frequency investigated and the duration of the measurement (as the sweep get longer the grid blocks can be smaller).

The main outcome of a measurement technique is to ensure accurate and reliable results. The smooth radiation maps presented in Figure 4 support the great potential of combining the Scan & Paint measurement techniques with the positional discrimination algorithm. The more measurements per plane, the more accurate the results will be since the small errors due to human factors can be minimized when averaging all the sessions. Besides, the fact that there are not physical fixed positions leads to minimize the interference effect of placing so many objects in the sound field.

7 CONCLUSIONS

A theoretical base for measuring time independent relative changes in a sound field has been derived. Moreover, an algorithm for selecting the spatial areas with same signal excitation has been proposed. The combination of the described principles with the scanning measurement technique Scan & Paint lead to a novel method for characterizing non-stationary sound fields using a scan based two-channel system. Results presented prove the successful implementation of the method. The measurement technique presented reduces the number of transducers, measurement time and cost, while maximizes the flexibility and simplicity of current methods.

REFERENCES

[1] J. Hald. Stsf - a unique technique for scan-based near-field acoustics holography without restrictions on coherence. Technical report, Bruel & Kjaer, 1989.

[2] 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 *Euronoise*, 2009.

[3] E. Tijs, H.-E. de Bree, and S. Steltenpool. Scan & paint: a novel sound visualization technique. In *Internoise*, 2010.

[4] H.-E. de Bree, J. Wind E. Tijs, and A. Grosso. Scan & paint, a new fast tool for sound source localization and quantification of machinery in reverberant conditions. In *VDI Maschinenakustik*, 2010.

[5] J. Hald. Non-stationary stsf. Technical report, Bruel & Kjaer, 2000.

[6] Moohyung Lee and J. Stuart Bolton. Scan-based near field acoustical holography and partial field decomposition in the presence of noise and source level variation. *Journal of the Acoustical Society of America*, 119:382–393, 2005.

[7] H.-S. Kwon, Y.-J. Kim, and J. Stuart Bolton. Compensation for source nonstationarity in multireference, scan-based near-field acoustical holography. *Journal of the Acoustical Society of America*, 113:360–368, 2003.

[8] Sandra Morales-Cervera. Virtual reality system for musical performance practice. Master's thesis, Institute of Sound and Vibration Research, 2011.

[9] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders. *Fundamentals of Acoustics*. Spon Press, 3rd edition, 1982.

[10] K. Shin and J. K. Hammond. *Fundamentals of signal processing for sound and vibration engineers*. John Wiley & Sons, 2008.

[11] Donald B. Percival and Andrew T. Walden. *Spectral analysis for physical applications*. Cambridge University Press, 1993.