A NOVEL IN-SITU CALIBRATION METHOD FOR ACOUSTIC PARTICLE VELOCITY SENSORS BASED ON SURFACE VELOCITY

Daniel Fernandez Comesana, Emiel Tijs, Martijn Janszen and Graciano Carrillo Pousa
Microflown Technologies, Tivolilaan 205, Arnhem, the Netherlands
email: fernandez@microflown.com

The lack of standardized procedures for characterizing particle velocity sensors has triggered the development of novel calibration methods. Most current techniques use sound pressure measurements in combination with acoustic impedance models in order to estimate the particle velocity perceived at a given location. Measurements performed in a standing wave tube allow for accurate acquisition of both quantities but in a rather constrained frequency range. Alternatively, a full-bandwidth calibration method has also been proposed based on a two-step approach: high frequency calibration in free field conditions and low frequency calibration measuring sound pressure inside the source. Despite the accuracy of the latter method, it is fairly complex and has to be performed in a controlled environment. In this paper, a novel calibration method is introduced based upon surface velocity measurements of a moving, rigid enclosure while the sensor remains static. It is shown that the surface displacement of the cavity is directly related to the particle velocity perceived by the sensor providing the wavelength of the sound is far greater than the cavity dimensions. The foundations of this in-situ technique are introduced along with the experimental investigation of a prototype calibrator.

1. Introduction

For several years the direct measurement of acoustic particle velocity in air has been possible using a particle velocity transducer called the Microflown [2]. The combination of a particle velocity sensor with a small pressure microphone yields a compact pressure-velocity sound probe suitable for multiple applications [3] such as sound intensity measurements [7], direct sound visualization [14], near-field acoustic holography [5], acoustic absorption and impedance [12], or sound energy analysis [6].

A reliable calibration procedure is crucial for relating sensor output to the physical quantity perceived. Unlike microphone calibration, there is no standardized procedures yet defined for characterizing the broadband response of particle velocity sensors. Microflown sensors were originally calibrated using a sound pressure microphone as a reference in a standing wave tube, where the ratio between sound pressure and particle velocity (i.e. acoustic impedance) is well understood. Later, more broadband methods such as the "Piston-On-a-Sphere" technique (POS) were developed [8]. This approach relies on a sound source of known impedance measured in free field conditions and achieves good results at mid and high frequencies. Thereafter, the POS method has been extended to lower frequencies by also measuring the acoustic pressure inside the sound source [1]. As a result, a full-bandwidth calibration procedure is now available by combining the two measurement procedures.

Most current particle velocity calibration methods rely upon the combination of a pressure microphone with an acoustic model of the sound source and/or the testing environment. These techniques are influenced by factors such as temperature, humidity or probe mounting. Although good results are achieved in controlled conditions with either a standing wave tube [8] or the POS method [13], both solutions are usually unsuitable for in-situ testing. It is therefore of high practical value to find a portable solution which enables the calibration of a particle velocity sensor before starting a measurement campaign.

A system employing surface velocity measurements as a reference can greatly reduce the sources of error in a calibration process. Several techniques have been proposed [4, 11, 10]. However, the current calibration procedures based upon this principle are rather cumbersome. In this paper, a novel method is introduced based upon surface velocity measurements of a moving, rigid cavity while the sensor remains static. The foundations of this technique are introduced along with the experimental validation of a prototype calibrator.

2. Sound field inside a moving rigid enclosure

The proposed calibration method benefits from the relationship between surface velocity and particle velocity inside a moving rigid enclosure. This section provides the formulation of the calibration method. Fig. 1 shows a sketch of the assessed scenario.

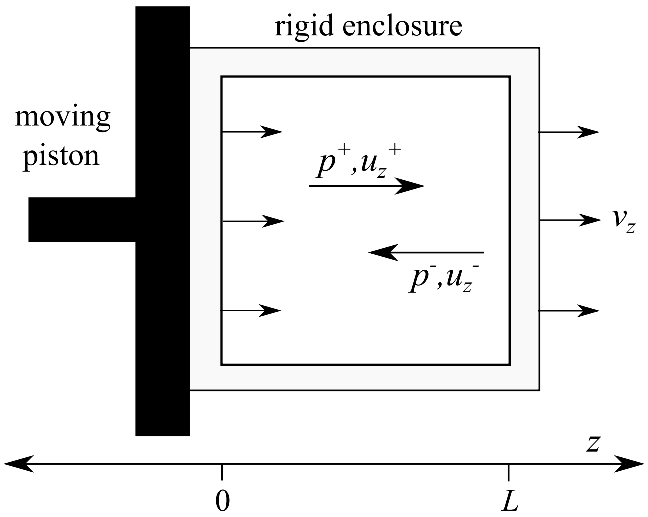

Figure 1: Sketch of the calibration device.

The sound field in a uniform cavity with rigid walls can be modeled as one-dimensional below a certain frequency which is dependent upon its cross-sectional shape and dimensions [9]. This effectively implies that the sound inside the enclosure can be understood as a superposition of plane waves traveling in opposite directions. For a harmonic excitation, the sound pressure p and the axial component of the particle velocity u_z become

$$p = p^+ + p^- = Ae^{-jkz} + Be^{jkz} \tag{1}$$

$$u_z = u_z^+ + u_z^- = \frac{A}{\rho_0 c_0} e^{-jkz} - \frac{B}{\rho_0 c_0} e^{jkz} \tag{2}$$

where A and B are the complex amplitudes of the plane waves traveling through the cavity; k is the wavenumber (ω/c_0) and $\rho_0 c_0$ is the characteristic acoustic impedance of the medium.

The amplitude and phase of each plane wave can be calculated by applying the corresponding boundary conditions. For the case studied, it is assumed that the enclosure moves with a surface velocity $v_z(0) = v_z(L) = U$ at both ends. Since particle velocity equals surface velocity at the rigid boundary the previous expressions yields

(3) $$A = \rho_0 c_0 U \left(\frac{e^{jkL}}{e^{jkL} + 1} \right)$$

(4) $$B = \rho_0 c_0 U \left(\frac{-1}{e^{jkL} + 1} \right)$$

The sound field along the tube can be then defined as

(5) $$p = \rho_0 c_0 U \frac{\left(e^{jk(L-z)} - e^{jkz} \right)}{e^{jkL} + 1}$$

(6) $$u_z = U \frac{\left(e^{jk(L-z)} + e^{jkz} \right)}{e^{jkL} + 1}$$

From the above expressions it can be inferred that the particle velocity measured at any point inside the cavity becomes approximately equal to surface velocity ($u_z \approx U$) when the product between wavenumber and enclosure length is sufficiently small ($kL << \pi$). Therefore, the frequency limit imposed by the enclosure length can be defined as

(7) $$\frac{2\pi f_c}{c_0} L = \pi \ \rightarrow f_c = \frac{c_0}{2L}$$

As an example, Fig. 2 shows the spatial distribution of sound pressure and particle velocity as well as the ratio between surface velocity and particle velocity measured along the moving cavity. Although the sound pressure distribution rapidly changes across the cavity, the particle velocity levels are almost constant and approximately equal to the surface velocity, illustrating the favorable conditions inside the moving cavity for calibrating particle velocity sensors.

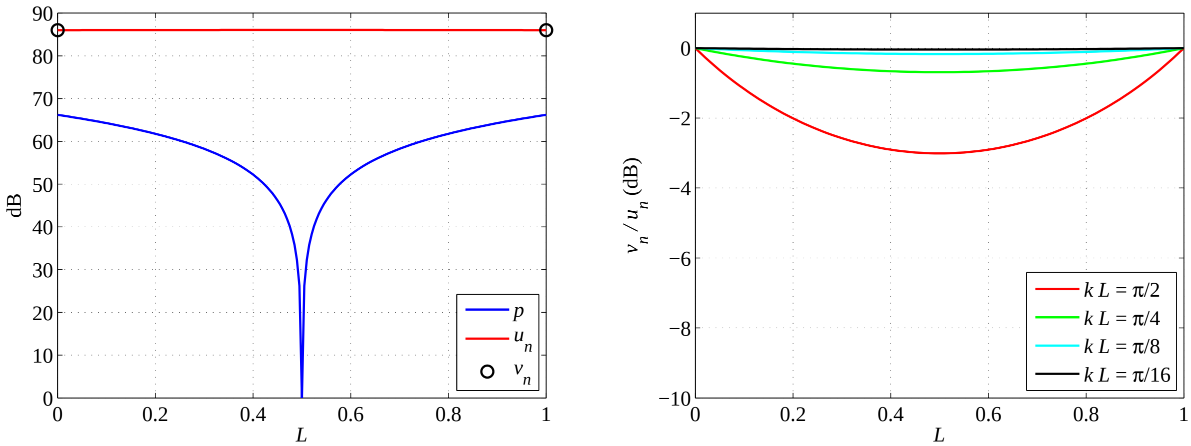

Figure 2: Spatial distribution of the sound pressure and axial particle velocity inside a moving cavity for $kL = \pi/16$ and $U = 10^{-4}$ m/s (left); and ratio between surface velocity and the acoustic particle velocity inside the cavity (right).

3. Simulation and prototype design

There are several aspects that must be addressed carefully in order to design a robust calibration device based on the moving enclosure principle. The main theoretical and practical considerations are assessed in this section.

3.1 Cavity dimensions

The frequency range in which particle velocity is approximately equal to surface velocity is determined by the dimensions of the moving cavity. The formulation derived in Section 2 holds as long as the sound propagation inside the cavity can be assumed one-dimensional, i.e. below the first non-axisymmetric mode of the enclosure. Different expressions to define critical frequency can be found depending on the cross-section of the enclosure. For a cylindrical shape with radius a, the maximum frequency for the plane wave assumption is defined as [9]

$$f_{circ} \approx \frac{1.84\, c_0}{2\pi a} \tag{8}$$

Alternatively, for an enclosure with a rectangular cross-section

$$f_{sq} = \frac{c_0}{2L_{max}} \tag{9}$$

where L_{max} corresponds to the maximum length that the section can have. Eq. 8 and Eq. 9 can be compared assuming that $L_{max} = 2a$ in order to choose the most efficient shape in terms of space. Applying this criteria it can be demonstrated that $f_{circ} > f_{sq}$ and therefore the circular cross-section is the most suitable due to its higher frequency limit.

Furthermore, as shown in Eq. 7, the length of the cavity also plays a key role in determining the frequency range of a calibration device. Fig. 3 presents the response obtained after evaluating Eq. 6 for several enclosure lengths. As can be seen, the shortest possible length leads to the best performance. However, the volume of the probe should be smaller than the cavity volume in order to minimize acoustic interferences. Thus, the practical limit should be defined via experiments.

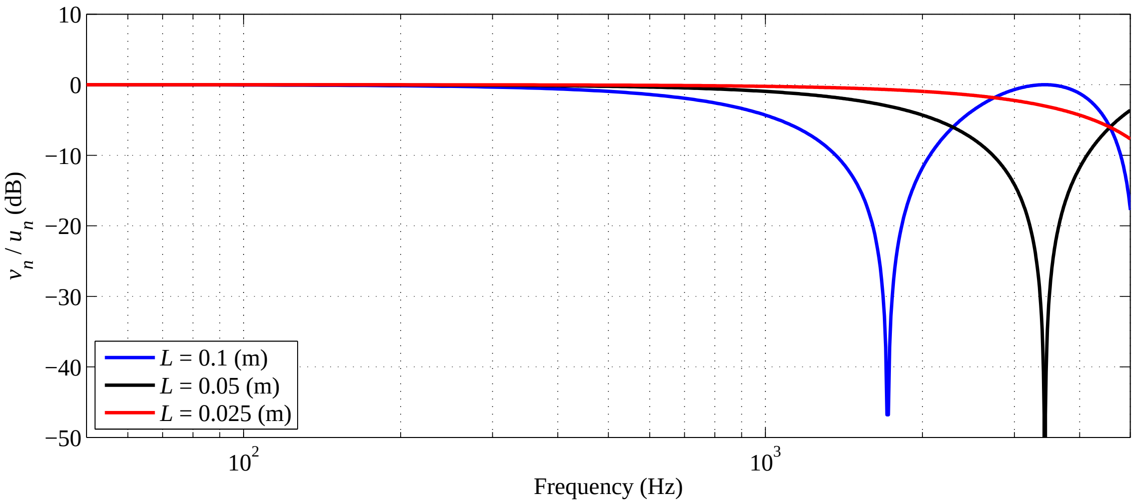

Figure 3: Ratio of surface to particle velocity against frequency for different cavity lengths.

3.2 Impact of the measurement conditions

Traditional calibration methods are influenced by environmental conditions, such as temperature and relative humidity. Those factors affect not only the specific impedance model used but also the reference sensor. The corresponding correction factors should therefore be applied every time a calibration is performed. One of the main aims of the proposed device is to be able to simplify the calibration process as much as possible whilst preserving accuracy. Fig. 4 illustrates the variations that appear with different speeds of sound either due to changes in temperature (left) or humidity (right) of a cavity of length $L = 0.03$ m and a diameter of $S = 0.03$ m. As shown, the effect is negligible in the studied frequency range, below 5 kHz.

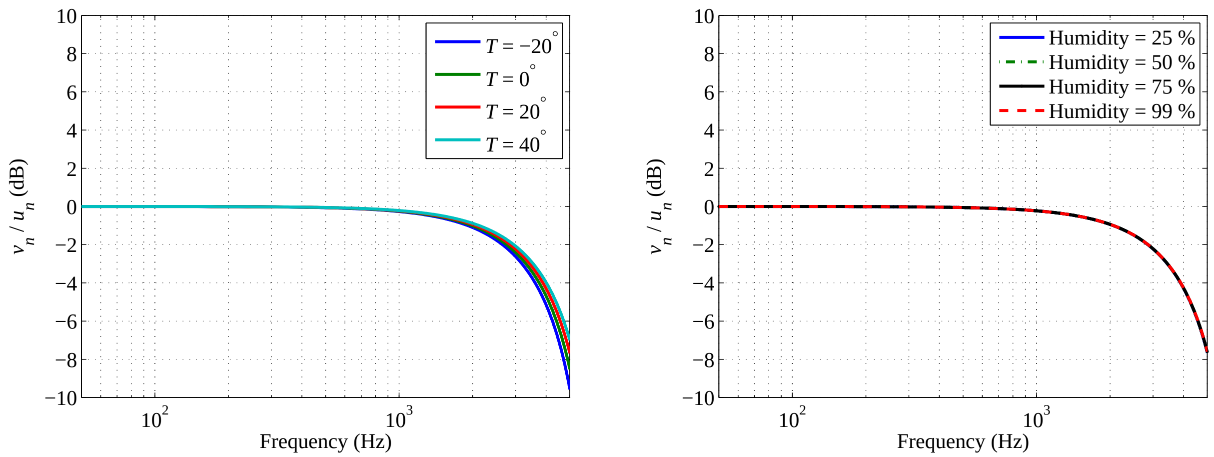

Figure 4: Ratio of surface velocity to particle velocity at the center of a moving cavity for several temperatures (left) and relative humidities (right).

3.3 Reference sensor

The oscillating movement of the enclosure can be measured using either contact or non-contact transducers. Laser Doppler vibrometers, optical probes, inductive sensors or capacitive sensors are able to estimate small displacements with high accuracy. However, the rather complex measurement setup, fragility or high price of the current available solutions hamper the implementation of such technologies. In contrast, there is a wide range of accelerometers available which also enable accurate surface velocity measurements providing that they are attached to the moving surface. In addition, accelerometers are small, can be integrated without affecting the sound field inside the device and are stable for different ambient conditions. Consequently, this technology has been selected for the reference sensor.

Surface acceleration is defined as the temporal derivative of the surface velocity. Therefore, for a stationary harmonic piston movement with a normal velocity of $v_n = Ue^{j(\omega t+k\phi)}$, it can be established that

$$a_z = \frac{\partial v_z}{\partial t} = j\omega U e^{j(\omega t+k\phi)} = j\omega v_z \tag{10}$$

This simple relationship enables the computation of surface velocity from the signal produced by an accelerometer. In addition, the calculation of the transfer function between the particle velocity sensor and the reference velocity (assuming that $kL << \pi$) will yield the following relationship

$$\frac{H_1(\omega)}{j\omega} = \frac{a_z}{j\omega u_z} \approx 1 \tag{11}$$

4. Moving cavity sensitivity

The sensitivity of a particle velocity sensor S_u can be determined by combining the ratio of the particle velocity signal (in Volts) and the output of the reference accelerometer sensor (in Volts) with some parameters that describe the cavity dimensions and the measurement position as such

$$S_u \left[\frac{\mathrm{V}}{\mathrm{ms}^{-1}}\right] = \frac{u_z}{a_z}\left[\frac{\mathrm{V}}{\mathrm{V}}\right] \cdot j\omega\, S_a \left[\frac{\mathrm{V}}{\mathrm{ms}^{-1}}\right] \cdot H_{vu}\left[\frac{\mathrm{ms}^{-1}}{\mathrm{ms}^{-1}}\right] \tag{12}$$

where S_a is the sensitivity of the reference accelerometer and H_{vu} is the theoretical ratio between surface velocity and particle velocity that can be extracted from Eq. 6, i.e.

$$H_{vu} = \frac{U}{u_z} = \frac{e^{jkL}+1}{e^{jk(L-z)}+e^{jkz}} \tag{13}$$

In practice, if the measurement is performed at the center of the cavity ($z = L/2$), the above expression simplifies to the real expression

$$H_{vu}(L/2) = \cos\left(\frac{kL}{2}\right) \quad (14)$$

5. Experimental evaluation

A series of experiments were carried out to evaluate the performance of the proposed calibration method. A testing prototype was build using a acrylic glass structure attached to a loudspeaker driver. Although several configurations were tested and compared to simulations achieving very similar results, for the sake of simplicity this section evaluates one particular configuration. A picture of the setup is shown in Fig. 5.

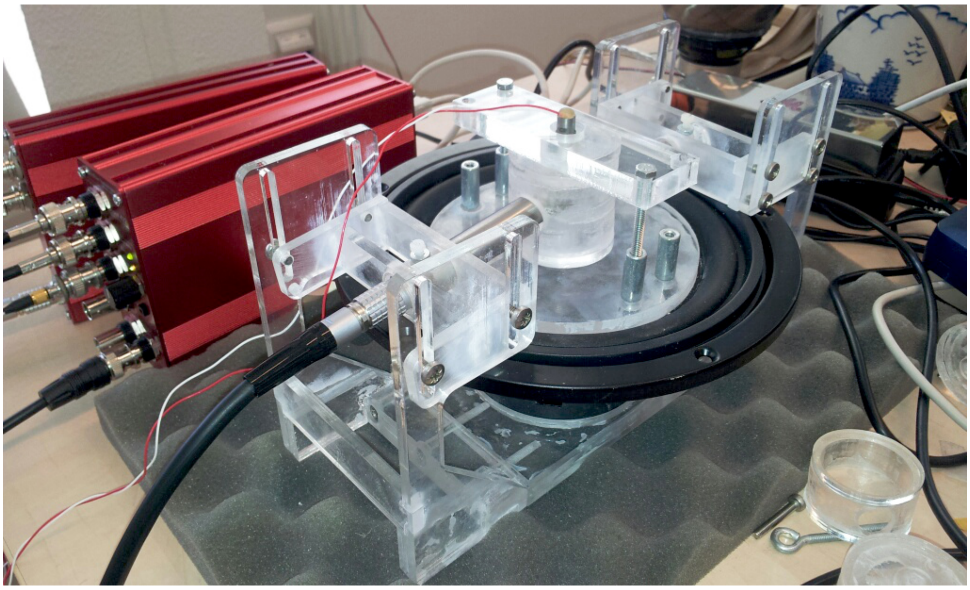

Figure 5: Picture of the measurement setup.

The investigation hereby presented is focused on studying the ratio of surface velocity to particle velocity using a cavity of length 31mm, diameter 41mm and wall thickness 1mm. The calibrated output signal from a Microflown *p-u* probe (using the regular POS method) was combined with the signal from a PCB 352C17 accelerometer taking into account the conversion factors from surface acceleration to velocity (see Eq. 10). A comparison of the experimental and simulated results is presented on the left hand side of Fig. 6. As shown, the theoretical model matches the experimental data in the frequency range of interest (approximately below 4 kHz). The small deviations at high frequencies could be due to the measurement setup since the size of the probe becomes comparable to the sound wavelength. However, the slight deviation measured at low frequencies could be introduced by either the reference accelerometer, the measurement setup or due to deviations in the original POS calibration. Nevertheless, similar results are achieved from 50 Hz to 4 kHz.

In addition, the original sensitivity provided by the manufacturer using the POS method is compared with the new sensitivity obtained according to Eq. 12. As can be seen, the new estimated calibration curve is very similar to the POS calibration in the frequency range where the moving enclosure principle can be applied, i.e. below the critical frequency of the cavity. Although the frequency range of the proposed method is more constrained than with conventional POS calibration, the simplicity of the setup and measurement process together with the robustness of the calibration principle raise the practical value of the introduced solution for in-situ testing.

In this paper only the magnitude of the particle velocity transducer has been taken into account, but as shown in Eq. 12, the phase relationship between the accelerometer and the particle velocity

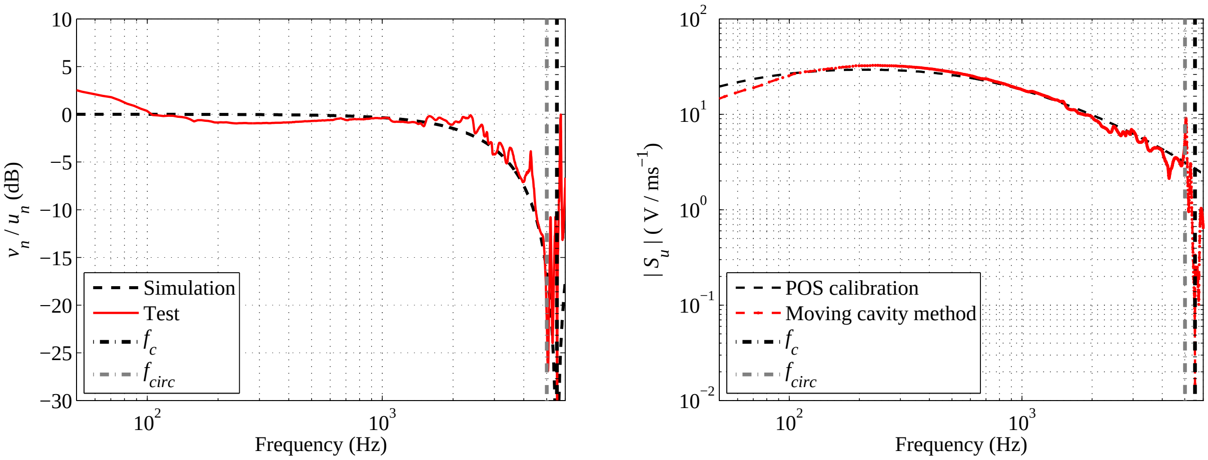

Figure 6: Simulated and measured ratio between surface velocity and particle velocity (left) and sensitivity comparison between the Piston-On-a-Sphere and the proposed method (right).

sensor should be linear. It is of practical interest though to characterize the relative phase between the particle velocity sensor and the pressure transducer of a *p*-*u* probe, since the relative phase change is of remarkable importance for intensity calculations [8]. Further investigation should be undertaken in order to achieve a pressure calibration using an accelerometer as reference to obtain a robust estimation of the relative phase between transducers.

6. Conclusions

A novel calibration principle has been introduced based upon the comparison of calibrated surface velocity measurements with the particle velocity perceived inside a moving, rigid enclosure. It has been proven that the surface displacement of the cavity is directly related to the particle velocity measured by the acoustic sensor providing the wavelength of the sound is far greater than the cavity dimensions ($kL << \pi$). The foundations of this technique have been evaluated throughout both simulations and experiments. Furthermore, test results demonstrate the high accuracy of the calibration method as well as a strong correlation with theoretical predictions, enabling the design of a prototype using the described theoretical framework.

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