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Simultaneous calibration of all three acoustic particle velocity components of a pressure-velocity probe

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ABSTRACT

The precise calibration of acoustic particle velocity sensors in pressure-velocity (p-v) probes is still a great challenge and not fully solved, since no standardized reference sensor exists. Current available techniques does not allow for simultaneous calibration of all three components of the particle velocity sensor. Furthermore, most of the available calibration procedures require anechoic conditions and guarantee the calibration just for a restricted frequency range. Therefore, we propose an advanced calibration technique for such p-v probes, which has the following properties: (1) simultaneous calibration of all three components of the particle velocity sensor; (2) does not need any anechoic conditions; (3) is not restricted to a specific frequency range. Thereby, the p-v probe is exposed to a sound field generated by a vibrating piston. The surface velocity of the piston itself is characterized over the whole frequency range by a laser vibrometer. This technique allows us to simultaneously calibrate all three components of the particle velocity sensor, if the azimuth and elevation angles are known. The advanced calibration technique for a three dimensional p-v probe is evaluated by showing first results and comparisons with the nominal correction curves specified by the manufacturer.

Keywords: Calibration, p-v probes, measurement technique

1. INTRODUCTION

The Microflown sensor, which is a Micro-Electro-Mechanical-System (MEMS) device, allows for a direct measurement of the acoustic particle velocity. There are different types of probes using the Microflown sensor. The standard probe (PU probe) is able to measure the particle velocity with one degree of freedom in translational direction (1D). The PU probe consists of a particle-velocity sensor in combination with a pressure microphone to determine sound intensity, sound energy and acoustic impedance in 1D. The state of the art sensor is the ultimate sound probe (USP). It is a three dimensional (3D) sound probe capable of measuring particle velocity in three orthogonal directions. The USP is able to measure the 3D particle velocity, the sound pressure, 3D sound intensity, sound energy and 3D acoustic impedance [10].

In this paper, we first provide an overview of the standard calibration. Moreover, we describe our advanced calibration technique by explaining the experimental setup, the theoretical background and showing first calibration results in comparison to the nominal correction curves.

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2. STANDARD CALIBRATION TECHNIQUES

The calibration of the pressure microphone is straight forward. We just need a calibrated microphone and then compare the microphone's frequency response to that of the USP pressure microphone. However, the calibration of the particle velocity is much more involved.

There are several p-v probe calibration techniques described in literature. First, there is the far field method that requires nearly free field conditions in an anechoic room. Second, two near field methods exist, where on the one hand the sound field in front of a small hole in a plane baffle is used, and on the other hand the sound is emitted from a hole in a spherical baffle. In addition to this, a calibration technique based on an impedance tube and a progressive plane wave calibration is described.

In the following, we will describe calibration methods based on sound fields with known acoustic impedance characteristic. With a calibrated pressure microphone, the resulting particle velocity can be calculated which is known as called indirect calibration.

2.1 Far field method

The simplest sound field is a propagating plane wave with its specific acoustic impedance

$$Z^{(1)} = Z_0 = \rho c, \tag{1}$$

where c is the speed of sound ρ the mean density of the medium. However, it has to be noticed that at low frequencies plane wave conditions cannot be achieved. In the far field of a point source the specific acoustic impedance computes by

$$Z^{(2)} = Z_0 \frac{jkr}{1 + jkr}. \tag{2}$$

In (2) k denotes the wave number and r the distance to the monopole source. A propagating plane wave can be assumed, when the phase is close to zero degree. In Figure 1 the phase of $Z^{(2)}$ is shown. At kr values of 50 the phase shift is approximately one degree. Nevertheless, at low frequencies of about a few hundred Herz the phase shift cannot be neglect even at a distance of four meters. Thus, a very large anechoic room of high quality and a monopole loudspeaker is needed. Furthermore, at low frequencies the background noise may be higher than the sound generated by the source. Therefore in combination with large distances to the sound source calibration errors will occur. Summarizing, this calibration technique is restricted to laboratory environments, and hence not feasible for practice.

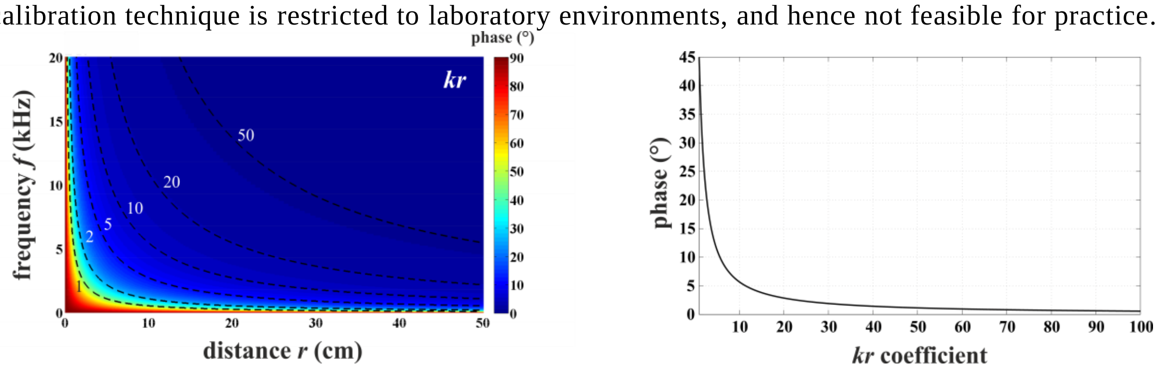

Figure 1 – Calculated phase computed according to $Z^{(2)}$.

2.2 Near field methods

Because there is no ideal monopole source, F. Jacobsen presented two solutions to perform calibrations with monopole like sources [1] in order to calibrate p-v probes by means of a well defined sound field with known relation between pressure and velocity.

2.2.1 Monopole on a rigid plane baffle

The first approach is based on a sound field directly in front of a hole in a large plane baffle. Thereby, the sound is generated by an enclosed loudspeaker on the back side of the plane baffle. The sound field can be modelled by a moving piston with radius a on an infinite baffle. The specific acoustic impedance computes as [2]

$$Z^{(3)} = 2Z_0\left[1+\frac{r}{\sqrt{a^2+r^2}} - j\left(1-\frac{r}{a^2+r^2}\right)\cot\left[\frac{k}{2}\left(\sqrt{a^2+r^2}-r\right)\right]\right]^{-1}. \quad (3)$$

2.2.2 Monopole on a rigid spherical baffle

Due to the finite dimensions of the plane baffle, there can be an influence of scattering and reflections from the edges of the plane baffle. Therefore, an acoustic source on a spherical baffle is proposed. The sound is generated a loudspeaker placed inside the sphere and radiates through a small hole in the hollow rigid sphere. The specific acoustic impedance in front of this circular hole of radius b in a spherical baffle with radius a can computed by [3]

$$Z^{(4)} = Z_0 \frac{\sum_{m=0}^{\infty}\left(P_{m-1}(\cos\alpha) - P_{m+1}(\cos\alpha)\right)\frac{h_m(kr)}{h_m^{'}(ka)}}{j\sum_{m=0}^{\infty}\left(P_{m-1}(\cos\alpha) - P_{m+1}(\cos\alpha)\right)\frac{h_m^{'}(kr)}{h_m^{'}(ka)}}. \quad (4)$$

In (4) α = arcsin(b/a), P_m is the Legendre function with order m and h_m the spherical Hankel function of second kind and order m. The hole in the spherical baffle can be modelled as a piston on a sphere. For the calibration of p-v probes a special loudspeaker (Piston on a Sphere Calibrator, POS) was designed by Microflown [4]. For this calibration method, a pressure microphone and the spherical loudspeaker are needed. The standard calibration is realized at high and low frequencies. Both calibration approaches were combined in order to calibrate the p-v probe. While calibrating a USP, with the three components of the velocity sensor, the calibration has to be performed three times since a simultaneous calibration of the three components is not possible.

2.3 Other techniques

A further method to calibrate the p-v probes by means of a known relation between acoustic pressure and particle velocity are standing wave tube techniques [5]. These approaches are limited to low frequencies, because of the tube’s cut-off frequency. Below this cut-off frequency the sound waves are assumed as plane.

Another technique, based on a plane wave assumption in a tube, is described in [6-7]. A plane wave sound field is generated inside an 84 m long and 2 cm wide tube. In this tube, the reference sound field can be modelled as a pure resistive constant impedance field with its specific acoustic impedance Z_0 described by (1) for frequencies below 10 kHz.

2.4 Electric model of the Microflown sensor

The frequency behaviour of a Microflown sensor can be modelled by an electric circuit, as depicted in Figure 2, consisting of two high pass filters (C_1, R_1 and C_4, R_4) and two low pass filters (R_2, C_2 and R_3, C_3). The first high pass filter represents the thermal boundary layer on the wires with a corner frequency in the order of f_1 = 50 Hz - 100 Hz. It takes time for heat to travel from one wire to the other one. This diffusion effects is modelled by the first low pass filter with a corner frequency of about f_2 = 1 kHz. The thermal mass of the sensor cannot vary at infinite speed is represented by the second low pass filter with a corner frequency in the order of about f_3 = 10 kHz.

As described in [8-9], the magnitude frequency response computes as

$$out = \frac{LFS}{\sqrt{1+\frac{f_1^2}{f^2}}\sqrt{1+\frac{f^2}{f_2^2}}\sqrt{1+\frac{f^2}{f_3^2}}\sqrt{1+\frac{f_4^2}{f^2}}}, \quad (5)$$

where LFS is the low frequency sensitivity at 250 Hz. The phase response is given by

$$phase = \arctan\left(\frac{c_1}{f}\right) - \arctan\left(\frac{f}{c_2}\right) - \arctan\left(\frac{f}{c_3}\right) + \arctan\left(\frac{c_4}{f}\right). \quad (6)$$

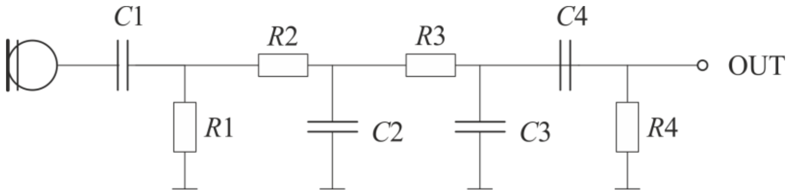

Figure 2 – Electric model of the Microflown sensor

The constants c_1, c_2, c_3 and c_4 are approximately the same as the corner frequencies f_1, f_2, f_3 and f_4. Equation (5) and (6) will be fitted to the default calibration results, obtained with the POS and provided by the manufacturer in order to obtain the calibration parameters. These calibration constants are provided for each particle velocity direction of the USP.

3. ADVANCED CALIBRATION TECHNIQUE

The calibration technique presented in this paper differs from the ones described in section 2 by the fact that we use instead of a reference sound field with known impedance a reference velocity field. This method is a direct calibration method and obtains the velocity sensors' magnitude and phase of the frequency response by means of a reference velocity field generated by a vibrating piston on an electrodynamic shaker.

3.1 Experimental setup

In the calibration procedure the B&K vibration exciter 4809 with a mounted vibrating piston, as displayed in Figure 3 is used. The surface velocity at the piston was characterized by a laser vibrometer

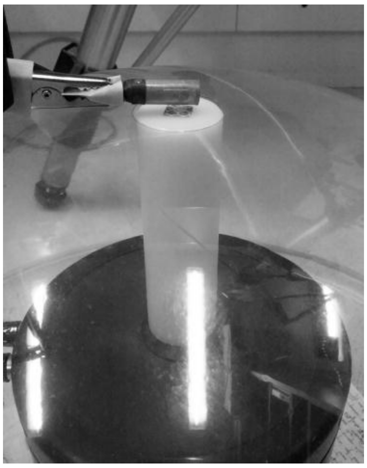
Figure 3 – Experimental set up; vibrating shaker with mounted piston.

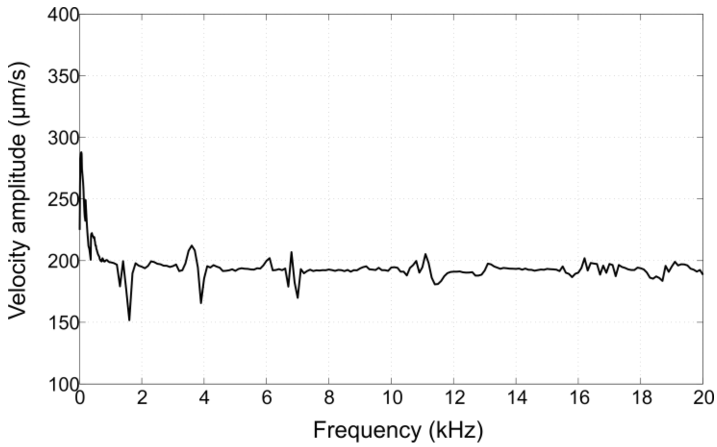

Figure 4 – Frequency depended velocity amplitude.

and a constant velocity amplitude at the surface of the piston is assumed over the frequency of interest. As depicted in Figure 4, we achieve almost a constant velocity amplitude over the whole audible bandwidth. Main deviations are just at low frequencies.

3.2 Theoretical background

The p-v probe is exposed to the known velocity field under two angles φ and θ which is described by a rotation of a coordinate system around two axis, starting with the initial system *xyz*. The velocity of the vibrating piston is only in *z* direction with its amplitude *v* and defined by

$$\vec{v} = v\begin{pmatrix}0\\0\\1\end{pmatrix}_{xyz}. \quad (5)$$

The coordinate system x*y*z*, shown in Figure 5 left, is obtained by rotating the initial coordinate system *xyz* by the angle φ around the *y*-axis. This new coordinate system is indicated by the index * and the velocity in * coordinates is defined by

$$\vec{v} = v\begin{pmatrix}\sin\varphi\\0\\\cos\varphi\end{pmatrix}_{*}. \quad (6)$$

If the *coordinate system is further rotated around the *x*-axis by an angle θ (see Figure 5 right) the velocity sensor in this new coordinate system ** is expressed by

$$\vec{v} = v\begin{pmatrix}\sin\varphi\cdot\cos\Theta\\-\sin\Theta\\\cos\varphi\cdot\cos\Theta\end{pmatrix}_{**}. \quad (6)$$

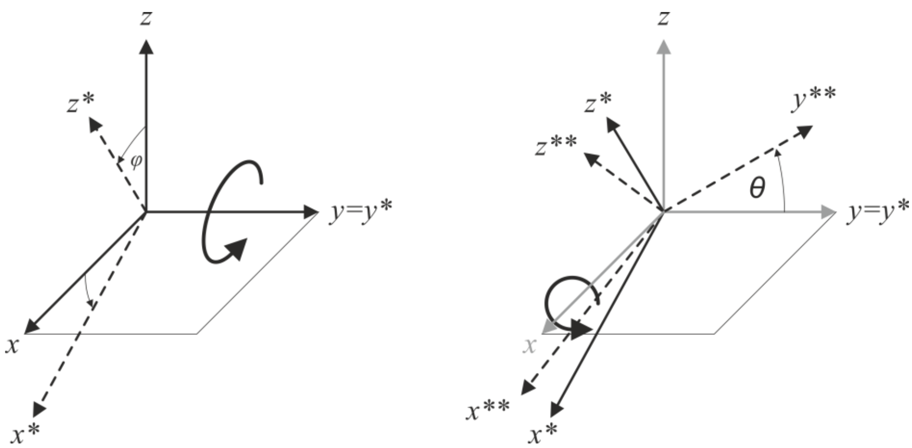

Figure 5 – Rotation of the coordinate systems.

In order to calibrate the three components of the particle velocity sensor, only the two angles φ and θ have to be known. This allows us to simultaneously calibrate the three components of the particle velocity by means of a reference velocity field generated by the vibrating piston.

4. FIRST RESULTS AND COMPARISON WITH STANDARD CALIBRATION

The introduced calibration procedure was performed in an ordinary room with no anechoic conditions. The device under test was a Microflown match sized USP with protection grid, which can be seen in Figure 3.

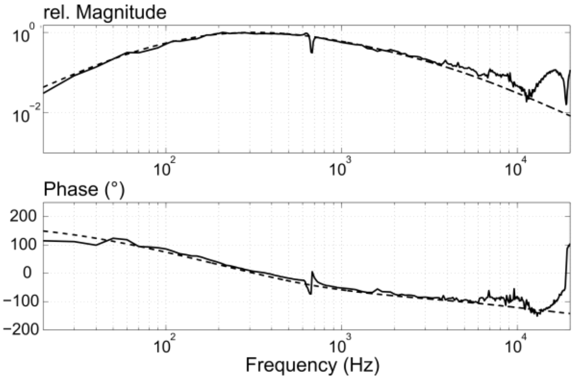

Figure 7 – Frequency response sensor 1.

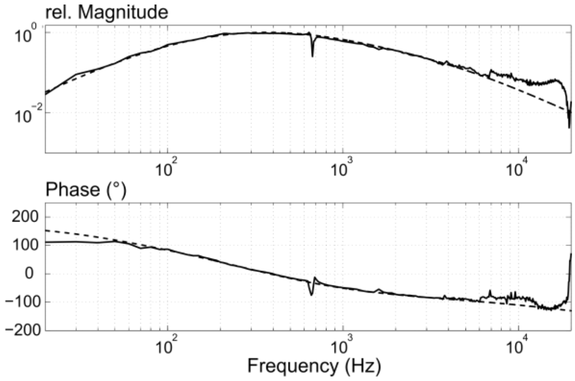

Figure 6 - Frequency response sensor 2.

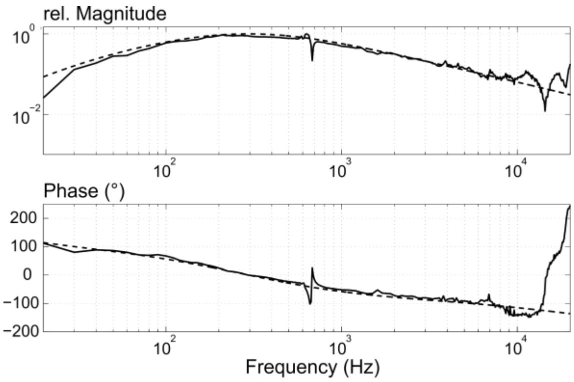

Figure 8 - Frequency response sensor 3.

Figures 6-8 show our first normalized calibration results. Currently an absolute calibration cannot be compared with the nominal correction curves, because there is an offset due to different distances of the three particle velocity sensors to the vibrating piston. The protection grid does not allow a placing of the p-v probe sufficiently close to the surface of the piston, in order to guarantee, that all three sensors are placed at the same distance from the piston’s surface. The calibration results given by the manufacturer and the electric circuit model (described in section 2.4) can be seen as dashed lines together with the determined magnitude and phase of the frequency response of each of the three components of the USP. From these results we can state that our calibration technique produces consistent data. It is obvious, that there is a deviation at low frequencies about a few hundred Herzz and above 10 kHz. Furthermore, there is a deviation at 600 Hz in every component of the p-v probe in magnitude and phase of the frequency response, because of an axial resonance of the shaker.

5. CONCLUSIONS

We have presented a recently developed calibration technique for the simultaneous calibration of all three particle velocity components of a p-v probe. Thereby, we use a known velocity field generated by a vibrating piston. This here presented method differs from known approaches that it allows to simultaneously calibrate all three components of the particle velocity. Furthermore, the presented technique is a direct calibration method for particle velocity sensors. The simultaneous calibration of the three particle velocity sensors was performed successfully in a wide frequency range in magnitude and phase. With an improved velocity controll, the deviation at low frequencies as well as at 600 Hz may be avoided. To perform an absolute calibration of the particle velocity sensors, the protection grid has to be removed for placing the p-v probe as close as possible to the vibrating surface of the piston.

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