

Measurement methods of the pressure-residual intensity index

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In IEC 1043 (Instruments for the Measurement of Sound Intensity, 2nd Committee Draft), the pressure-residual intensity index is defined for the evaluation of the phase mismatch between two channels of a sound intensity measuring instrument. However, an evaluation method of the intensity probe is not described clearly in the draft. This may cause a confusion when they are standardized and actually applied for the evaluation of intensity measuring instruments. In this technical report, we propose a method that is carried out in an anechoic room for the evaluation of an intensity probe or an instrument as a whole. Some technically important points are also mentioned. The accuracy of this method is confirmed by comparing its result with that obtained by a calibrator.

Keywords: Sound intensity, IEC standard, Pressure-residual intensity index

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1. INTRODUCTION

The sound intensity measurement is getting more and more important for *in-situ* radiated power evaluation and visualization of a sound field. It seems that the theoretical aspects of this technique has been well investigated. However, in the technical sense, this method is still progressing. Obviously, the most difficult part of this method is that the particle velocity must be measured directly or indirectly to obtain the sound intensity. This causes different types of measurement errors. The phase mismatch between the two microphones (when a two-microphone type probe is used) causes errors mostly at low frequencies where the true phase difference between the two microphone positions in the sound field gets very small. The pressure gradient, whose time integral is proportional to the particle velocity, is approximated by the difference of the two pressure signals causing errors in the high frequency region. A geometrical complexity of the

probe is another problem that must be solved technically.

In this report, we propose two methods how to measure the phase mismatch between two microphones of an intensity probe in an assembled form. One method we propose here is carried out in an anechoic room and another is by use of a phase calibrator. The two values are compared with each other and the accuracy is evaluated in terms of the pressure-residual intensity index.

2. PRESSURE INTENSITY INDEX AND PRESSURE-RESIDUAL INTENSITY INDEX

A p-p type probe is shown in Fig. 1. Two microphones are separated by a distance d in the direction of measurement. The time-averaged intensity of a sinusoidal wave obtained by the two-microphone method is given by¹⁾

$$I_a = P_1 P_2 (\sin \phi) / 4\pi f \rho d \quad (1)$$

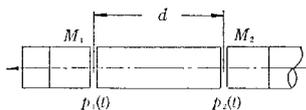


Fig. 1 A p-p type intensity probe.

where I_a is the intensity, P_1 and P_2 are the pressure at two microphone positions, ϕ is the phase difference, f is the frequency, and ρ is the air density. Then the intensity measurement error, when a system with a phase mismatch $\Delta\phi$ is used, is given by

$$I_a'/I_a = \sin(\phi + \Delta\phi)/\sin\phi \approx 1 + \Delta\phi/\phi \quad (2)$$

where I_a' is the measured intensity and ϕ and $\Delta\phi$ are both assumed to be much smaller than unity. Eq. (2) indicates that the error due to the phase mismatch is determined by the ratio of the phase mismatch and the true phase difference at the two microphone positions. For the same phase mismatch, the measurement error is the smallest if the probe is placed in a plane progressive sound field in the direction of the wave propagation, since ϕ is the largest ($=kd$, k is the wavenumber) in this case. Therefore, the ratio of kd to ϕ is an indication of the difficulty of the measurement. This ratio is equal to the pressure intensity index (abbreviated as PII hereafter)

$$\delta_{PI} = L_p - L_1 \quad (3)$$

In Ref. 2), $-\delta_{PI}$ is defined as reactivity index. This is rewritten as

$$\begin{aligned} \delta_{PI} &= 10 \log [(P^2/2\rho c)/(P_1 P_2 \sin \phi)/4\pi f \rho d] \\ &\approx 10 \log |kd/\phi| \end{aligned} \quad (4)$$

where L_p and L_1 are the sound pressure level and intensity level, respectively, and P is the pressure at the measurement point (assumed to be equal to the average of P_1 and P_2). PII is large in a sound field with reflections or when the direction of the probe axis is perpendicular to the direction of the wave propagation.

If the two microphones are placed in a sound field with no phase difference, the sound intensity level should be zero. However, there is a remaining intensity due to the phase mismatch. An index similar to δ_{PI} is called a pressure-residual intensity index (abbreviated as PRII hereafter), which is defined by

$$\delta_{PIo} = L_p - L_{Io} = 10 \log |kd/\Delta\phi| \quad (5)$$

where L_{Io} is the residual intensity due to the phase

mismatch. PRII is an indication of the smallness of the phase difference between the two microphones. The difference between δ_{PIo} and δ_{PI} indicates the accuracy of the intensity measurement, since

$$\delta_{PIo} - \delta_{PI} = 10 \log |\phi/\Delta\phi| \quad (6)$$

3. A PHASE MISMATCH MEASUREMENT METHOD IN AN ANECHOIC ROOM

Reference 3) says that PRII should be obtained by adding identical pink noise to the two microphones in one or one-third octave bands. However, there is no more detailed description how to place two microphones in an "identical" sound field. An important thing that should be reminded here is that the intensity probe should be tested in an assembled form. What we propose here is a reversing method in an anechoic room that might be used as one of standard methods to obtain PRII.

One possible method is to create a sound field by a loudspeaker in an anechoic room and hang the intensity probe with a thin string in front of the loudspeaker perpendicular to the direction of the wave propagation. A problem of this method is that the exact direction of the wave propagation is unknown. Also, even in a high quality anechoic room, there is some reflections that degrade the sound field. To hang the probe in the anechoic room is another troublesome task to achieve.

A very effective method of removing the effect of reflections and misalignment of the probe from the desired direction is to reverse the probe 180 degrees during the measurement. By reversing the probe, the two microphones occupy the same two positions each other. This is equivalent to placing the two microphones in the identical sound field. An actual test setup is shown in Fig. 2. A large loudspeaker system is in an anechoic room with an effective volume of 350 m³. The probe is placed in front of the loudspeaker system with a distance of approximately 1 m. The probe and the loudspeaker is mechanically isolated to prevent errors at resonances of the loudspeaker enclosure. The probe position is fixed by a holder attached to an acrylic plate, which is used just for convenience in this case. It would be desirable to replace this by a beam structure with smaller reflecting surfaces. The probe direction should be perpendicular to the direction of the wave propagation, but it does not have to be

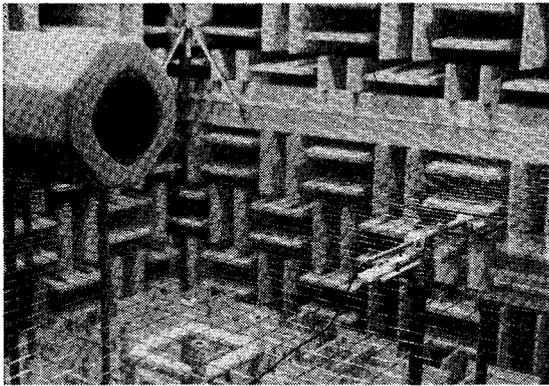


Fig. 2 A test setup for the measurement of a pressure-residual intensity index.

exactly so. The frequency response functions (abbreviated as FRF hereafter) between the two microphone outputs are measured first for one direction and then for the reversed direction. The probe holder is made so that the two microphones occupy the same positions to each other if the probe direction is reversed. The phase and the pressure sensitivity differences are obtained from the average of the two FRF's. Let ϕ and $\Delta\phi$ be the true phase difference between the two microphone positions and the phase mismatch between the two microphones, respectively. Then the measured phase differences are given by

$$\phi_+ = \phi + \Delta\phi \quad (7)$$

and

$$\phi_- = -\phi + \Delta\phi \quad (8)$$

where ϕ_+ and ϕ_- are the phases of the FRF's for the original and reversed directions, respectively. The phase mismatch is then obtained by

$$\Delta\phi = (\phi_+ + \phi_-) / 2 \quad (9)$$

The true phase difference, which is small in this case, is removed by the reversing method, giving a very accurate phase mismatch. Of course, care should be taken to make the true phase difference as small as possible to increase the measurement accuracy. Those are:

- 1) Use a large loudspeaker system so that a low frequency sound may be produced.
- 2) Place the loudspeaker and the probe parallel to the side walls and with the same distance from them.
- 3) Use a symmetric (with respect to the direction

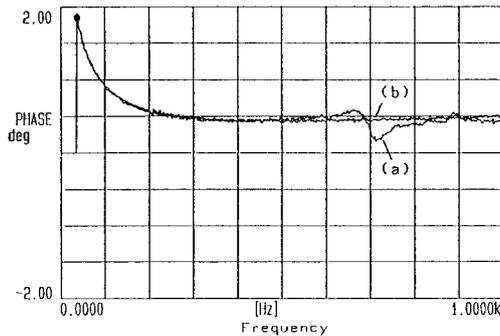


Fig. 3 Phase mismatches obtained by the method in an anechoic room (a) and by the calibrator method (b).

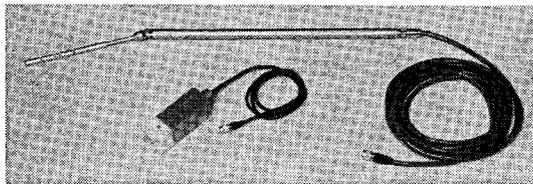


Fig. 4 The intensity probe and the calibrator used for the experiment.

of the sound propagation) holder with a small reflecting surface.

- 4) Use a two-channel FFT analyzer with a high phase measurement resolution.

An example of the phase mismatch of a 1/4" probe is shown by curve (a) of Fig. 3. PRII can be obtained by use of Eq. (5) if desired.

4. A PHASE CALIBRATION METHOD

The probe under test needs a phase compensation since the microphones are not phase-matched. For this purpose, a specially designed calibrator is used, which is shown in Fig. 4 together with the intensity probe. The intensity probe shown in Fig. 4 (also in Fig. 2) has four microphones built in a straight tube. The outer and inner two microphone pairs are used for the low and high frequency range measurements, respectively. Since the outer two microphones are separated by 50 mm, they cannot be inserted simultaneously in a small space of the calibrator. Instead, each microphone is inserted one after another and four FRF's are measured between the microphone outputs and the electrical input signal to the condenser type loudspeaker in the calibrator. By

dividing the first FRF by the fourth FRF and the second FRF by the third FRF, two new FRF's are obtained, which give the phase and the pressure sensitivity mismatches.

A phase mismatch of the low frequency pair microphones obtained by this calibrator is shown by curve (b) in Fig. 3. Curves (a) and (b) are almost identical except some differences at around 700 Hz. Since, in general, the phase mismatch between two microphones of the same type has a slowly varying nature, we believe that the phase difference around 700 Hz is due to reflections around the probe holder. The fact that two completely different methods give the almost identical phase mismatch indicates that the both methods are very accurate.

5. PRII AND SENSITIVITY CHARACTERISTICS OF A 1/4" PROBE

Since the phase mismatch obtained by the calibrator is used as phase compensation data, PRII of the probe shown in Fig. 4 is given by

$$PRII = 10 \log [kd / |\phi_a - \phi_b|] \quad (10)$$

where ϕ_a and ϕ_b represent curves (a) and (b) in Fig. 3, respectively. Figure 5 shows the PRII obtained from Eq. (10). A requirement³⁾ with respect to PRII of class 1 intensity probe, which is shown by the chain line in the figure is satisfied except within a small frequency range above 700 Hz. Figure 6 shows a PRII of the two microphone pair used for the high frequency range measurement. A much smaller loudspeaker was used for this test. The present intensity probe satisfies the requirement for a class 1 intensity probe (14.5 dB above 1 kHz

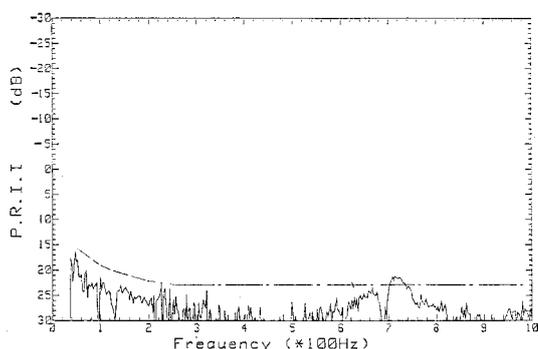


Fig. 5 Pressure-residual intensity index of the low frequency pair.

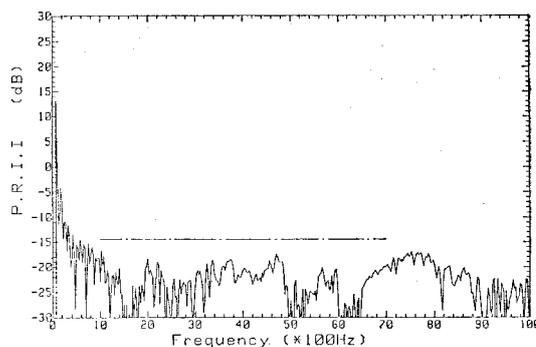


Fig. 6 Pressure-residual intensity index of the high frequency pair.

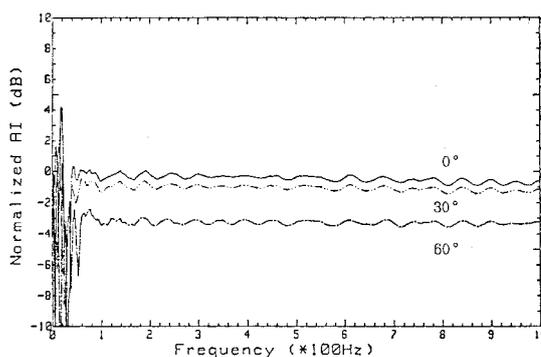


Fig. 7 Intensity sensitivities of a 1/4" intensity probe for 0, 30, and 60 degree incident angles.

for a probe with a microphone separation of 7 mm).

In order to measure the intensity sensitivity for 0, 30, and 60 degree incident angles, the same small loudspeaker as the last experiment was used. The probe was hung by a string. The distance between the loudspeaker and the probe was approximately 1 m. A sound pressure level at the measurement position was also measured by a 1/4" microphone after removing the probe. The intensity level was normalized to the sound pressure level assuming that a plane progressive wave was achieved at the measurement position. The results are shown in Fig. 7. The sensitivity characteristics are very smooth except small fluctuations. This is due to the reflections in the anechoic room. The sensitivities for 30 and 60 degree incident angles decrease approximately by 0.64 and 2.8 dB, respectively,

which are very close to the theoretical values (0.6 and 3 dB).

6. CONCLUSIONS

Two methods to measure the phase difference between two microphones used for the intensity probe were reported. The reversing method in an anechoic room seems to be a good candidate as a standard method to obtain the true phase difference. An important feature of this method is that the probe can be tested in an assembled form. A reversing of the probe in an anechoic room is easy if once a holder is prepared. The phase mismatch obtained by this method was compared with the one obtained by use of a calibrator. The result was evaluated in terms of the pressure-residual intensity index (PRII). PRII of a 1/4" intensity probe satis-

fied the class 1 requirement³⁾ except within a very narrow frequency range. We hope that the reversing method in an anechoic room can be used as one of standard methods in measuring PRII of an intensity probe or a system including a processor.

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