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CALIBRATION OF P-U INTENSITY PROBES

Virginie Jaud and Finn Jacobsen

Acoustic Technology, Ørsted•DTU
Technical University of Denmark, Building 352, DK-2800, Kgs. Lyngby, Denmark
virginie.jaud@gmail.com; fja@oersted.dtu.dk

ABSTRACT

A pressure-velocity sound intensity probe (or a '*p-u* intensity probe') is a device that combines a pressure microphone with an acoustic particle velocity transducer. Such devices are mush more difficult to calibrate than sound intensity probes that combines closely spaced pressure microphones ('*p-p* intensity probes'). Various methods of calibrating *p-u* sound intensity probes are examined: a far field method that requires an anechoic room, a near field method that involves sound emitted from a small hole in a plane baffle, and a near field method in which the sound is emitted from a hole in a spherical baffle. The performance of the two near field methods is examined both in an anechoic room and in various ordinary rooms. It is shown that whereas reflections from the edges from a plane baffle disturb the calibration, the method based on a spherical baffle gives acceptable results from in a wide frequency range even when the calibration is carried out in a small office, provided that the distance between the hole and the device under test is between 5 and 10 cm.

1 INTRODUCTION

Until recently direct measurement of the acoustic particle velocity was almost impossible. However, a *p-u* sound intensity probe based on a particle velocity transducer called the 'Microflown' combined with a small pressure microphone has now been available for some years [1], and recent results seem to indicate that it is viable [2]. The potential applications of such a device include the applications of the conventional, standardised sound intensity measurement technique based on pairs of matched condenser microphones, that is, measurement of sound power, identification and ranking of noise sources, visualisation of sound fields, measurement of transmission loss, identification of transmission paths, etc. [3], but there seem to be additional potential applications, for instance measurement of sound absorption [4], and near field acoustic holography [5]. Most of these applications rely on accurate calibration of the two transducers of the *p-u* probe, but whereas calibration of the pressure microphones of a *p-p* sound intensity probe is simple and unproblematic, there is no established method of calibrating a *p-u* probe [3]. The two transducers are completely different and cannot be expected to have the same amplitude and phase response, and therefore it is necessary to determine a correction of one of them relative to the other.

Calibration of a *p-u* intensity probe involves exposing it to a sound field with a known relationship between the sound pressure and the particle velocity. Several methods have been described in the literature. One can expose the device under test to the sound field in a rigidly terminated tube [1], but since modes of higher order must be avoided the frequency range will be limited to a few kilohertz. One can also calibrate in a large anechoic room [2]. However, there is obviously a need for a calibration technique that covers a substantial part of the audible frequency range and can be used *in the field*. If the measurement is carried out very close to a source then reflections from the surroundings can perhaps be ignored. The purpose of this paper is to examine and compare various methods of calibrating *p-u* sound intensity probes, including two near field techniques that might work also in ordinary rooms.

2 OUTLINE OF THEORY

The ratio of the 'true' specific acoustic admittance in the sound field at the position where the *p-u* intensity probe is placed during calibration, H_{pu}, to the corresponding measured frequency response between the signals from the probe, $H_{p\hat{u}}$, provides a correction of the particle velocity signal relative to the pressure signal, to be used in subsequent measurements of the complex sound intensity as follows,

$$I_r = \mathrm{Re}\left\{S_{pu}\right\} = \mathrm{Re}\left\{S_{p\hat{u}}\left(H_{pu}/H_{p\hat{u}}\right)\right\}, \tag{1}$$

where I_r is the intensity, S_{pu} is the corrected and $S_{p\hat{u}}$ is the measured cross spectrum between the sound pressure and the particle velocity.

2.1 Far field calibration under free-field conditions

The simplest solution would be to expose the device under test to a propagating plane wave in which the specific acoustic admittance equals the reciprocal of the characteristic impedance of the medium,

$$H_{pu}^{(1)} = 1/(\rho c). \qquad (2)$$

However, one cannot obtain plane wave conditions at low frequencies even in the largest anechoic room [2]. If the source can be assumed to be a monopole a distance of r from the observation point then Eq. (2) becomes

$$H_{pu}^{(2)} = \left(1/(\rho c)\right)\left(1 + 1/(\mathrm{j}kr)\right), \qquad (3)$$

where k is the wavenumber. No ordinary loudspeaker resembles a monopole in its near field, and therefore a distance of several meters is needed. However, the phase shift associated with the finite distance cannot be neglected below a few hundred hertz even at a distance of 4 m. Thus a very special source or a large anechoic room of high quality is required.

2.2 A monopole on a rigid plane baffle

If the sound field could be generated by a real monopole one might use Eq. (3) also very near the source, perhaps even without an anechoic room. Unfortunately it is very difficult to construct a ‘real monopole’, that is, an omnidirectional source that can cover a wide frequency range. On the other hand, a small circular hole in a large plane baffle, driven by an enclosed loudspeaker on the other side of the baffle, might approximate a monopole on a baffle and thus generate a simple spherical sound field in the half-space in front of the baffle. In principle the hole should be as small as possible, and the *p-u* intensity probe should be placed very near the hole. In practice the dramatic increase of the particle velocity level relative to the sound pressure level very near a monopole, the need for a well-defined distance between the hole and the transducer, the influence of scattering caused by the transducer, and the influence of reflections from the edges of the baffle call for a compromise. See Figure 1(a).

2.3 A monopole on a rigid spherical baffle

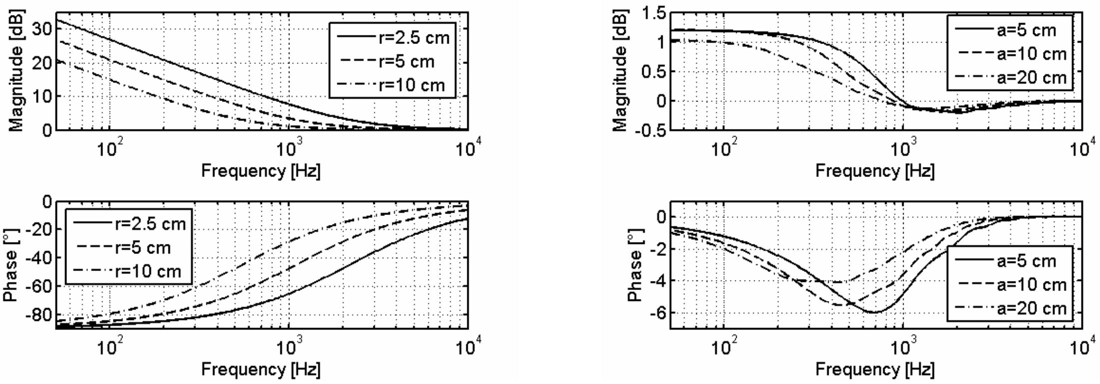

Fig. 1. (a) Specific acoustic admittance at a distance r from a monopole on a plane baffle, and (b) ratio of the specific acoustic admittance 5 cm from a monopole on a rigid sphere of radius a to the specific acoustic admittance 5 cm from a monopole on a plane baffle.

An alternative solution might be to let the source be a small hole in a hollow rigid sphere driven by a loudspeaker inside the sphere. In the sound field generated by a point source on a rigid sphere the specific acoustic admittance on the axis has the value [6]

$$H_{pu}^{(3)} = \frac{\mathrm{j}}{\rho c}\left(\left(\sum_{m=0}^{\infty}\left(m+\tfrac{1}{2}\right)\frac{h_m'(kr)}{h_m'(ka)}\right)\Big/\left(\sum_{m=0}^{\infty}\left(m+\tfrac{1}{2}\right)\frac{h_m(kr)}{h_m'(ka)}\right)\right), \tag{4}$$

where *a* is the radius of the sphere, *r* is the distance from the observation point to the centre of the sphere, h_m is the spherical Hankel function of the second kind and order *m*, and h_m' is its derivative. Figure 1(b) shows the ratio of the specific acoustic admittance in front of a monopole on a spherical baffle, $H_{pu}^{(3)}$, to the specific acoustic admittance in front of a monopole on a planar baffle, $H_{pu}^{(2)}$, at a distance of 5 cm. It is apparent that they are very similar.

3 EXPERIMENTAL RESULTS

The two near field methods described in Sections 2.2 and 2.3 have been examined both in a large anechoic room that provides a good approximation to free-field conditions down to 50 Hz and in an ordinary room of about 180 m^3 and a reverberation time of about 0.5 s. In the anechoic room the far field method was also applied since, presumably, this method is the most accurate one. In all cases a Brüel & Kjær (B&K) ‘Pulse’ analyser of type 3560 in one-twelfth octave mode was used (although the results presented in what follows are plotted in one-third octave bands). The device under test was a Microflown ½-inch *p-u* sound intensity probe. Three sources were used in these experiments. In the far field measurements the source was a 60-mm diameter two-way ‘coincident-source’ loudspeaker unit produced by KEF, mounted in a rigid plastic sphere with a diameter of 270 mm. The ‘monopole on an infinite baffle’ was a wooden IEC baffle for loudspeaker testing with dimensions 1.35×1.65 m with a 20-mm diameter hole (with a brass ring so as to reduce flow noise caused by the high air velocity) driven by a conventional small enclosed loudspeaker unit produced by VIFA behind the baffle. The ‘monopole on a sphere’ was 90-mm VIFA unit mounted inside a rigid plastic sphere with a diameter of 270 mm with a 20-mm diameter hole in front of the loudspeaker. All loudspeakers were driven with signals generated by the ‘Pulse’ analyser and passed through a one-third octave band equaliser.

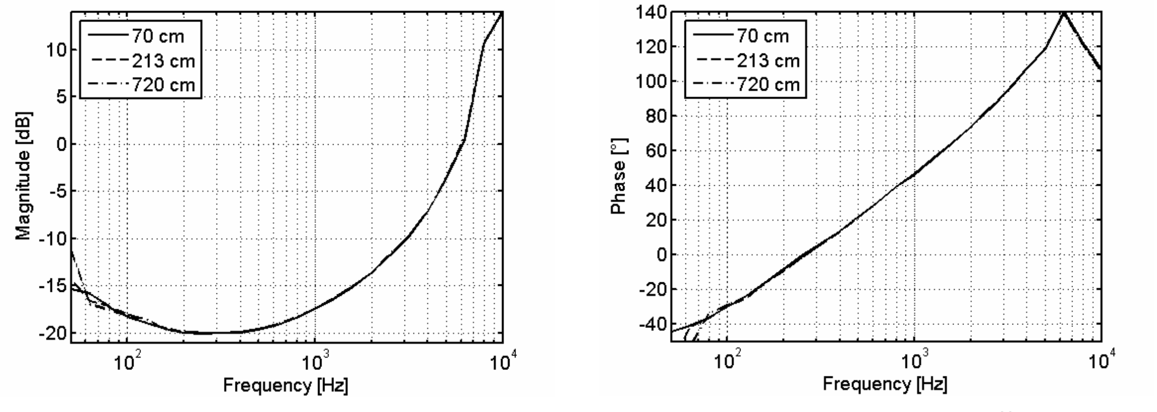

Fig. 2. Amplitude and phase calibration measured in an anechoic room at three different distances from a ‘coincident source’ loudspeaker mounted in a sphere.

Figure 2 shows the amplitude and phase correction of the *p-u* probe measured with the KEF loudspeaker in the anechoic room at three different distances from 70 cm to 7.2 m. Close examination reveals some small irregularities in the amplitude and phase determined at the longest distance where the source has probably been too close to the wedges of the anechoic room, but on the whole the results agree within ±0.3 dB and ±1° above 100 Hz. Accordingly, the correction obtained at a distance of 70 cm is used as a reference in what follows.

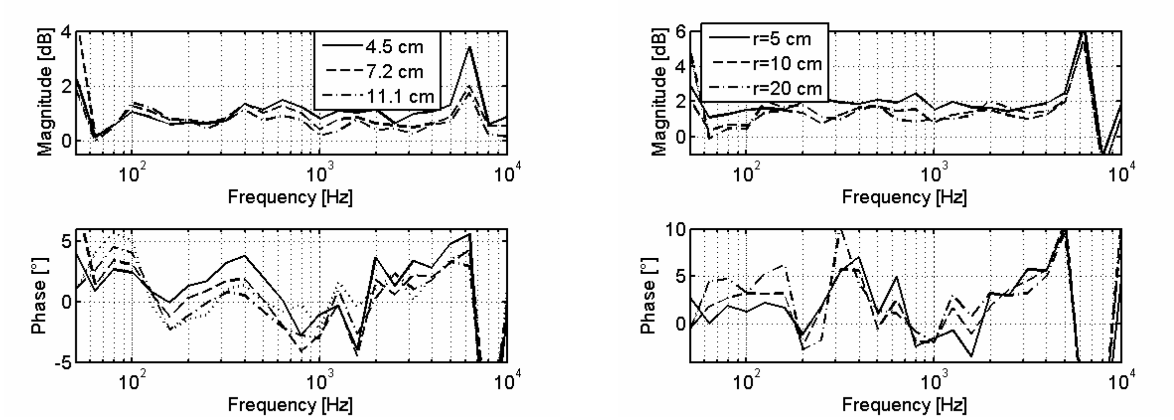

Fig. 3. Amplitude and phase calibration relative to the reference measured at different distances from the 'monopole on a plane baffle'. Left-hand figure: anechoic room; right-hand figure: ordinary room.

Figure 3(a) show the results of the measurements close to the 'monopole on a plane baffle' in the anechoic room. In this case somewhat larger systematic deviations (within ±4°) between the phase and the reference phase occur. These deviations, which are also observed in measurements carried out in the ordinary room shown in Figure 3(b), are undoubtedly caused by reflections from the edges of the baffle.

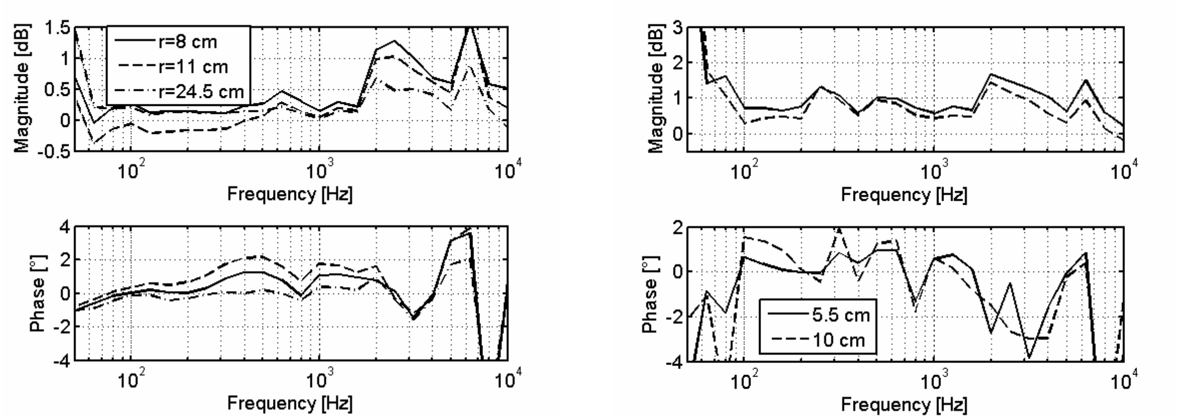

Fig. 4. Amplitude and phase calibration relative to the reference measured at different distances from a 'monopole on a rigid sphere'. Left-hand figure: anechoic room; right-hand figure: ordinary room.

Figure 4(a) show the amplitude and phase correction determined at three different distances from the 'monopole on a sphere' in the anechoic room, normalised with the reference calibration. In a substantial part of the frequency range the results agree with the reference measurement within ±0.5 dB and ±2°. The agreement is less perfect but still quite good between 2 and 8 kHz. Figure 4(b) show the results of similar measurements at two different distances from the 'monopole on a sphere' in the ordinary room. Above 100 Hz the results are very similar to the results obtained with the same source in the anechoic room, although there are more erratic (small) variations with the frequency. Results obtained at other positions in the same room (not shown) were very similar except below 100 Hz, where the room has a significant influence. There is no obvious explanation for the (small) systematic shift in the magnitude seen in Figures 3(a), 3(b) and 4(b).

4 DISCUSSION

It seems clear that the most accurate calibration method requires a large anechoic room. However, from a practical point of view the near field method based on a ‘monopole on a sphere’ is more interesting. The most obvious contribution to the measurement uncertainty with this method is probably associated with determining the physical distance r in Eq. (4). If the uncertainty on a ‘true’ distance of 5 cm amounts to, say, 0.5 mm, then the resulting uncertainty will take values up to 1 dB and 3°. On the other hand, increasing the distance obviously increases the influence of deviations from perfect free-field conditions unless the measurement takes place in an anechoic room. Reflections of extraneous noise from the sphere may disturb the weak pressure signal, and this problem is probably most serious if the transducer is very close to the sphere. A distance between 5 and 10 cm seems a good compromise.

The required accuracy of the calibration depends on the application of the *p-u* intensity probe. In Ref. 4 it was concluded that reliable measurement of absorption coefficients with such a device calls for calibration errors within 0.5 dB and 2°. It seems that this accuracy can be achieved in a large anechoic room of good quality. However, it also seems that it is only just possible to satisfy this requirement with the “monopole on a sphere” in an ordinary room.

5 CONCLUSIONS

Several methods of calibrating a *p-u* sound intensity probe have been examined. The most accurate method requires an anechoic room of good quality and a ‘coincident source’ loudspeaker mounted in a sphere. If the anechoic room is sufficiently large then an ordinary loudspeaker placed far from the transducer under test can be used instead. A near field method involving sound emitted from a hole in a hollow rigid sphere gives slightly less accurate results, but has the significant advantage that it can be used in the field. Alternatively, a similar near field method with a plane baffle can be used, also in the field, but this method is less accurate than the method based on a sphere because of reflections from the edges of the baffle.

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