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PERFORMANCE OF P-P AND P-U INTENSITY PROBES USING SCAN & PAINT

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This paper aims to clarify the principal advantages and disadvantages of using sound intensity probes which implement different measurement principles: p-p probes versus p-u probes or Microflowns. A novel measurement technique based on scanning principles called "Scan & Paint" had been chosen to evaluate their performance.

1. Introduction

Scan & Paint is a novel measurement technique under development for mapping stationary sound fields [1–3]. It minimises the measurement time whilst maximising the flexibility. Basically, a transducer is swept around a virtual 2D plane close to a noise source while a video is recorded. Sound maps can be created by mixing the tracking information with the signal acquired. Sound intensity can be characterised either using a p-u probe or Microflown intensity probe to measure pressure and particle velocity directly; or using a p-p probe to approximate the velocity from the gradient between two pressure microphones close to each other. Advantages and disadvantages of each method have been discussed.

2. Theory

2.1 Particle velocity

The local velocity of a fluid moving backwards and forwards due to a moving surface which displaces a volume is known as particle velocity. Consequently, this magnitude is proportional to the excitation source displacement. Depending on the direction of the flow this quantity can be positive or negative. Then, this magnitude can be defined as

$$\vec{u}(t) = \frac{\partial \vec{\xi}}{\partial t} \tag{1}$$

where $\vec{\xi}$ is the particle displacement. If only the normal velocity is considered, Equation (1) can related to the pressure by

$$u_n(t) = -(1/\rho_0) \int_{-\infty}^{t} (\partial p(\tau)/\partial \vec{n})\, d\tau \tag{2}$$

where ρ_0 is the density of air and p is sound pressure. There are two different approaches to measure $u_n(t)$: directly with a Microflown, or indirectly from pressure measurements.

Direct method

Nowadays, the Microflown particle velocity sensor is the only way to measure acoustic particle velocity directly. The response of this transducer has to be corrected in order to reach a flat frequency response with also linear phase. Sensitivity (S_c) and phase response (ϕ_c) of the sensor have been measured and combined into a complex correction function $C_f(\omega)$

$$C_f(\omega) = S_c\, e^{j\phi_c} \tag{3}$$

Then, any measured signal will be divided by this correction function in the frequency domain.

Indirect method

Indirect methods of measuring particle velocity are based on an approximation of the pressure gradient shown in Equation (2) by taking the pressure difference between signals produced by two microphones situated close to each other, separated by a distance d [4],

$$u_n(t) \approx -(1/\rho_0\, d) \int_{-\infty}^{t} [p_2(\tau) - p_1(\tau)]\, d\tau \tag{4}$$

Next, the Fourier transform of the last expression can be undertaken in order to reach a definition in the frequency domain. Hence,

$$U_n(\omega) \approx -\frac{1}{j\omega\, \rho_0\, d}[P_2(\omega) - P_1(\omega)]\, d\tau \tag{5}$$

Now, the square magnitude of the normal particle velocity can be defined as

$$|U_n(\omega)|^2 \approx -\left|\frac{1}{j\omega\, \rho_0\, d}\right|^2 (|P_1(\omega)|^2 + |P_2(\omega)|^2 - P_1(\omega)P_2{}^*(\omega) - P_2(\omega)P_1{}^*(\omega)) \tag{6}$$

Furthermore, the above expression can be simplified by calculating the power spectral density and the cross-spectral products between the two pressure signals in order to reach a simplified expression.

$$|U_n(\omega)|^2 \approx -\left|\frac{1}{j\omega\, \rho_0\, d}\right|^2 (S_{p_1p_1}(\omega) + S_{p_2p_2}(\omega) - S_{p_1p_2}(\omega) - S_{p_2p_1}(\omega)) \tag{7}$$

Finally, the sound particle velocity level can be calculated by taking the logarithmic form of Equation (7), i.e.

$$SUL(\omega) \approx 10\, log_{10}\left(\frac{|U_n(\omega)|^2}{U_{ref}{}^2}\right) \tag{8}$$

where U_{ref} is the particle velocity reference (in air 5x10^{-8}).

2.2 Sound intensity

The instantaneous intensity $I(t)$ of a sound wave is the instantaneous rate per unit area at which work is done by one element of fluid on an adjacent element [5]. It is obtained as the product of pressure and particle velocity ($I(t) = pu$). It is a measure in Watts per square meter (W/m^2). The intensity I is usually defined as the time average of $I(t)$, so the time-averaged rate of energy transmission through a unit area normal to the direction of propagation,

$$I = < I(t) >_T = < pu >_T = \frac{1}{T}\int_0^T pu\, dt. \tag{9}$$

Because of its intrinsic dependency on particle velocity, there are two methods to estimate sound intensity: direclty using a p-u intensity probe; or indirectly by using a p-p intensity probe (two pressure microphones). An interesting discussion of the limitations of direct and indirect principles is given in [6].

Direct method

In order to obtain the time-averaged intensity using a p-u probe, the general expression (Equation (9)) can be implemented as,

$$I(\omega) = \mathrm{Real}(S_{pu}(\omega)) \tag{10}$$

where S_{pu} is the cross spectrum between the pressure and particle velocity signals acquired.

Indirect method

Using a p-p probe, an approximate method for estimating sound intensity has to be used. Starting with Equation (9), particle velocity can be approximated as the gradient between two pressure microphones close to each other (see Section 2.1)

$$I_n(t) \approx (1/2\rho_0\, d)[p_1(t) + p_2(t)] \int_{-\infty}^{t} [p_1(\tau) - p_2(\tau)]\, d\tau \tag{11}$$

Now, taking the Fourier Transform of Equation (11) leads to an expression for calculating sound intensity in the frequency domain,

$$I(\omega) \approx -\frac{1}{\omega\rho_0 d}\mathrm{Imag}(S_{p_1p_2}(\omega)) \tag{12}$$

where $S_{p_1p_2}$ is the cross spectrum of the two pressure measured.

3. Measurement procedure

The measurements undertaken aim to characterise intensity variations in a virtual 2D plane. Moving the transducer perfectly on this virtual plane is impracticable, a robot arm would be required and it would increase the cost of the experiments and, at the same time, it would decrease the flexibility of the measurement technique. Consequently, alternative ways of defining, at least, a reference have been established.

A cross-laser can be used to create a visual reference to move the microphone across a plane. Even without any measure of the positioning error, the lack of technology may be replaced by carefulness. A visual mark can be made in the microphone to move it with the laser light always close to the mark. The accuracy of the measurements then depends on the person who undertakes the measurements. However, due to the intrinsic averaging of several sweeps, human error can be neglected, as can be seen in the next section.

4. Results and discussion

Intensity probes have to be tested under critical conditions in order to see their limitations clearly. Therefore, a fairly soft broadband noise source would be a proper device to be measured. Following this criterion, the noise from a laptop computer has been measured with p-p and p-u intensity probes. Three different measurement environments were evaluated: the ISVR anechoic chamber (Southampton, UK), a semi-anechoic chamber in the University of Vigo (Spain) and a small isolated room at Microflown (Holland). According to [7], it has been proven that the measurement scenario does not bias the results significantly as far as the noise floor remains constant. Due to the proximity of the measurement plane, only high reverberation would spread the energy smoothly around the main noise source. Nonetheless, the sound maps shown are not much affected by the environment due to the low reverberation time of all rooms.

Furthermore, the physical characteristics of p-p and p-u probes are another important point to take into account. The technique relies on tracking the position of an LED light attached to the transducer. The height difference between the light and transducer has to be corrected. The projection error corrections are explained in detail in [7], but it is important to consider that if the LED is far away from the transducer, systematic errors will increase. For instance, the commercial p-p probe used for taking the measurements presented (B & K 3595) had the LED attached 0.12 m away from the transducer centre. In contrast, using the Microflown p-u probe, the LED was coupled only 0.02 m away from the sensor, leading to significantly reduced errors on the projection correction.

The efficiency of p-p and p-u probes have been compared in the following sections assessing several frequency bands. Moreover, results have been presented in multiple figures which follow a common pattern. Two different situations have been distinguished. First row shows intensity maps with low fan speed in an anechoic chamber using p-p probes using different techniques: step-by-step (left) and Scan& Paint (right). On the other hand, the second row presents Scan& Paint results from high fan speed measurements using a p-u (left) and a p-p probe (right) at Microflown Technologies and a semi-anechoic chamber, respectively. Therefore, the top left pictures should be considered as the reference, since each point of the mesh has been measured individually, taking more than 3 hours to acquire all data; whereas, the other three intensity maps were measured using Scan& Paint with different probes which only took 3 minutes to record the data.

4.1 Lower frequencies

Manipulation noise has been proven to be the most critical issue using p-p probes [7]. Disturbances are produced due to dragging the cable over the floor when the probe is swept. The lack of isolation of commercial p-p probes to structural vibrations is the weakest feature of its performance. Manipulation noise mainly affects the lower frequencies, leading to random peaks in the sound intensity maps up to 1 kHz. In contrast, Microflown transducers are highly isolated against structural noise, leading to better results in the lower bands.

Figure 1 shows intensity maps in the 125 Hz octave band. As can be seen from these figures, p-u probes perfectly works from 125 Hz, achieving an outstanding signal to noise ratio against manipulation noise. There are no perceivable peaks at any point over the map even with a very low minimum level (32 dB). In contrast, p-p probes cannot visualize any clear pattern at all for 125 Hz. Results are even more similar to the step-by-step measurements in the next octave band, at 250 Hz, but the p-p performance is still far better than the p-u probe.

4.2 Middle frequencies

There is not much influence of manipulation noise at frequencies over 500 Hz. At middle frequency bands, measurements undertaken with a p-p probe are not biased by any huge peak which

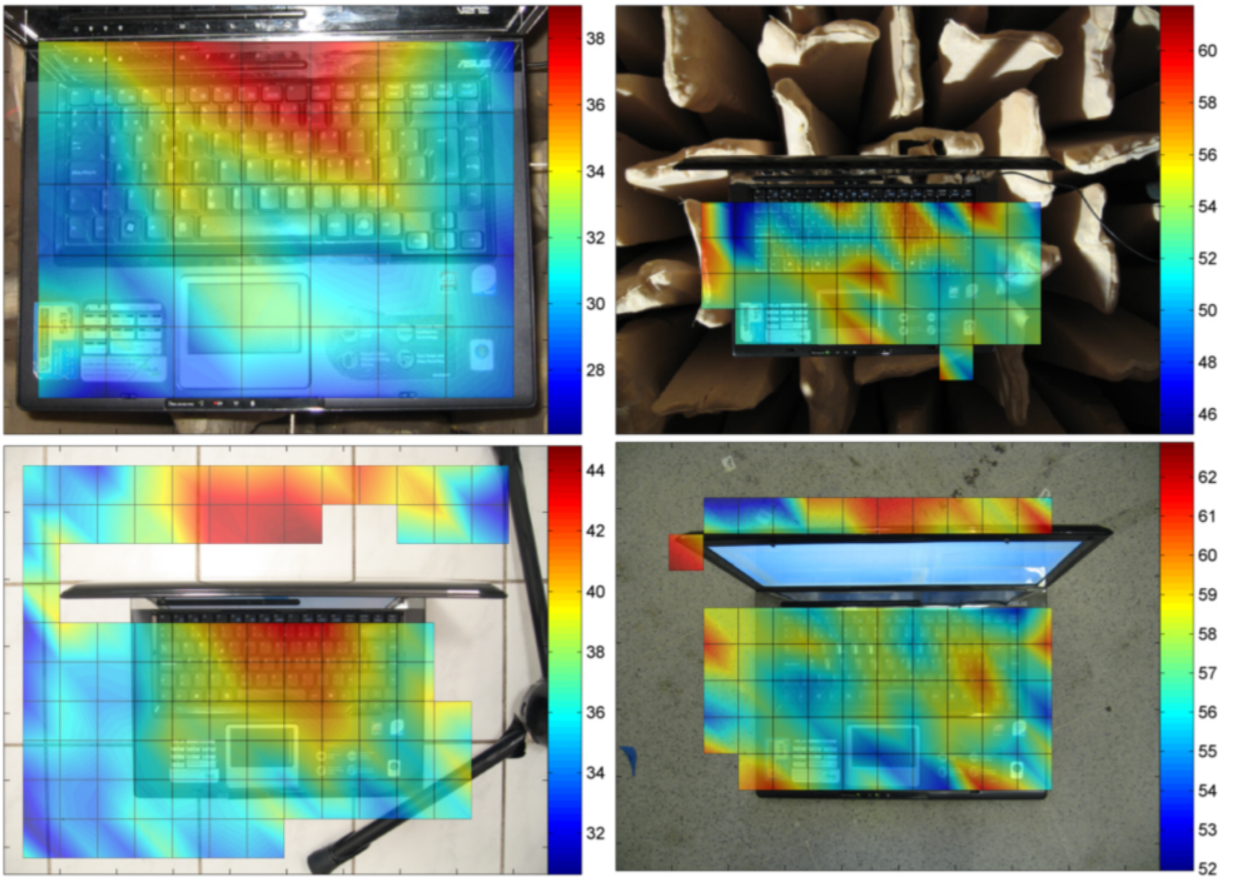

Figure 1: 125 Hz intensity maps: step-by-step measurements with p-p probe and low fan speed (top-left); Scan&Paint with p-p probe and low fan speed (top-right); Scan&Paint with p-u probe and high fan speed (bottom-left); Scan&Paint with p-p probe and high fan speed (bottom-right).

masks the useful information, as can be seen from Figure 2. Now, the intensity maps match perfectly with each other[1].

Evaluating in detail the contour shapes, measurements undertaken using p-u probes have more regular maps giving clearer pictures charactering intensity variations. Consequently, even without much influence of manipulation noise, again in the middle frequencies, p-u presents better performance.

4.3 Higher frequencies

High frequency octave bands are completely isolated against manipulation noise. Consequently, the sound maps generated, either with the p-p probes or with p-u probe, perfectly measure the sound pressure and intensity variations around a virtual surface as far as there is no errors in the projection correction.

Figure 3 present results obtained from different tests performed with high and low fan noise. As can be seen from these figures, all results perfectly match independently of the environment or transducer used.

5. Conclusions

Either p-p or p-u intensity probes can be used to undertake scanning measurements such as using the Scan&Paint method. However, it has been proven that p-u probes are able to measure at lower

[1]Note that intensity levels of graphs excited with high fan speed (first and second row) and low fan speed (third and fourth row) have to be compared separately

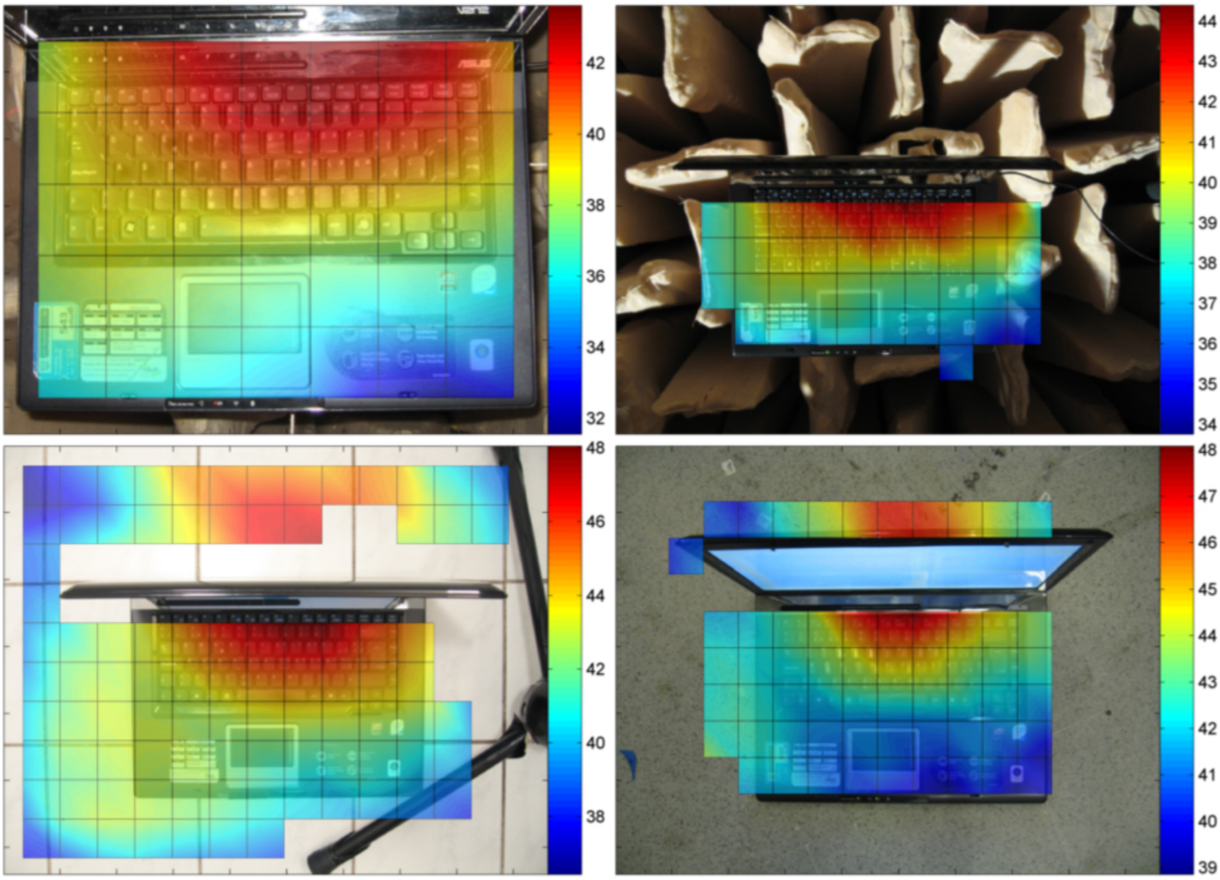

Figure 2: 1 kHz intensity maps: step-by-step measurements with p-p probe and low fan speed (top-left); Scan&Paint with p-p probe and low fan speed (top-right); Scan&Paint with p-u probe and high fan speed (bottom-left); Scan&Paint with p-p probe and high fan speed (bottom-right).

frequency bands very clearly, with a high signal to noise ratio; while p-p probes cannot do it due to its poor isolation from handling noise. Furthermore, p-u probes also present a significant performance improvement in middle frequency bands. Moreover, systematic errors are minimised using a p-u probe, due to its geometric features: it is possible to couple the LED light closer to the transducer, reducing errors on the projection correction. Therefore, it can be concluded that p-u intensity probes have much better performance than p-p probes for measuring with scanning techniques.

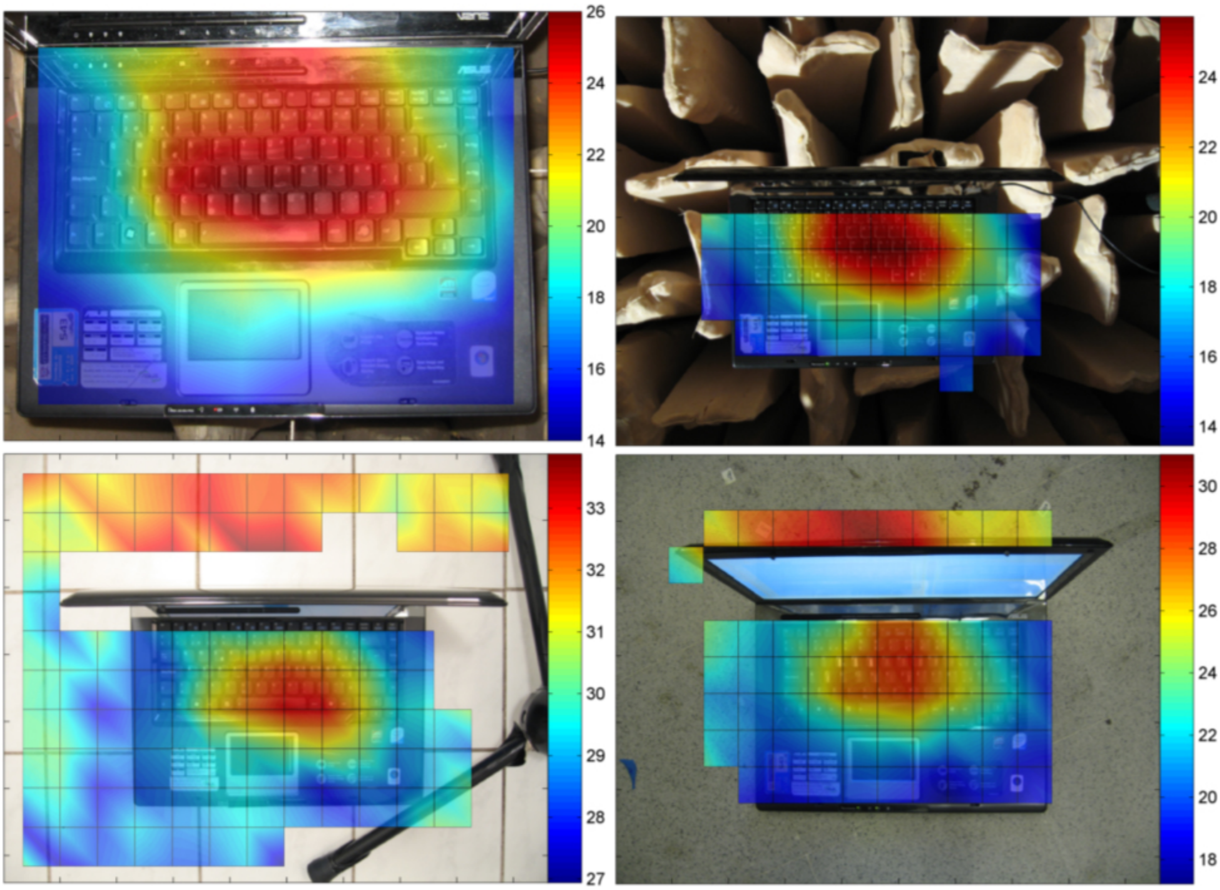

Figure 3: 8 kHz intensity maps: step-by-step measurements with p-p probe and low fan speed (top-left); Scan&Paint with p-p probe and low fan speed (top-right); Scan&Paint with p-u probe and high fan speed (bottom-left); Scan&Paint with p-p probe and high fan speed (bottom-right).

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