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A NEW METHOD FOR AXIAL P-V PROBE CALIBRATION

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A full bandwidth absolute calibration of axial p-v probes using progressive plane waves as a reference field is here proposed. The sound field has been obtained by means of an 84 m long, 2 cm wide one-dimensional wave guide installed, in a joint effort with the Italian Research Council, at the LARIX Laboratory, Department of Physics, University of Ferrara. The calibration process consists of two stages: the first one, when the pressure sensor of the intensimetric probe (in our case a match size Microflown® probe) is calibrated in the reference field by comparison with a standard pressure microphone, and the second one, when the relative calibration of the pressure-velocity sensors of the probe, is done, thanks to theoretically known energetic properties of the reference field. A brief discussion of obtained results is outlined in the paper.

1. Introduction

The recent commercialisation of a new generation of intensimetric p-v sound probes, based on direct acquisition of the air vibration velocity signal through thermo-acoustic sensors [1,2], encouraged the development of new and specific calibration methods. These methodologies have the main objective to standardise measurements of energetic acoustic quantities in very different applications: from sound power determination of noise sources to the monitoring of sound radiation of music instruments. But they also provide a necessary tool to develop new active technologies based on the intensimetric control of sound fields and finally for the experimental exploration of spatial differential properties of sound intensity fields (sound hyper-intensimetry).

A general view of the possibilities till now available to calibrate p-v intensimetric probes is given in [3], while details about one-dimensional stationary wave field (Kundt tube) and spherical wave calibration can be found respectively in [4] and [5].

Unlike the above cited methods, where the a-priori known impedance of the reference acoustic field depends on the spatial coordinates, the one here proposed takes as reference the simplest acoustic field: the progressive plane wave one. This field has been created within an 84 m long, 2 cm wide one-dimensional wave guide installed, in a joint effort with the Italian Research Council, at the LARIX Laboratory, Department of Physics, University of Ferrara and supported by the IP-Racine European research project (IST-2-511316-IP).

A brief description of the calibration facility and theoretical background for the implemented methodology will be presented in section 2. Obtained results are reported in Section 3, while a brief discussion and some hints for further developments are given in the concluding section.

2. Calibration facility and methods

In order to calibrate any p-v sound intensity probe, a reference field is needed whose admittance Y^0_{true} can be considered as an a-priori known (true) acoustic quantity. If the true admittance is independent of frequency and position, such as in the case of the here selected progressive plane sound wave model, then the created reference field offers the simplest measure conditions for any calibration procedure.

Following similar experimental set-ups as reported in [6,7], this particular acoustic field has been generated inside an 84 m long, 2 cm wide aluminium tube, by means of a dual cone loudspeaker coupled with a tenor trombone bell, used as an impedance adaptor, to optimally excite the air column. The tube works as a one-dimensional progressive plane wave guide up to about 10 kHz, when transversal modes start to be excited due to the geometry of the tube. The environment, where the wave guide is built in, is a 100 m underground corridor, which provides a good homogeneity of medium thermodynamic characteristics, such as air temperature and humidity (Fig. 1). The acoustic source allows a good sound radiation into the wave guide in the whole frequency range from 20 Hz to 10 kHz (Fig. 2). This makes possible the full bandwidth calibration of any p-v probe to be executed with a single measuring session, using a wide band input signal (random noise or swept sine). The calibration procedure here described has been tested on the Microflown® Match Size probe PT0702-03, with the built-in filtering circuitry of the

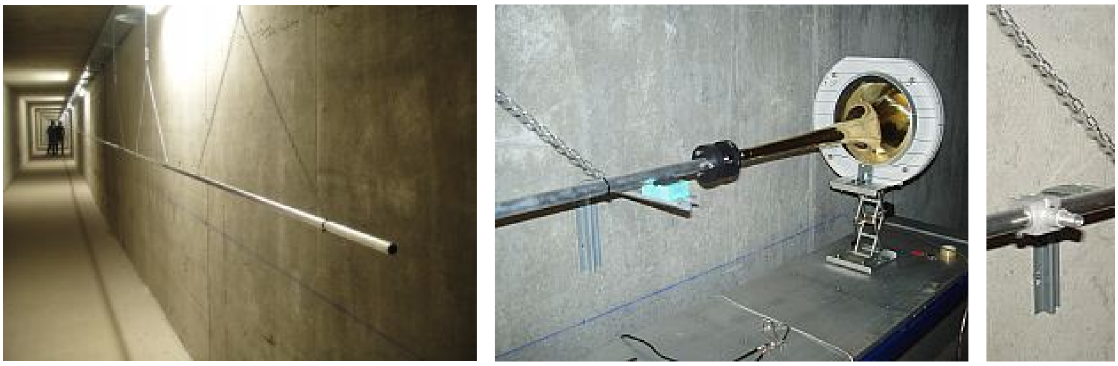

Figure 1. Progressive plane wave apparatus used for p-v probes calibration. Left: 84 m long, 2 cm wide acoustic waveguide in LARIX; centre: sound source; right, p-v probe mounting system.

signal conditioning hardware switched off. The probe has been inserted in the mount, positioned at about 7 m far from the sound source, with its 0° axis parallel to the tube axis.

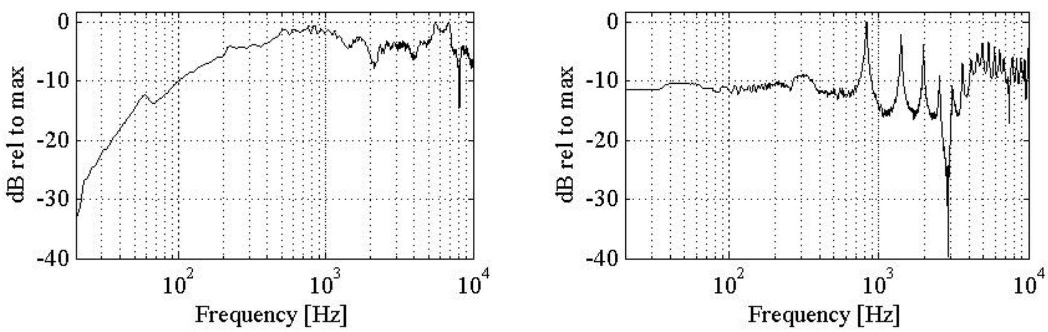

Figure 2. Radiation from sound source. Loudspeaker without (left) and with (right) the impedance adaptor.

The signal acquisition chain was based on a portable PC equipped with a MOTU Traveller I/O external board and a power amplifier for output signals driving the bi-conical loudspeaker. DSP and further numerical elaboration has been performed by means of a dual-channel FFT software and MatLab® routines. As it is going to be better explained in next paragraphs, the FFT device was calibrated by means of a B&K mod. 4939, ¼" pressure microphone, successively used as reference microphone for absolute calibration of the p-v probe.

2.1 Preliminary coherence test

Before applying the calibration procedure, it is fundamental to know the frequency range, where any intensimetric probe correctly works: in fact, experimental measures of acoustic pressure and air particle velocity signals must obey the same relation as predicted by theory. Linear Acoustics states that, since pressure and particle velocity fields can be obtained by differentiation of the single velocity potential $\phi(\mathbf{x},t)$ as:

$$p(\mathbf{x},t) = -\rho_0 \frac{\partial \phi}{\partial t}, \qquad \mathbf{v}(\mathbf{x},t) = \nabla \phi, \tag{2.1}$$

where ρ_0 is the unperturbed air density, then the relation between the two observable fields $p, \mathbf{v}$ are linear and given by the Euler's equation and the mass conservation equation [8]. This implies that a preliminary test any sound intensity probe has to undergo, before the application of any calibration procedure whatsoever, is the linearity check of pressure and velocity signals. In DSP this is usually done by means of the coherence function $\gamma(f)$, given by:

$$\gamma(f) = \sqrt{\frac{\left|S_{PV}(f)\right|^2}{S_{PP}(f) S_{VV}(f)}} \tag{2.2}$$

where S_{PV} is the cross-spectrum of the two signals and S_{PP}, S_{VV} the respective auto-spectra [9]. As long as this function is equal to 1, the linearity between pressure and velocity is assured, so the correct functioning of the probe is guaranteed. At higher frequencies, where the coherence starts to decrease, the output from the device under test can scarcely be considered to reproduce faithfully the acoustical phenomenon, so it limits its functioning as a sound intensity probe. This allows in practice to determine the high frequency cut-off of the acoustic band-pass filter of any p-v probe, which only depends on the built-in technical features of each single probe and cannot be changed with the calibration procedure.

The preliminary coherence test can be easily performed by checking the coherence function of the probe under test in the whole 20-20000 Hz audio range and then decimating, appropriately, the recorded signals, in order to process only the pressure and velocity signals belonging to the acoustic band-pass of the probe. Figure 3 shows the coherence function obtained for the probe under test. As it can be seen, the high frequency cut-off of the acoustic band-pass filter of the tested Microflown® Match Size probe PT0702-03 is found at about 7000 Hz. The loss of coherence at 1500 Hz is due to the radiation characteristics of the exciting source (see Fig.2) and does not affect calibration results.

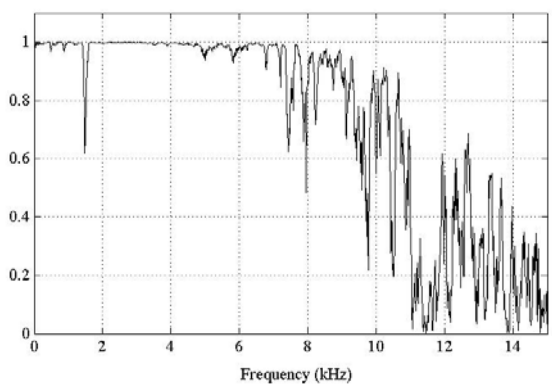

Figure 3. Coherence function of the Microflown® Match Size probe PT0702-03 under test.

2.2 Absolute calibration

This first step of the calibration process consists in finding the constant factor to convert voltage data, obtained with the pressure microphone of the probe, to proper physical units of measure, such as Pascals. This operation needs the availability of a reference pressure microphone to calibrate the FFT device used in turn for calibrating the p-v probe. To this aim a B&K type 4231 calibrator generating a 94 dB SPL-rms sound at 1 kHz and a B&K mod. 4939, ¼" pressure microphone have been employed. Then, two measures have been performed under the same field conditions, with both, the pressure microphone of the sound intensity probe under calibration, and the reference one; these two measures were finally compared and the conversion factor has been calculated. In our case, the B&K reference microphone and the pressure microphone of the Microflown® probe have been exposed to a random noise generated inside the wave guide under the same boundary conditions and their outputs have been compared in the 1 kHz third-octave band. Then, the absolute calibration constant (conversion factor) was calculated, so to match the two band levels in the reading from the FFT calibrated device. The obtained values are reported in the following table 1.

Table 1. Absolute calibration constants

Pressure Microphone	*SPL @ 1 kHz*	*Conversion Factor* (Π)
B&K® mod. 4939	85.9 dB	1.00
Microflown® PU Match Probe PT0702-03	79.9 dB	2.01

Once the conversion factor Π has been determined the absolute calibration procedure concludes by multiplying simply the not-calibrated pressure amplitude spectrum detected with the probe pressure microphone by Π in order to get the correctly measured values P^0_{meas} inside the reference field

$$P^0_{meas} = \Pi P^0_{notcal} . \quad (2.3)$$

2.3 Relative calibration

The second step of the p-v probe calibration consists in adjusting the velocity signal, so that it has the right amplitude-phase relation with the pressure one. As mentioned above, in our case the particular choice of the calibration field, makes the true ratio between the observable pressure and velocity fields particularly simple. In fact, as well known, the impedance of a plane progressive wave field is $z_0 = \rho_0 c$ and can be easily used as a target to calculate, for each single frequency, the correction curve to be applied to the impedance as detected with the not-calibrated probe.

In general it can be demonstrated that the correction curve $\Gamma(f)$, is given by the ratio of the true (i.e. a-priori known from a theoretical model of the calibration field) admittance Y^0_{true}, to the admittance Y^0_{notcal} experimentally determined from a not-calibrated p-v probe exposed to the calibration field implemented from the model. In formulas:

$$\Gamma(f) = \frac{Y^0_{true}}{Y^0_{notcal}} \quad (2.4)$$

where the superscript 0 indicates that measurements have to be done inside the calibration field. In our special case Eq. (2.4) can be simply re-written as

$$\Gamma(f) = \frac{1}{z_0} \cdot \frac{P^0_{notcal}}{V^0_{notcal}} \quad (2.5)$$

and can be easily evaluated for frequencies belonging to the acoustic band-pass of the p-v probe under testing by means of the calibration facility illustrated in Fig. 1.

3. Experimental results

Calibration results obtained for the p-v probe under test are here reported.

In Fig. 4 the correction curve calculated from Eq. (2.5) is shown.

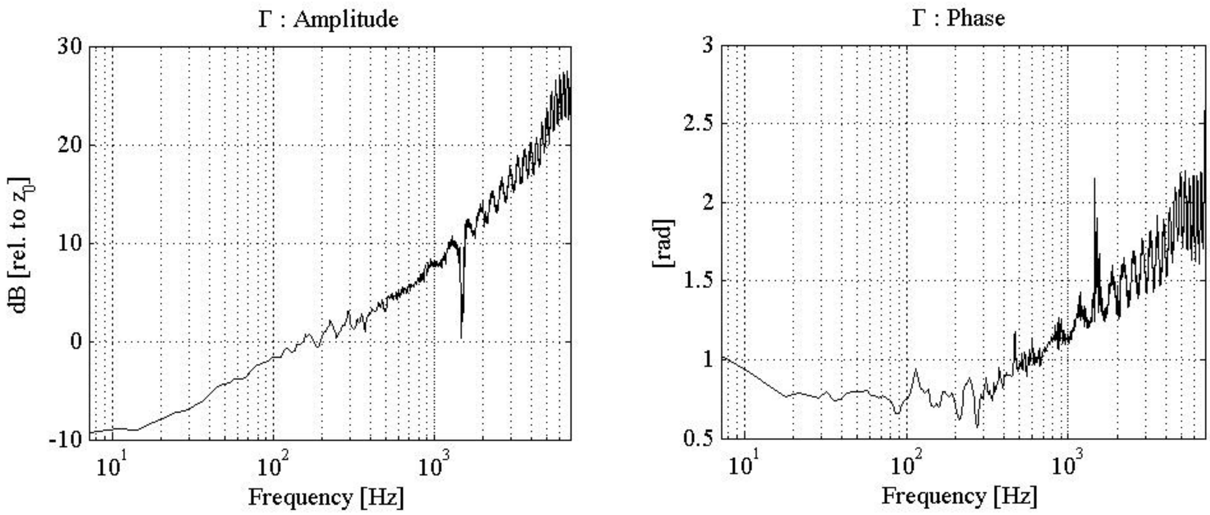

Figure 4. Relative correction curve: magnitude (left) and phase (right).

In Fig. 5 the amplitudes of pressure and velocity before and after calibration are plotted. The pressure amplitude, as expected, is just scaled by the factor Π reported in table 1 and keeps its profile with respect to the frequency axis. On the contrary the velocity, after being applied by the correction curve $\Gamma(f)$, changes its shape becoming pretty equal to the pressure signal after the calibration as could be expected from the model. In particular, the typical high-frequency sensitivity loss of the velocity sensor is here corrected, within the coherence range.

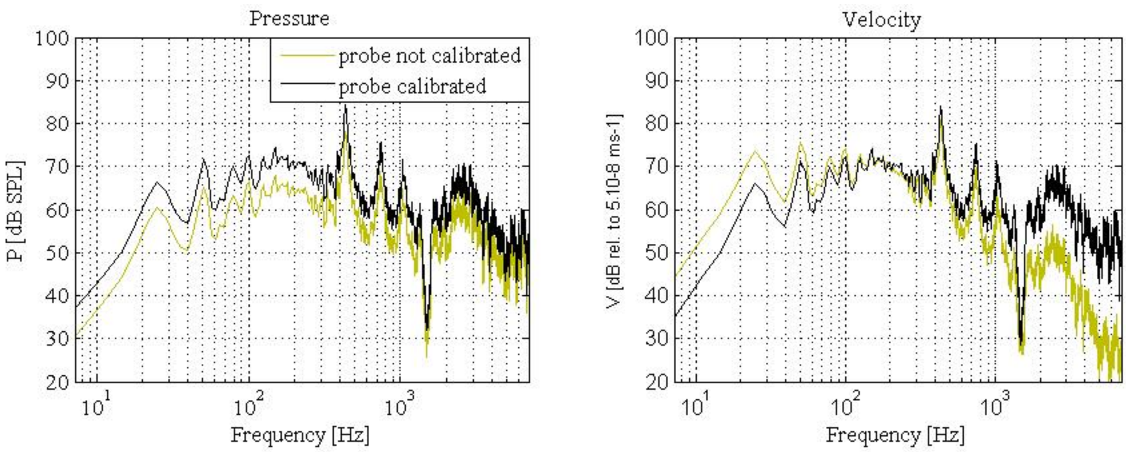

Figure 5. Pressure and velocity measures before and after calibration.

Fig. 6 shows how the phase difference between pressure and velocity is affected by calibration. Here, the non-zero phase difference drifting with frequency before calibration is clearly removed by the application of the calibration curve $\Gamma(f)$ as expected from the model (see Eq.(2.5)).

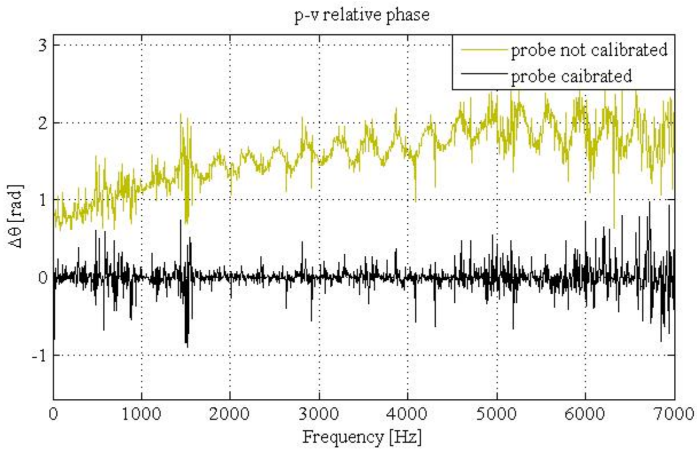

Figure 6. Phase difference between p and v before and after the calibration.

4. Discussion and further developments

As shown in the former section the effect of the calibration over the pressure and velocity signals is in a substantial agreement with results expected from the model, but some discrepancies, that a more careful analysis shows to depend from the loss of coherence (see Fig. 3). This means that the preliminary coherence test has to be considered as an integrating part of any calibration procedure of p-v sound intensity probes. Moreover the coherence loss between pressure and velocity signals may depend, other than the characteristics of the probe under test, also from other causes such as the signal-to-noise ratio of the exciting source system to background noise. Then the coherence test can give useful practical information for optimizing, by trial and error, the experimental setup used for calibration. In our case, better results can surely be achieved by adjusting the impedance adaptor coupled to the loudspeaker so to assure more uniform transfer of the acoustic energy to the tube so removing the deep negative peak at 1500 Hz just few dBs above the background noise level.

Apart from unavoidable experimental errors affecting the calibration results, we can then conclude that both the conversion constant Π and the correction curve $\Gamma(f)$ here determined, depend only on the built-in features of the sound intensity probes and not on the particular choice of the reference field. This, which is clearly a must of any calibration procedure, suggests that any p-v probe should be equipped with specific calibration data allowing to measure the pressure and air particle velocity fields in any sound field whatsoever by simply applying the formulas:

$$P_{meas} = \Pi P_{notcal} ; \qquad V_{meas} = \left(\Pi \cdot \Gamma(f)\right) V_{notcal} \tag{2.6}$$

where the superscript 0 has disappeared because this relation is absolutely general.

Next developments planned at our Lab, will just regard the optimization of the wave guide facility in order to standardize the here described calibration procedure.

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