INSTRUMENTS FOR THE MEASUREMENT OF SOUND INTENSITY: CALIBRATION AND PERFORMANCE TESTS

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1. INTRODUCTION

Sound intensity measurements provide a convenient basis for the determination of the sound power output of machines in situ. However, before they can be used in legal metrology, for example in noise declarations to satisfy EEC directives, accepted methods for the conduct of the measurements and standardised performance requirements for the measuring instruments need to be developed. The International Organization for Standardization (ISO) has prepared the first in a series of Standards for the test methods (ISO 9614-1[1]) and the International Electrotechnical Commission has prepared another Standard for the instruments (IEC 1043[2]).

The EC Community Bureau of Reference (BCR) has part-funded a collaborative research project led by the National Physical Laboratory to develop tests and calibration methods for the instrumentation Standard. This paper outlines the scope of the new Standard and explains some of the requirements it places on sound intensity instruments.

The purpose of the instrumentation Standard is to ensure the accuracy of measurements of sound intensity in accordance with ISO 9614. Instruments are required to analyze the sound intensity in one-third octave or octave bands between 45 Hz and 7.1 kHz, and optionally to provide A-weighted band levels. They are also required to measure sound pressure level in addition to sound intensity level.

The Standard only applies to instruments which detect sound intensity by pairs of spatially separated, pressure sensing, microphones. It also gives requirements for sound calibrators, sound intensity calibrators and pressure-residual intensity index testing devices. Early drafts had included instruments which measure intensity by detecting pressure and particle velocity directly, but no field calibrator was available for these probes so they are not now included in the Standard.

The requirements are intended to reduce to a practical minimum any differences in equivalent measurements made using different instruments, including instruments comprising probes and processors from different manufacturers. Consequently the probes and processors are specified separately and the instrument is defined in terms of the properties of its probe and processor.

The Standard defines two classes of instrument. Both classes have essentially the same requirements but a class 1 instrument has tighter tolerances than a class 2 instrument. The classes are aligned to the measurement requirements in ISO 9614; precision and engineering grade measurements require a class 1 instrument while survey measurements can be made with a class 2 instrument. To simplify this paper any tolerances quoted will be those for a class 1 device.

2. THE TWO-MICROPHONE METHOD OF MEASURING INTENSITY

The two-microphone method measures pressures P_1 and P_2 at two positions separated by a distance Δx. The pressure mid-way between the two microphones can be estimated from the mean value of the two pressures, and the particle velocity at the mid point can be found by integrating the acceleration of an air-disc due to the pressure difference. Acoustic intensity is the product of acoustic pressure and particle velocity and so can be found from

$$I = \frac{P_1+P_2}{2} \int \frac{P_1-P_2}{\rho \Delta x} dt$$

where ρ is the density of the air.

This method assumes that Δx is small compared to the wavelength of the sound and that the pressure varies linearly between the two microphones. At high frequencies this is not valid and the method introduces an error in the intensity level of $10 \lg(\sin\theta / \theta)$, where θ is the phase difference in the sound field between the two microphones. This error determines the high frequency limit of a probe.

The measurement depends critically on the accuracy with which the phase difference between the two pressures can be determined. Only with modern digital instruments has it been possible to achieve phase differences between the two measurement channels of less than 0.01° so ensuring that measurements are accurate. The phase matching becomes increasingly critical at low frequencies and hence determines the low frequency limit of a probe.

3. PROBE REQUIREMENTS

The high- and low-frequency limits of the probes bar the use of a single probe (ie one with a single fixed spacing) to cover the whole frequency range of interest. Consequently the Standard only requires that a probe should cover at least 3 octave bands with given microphones and spacing, and hence more than one probe is usually required in an instrument.

The tests for the probes are divided into two groups; those concerned with the behaviour of a probe in an active field where the tests use plane progressive waves, and those concerned with the behaviour of the probe in a reactive field where the tests use or simulate standing waves.

3.1 Tests in an active field

Confusion has sometimes arisen because different processors present a single sound pressure indication from the two microphone outputs using different calculation procedures. Early drafts of the Standard included requirements on the `probe pressure response' but it became apparent that some processors combine the two microphone signals taking phase into account and then take a rms value, while others take the rms value of each channel and then present a mean value of the two channels. This difference can lead to discrepancies of more than 1 dB at the upper frequency limit of the probes. Because the `probe pressure response' could not be disassociated from the type of processor that the probe was connected to, the term was abandoned. The requirement in the Standard for sound pressure measurements is that there should be no error in the response of a *single* microphone channel within a given tolerance.

In contrast, the finite difference approximation in the method of calculating intensity has a built-in error in the intensity level of $10\ \lg(\sin\theta/\theta)$, where θ is the phase difference in the sound field between the two microphones, so the Standard does not require the probe to measure intensity with zero error but rather requires the probe to measure with the theoretical error within a given tolerance. The probe is then limited to the frequency range where the theoretical error is less than 1 dB. As the direction of the intensity is important to the determination of sound power, the Standard also places limits on how well the directional response of the probe must follow the cosine law for resolving vectors.

The pressure response of the microphones in the probe, and the intensity and directional responses of the probe, are all measured in plane progressive waves in a free-field room. The Standard requires the frequency response of the probe to be tested in a plane progressive wave by comparison with a microphone of known free-field response in the frequency range 500 Hz to 6.3 kHz. However it gives considerable choice on the method of signal processing:

> 'Testing may be carried out using continuous sinusoidal signals, or tone bursts gated electronically into the processor. The use of continuous sinusoidal signals places extreme demands on the quality of the free–field chamber in which testing is carried out, and may not be practicable. Alternatively, testing may be carried out using pink noise, in which case the demands on the quality of the free–field room are less severe. The source should be small compared to the measurement distance, e.g. for a source diameter of 25 mm the optimum distance between the source and the probe is 250 – 350 mm.'

All three of these methods have been implemented at NPL. Using the same measurement time for each method, the most accurate results were obtained using bands of noise. The use of sine wave signals requires measurements at several distances to eliminate the effects of reflections in the room, while the use of gating techniques requires a large room to ensure that the measurement time does not become impractical.

3.2 Tests in a reactive field

For intensity measurements concerned with sound power, it is necessary to measure the energy flowing from the source in order to deduce the power output. Any energy that is stored in the sound field must be ignored. There are two tests for the probe which determine its immunity to these reactive fields.

Probes designed to operate at frequencies below 400 Hz are tested in a plane standing wave field using a standing wave ratio of 24 dB at a frequency of 125 Hz (or the lowest frequency of operation claimed by the manufacturer if this is higher than 125 Hz). The probe is aligned so that its axis is perpendicular to the wave fronts and it is displaced relative to the sound field, for three–quarters of the wavelength of the sound. The indicated sound intensity is required to be constant within a given tolerance.

Various methods of establishing the standing wave field have been tried. The successful methods rely on a planar loudspeaker occupying one end of a duct and differ only in the design of the termination that controls the standing wave. For testing a restricted range of probes it is possible to design a duct with a fixed length and a fixed passive absorber that will provide the required standing wave ratio over a wide range of frequencies. For a more flexible arrangement a passive absorber can be made adjustable, and the length of the tube can also be adjusted, so that a range of standing wave ratios at a range of frequencies can be produced. Methods have been tried which use a short fixed length of tube and two loudspeakers, with the aim of moving the field past a fixed probe rather than traversing a probe through a fixed field. These proved to be impracticable.

When a probe is presented with two signals of the same phase then any phase mis-match between the two channels will cause the processor to display a 'residual intensity'. The difference between the sound pressure level displayed and the residual intensity is called the pressure-residual intensity index . The Standard defines pressure-residual intensity index as:

> 'difference, in decibels, between the indicated sound pressure levels and the indicated residual intensity levels, calculated with air density of 1.2048 kg m^{-3}, in one octave or one-third octave bands, when the processor is subjected to identical electrical pink noise inputs to the two channels, or when the transducers connected to the inputs are subjected to identical pink noise sound pressure inputs. This index applies only where it is essentially independent of indicated sound pressure level.'

and gives instructions on how to measure the pressure-residual intensity index of a probe:

> 'Connect the probe to a class 1 processor appropriate to the probe and adjust the sensitivity of the complete system using the calibration device specified by the probe manufacturer, in accordance with the manufacturer's instructions.
>
> Determine the pressure-residual intensity index at one-third octave intervals in the frequency range 50 Hz to 6,3 kHz excluding any frequencies outside the range of operation claimed by the manufacturer. This may be carried out by the application of identical acoustical pink noise signals to the microphones of the probe, or by simulating identical acoustical pink noise signals to the microphones using electrostatic actuators driven from the same electrical noise source. The actuator test is not valid below 500 Hz so it is necessary to use an acoustical source for low frequencies. The processor shall itself have a pressure-residual intensity index more than 5 dB greater than the probe in every one-third octave band tested.'

The Standard places requirements on the pressure-residual intensity index of a probe, but these requirements depend on the microphone spacing so that they are essentially requirements on the phase difference between the two probe channels. An actuator method is not valid below 500 Hz because it does not excite the microphone vent. Measuring the low frequency pressure-residual intensity index of a probe that uses conventional microphones, requires that both the diaphragm and the vent of the microphones are subjected to the same acoustic pressure. At NPL three different acoustical environments were used to determine the probe phase difference: the NPL laser pistonphone[3], a Brüel & Kjær calibrator type 3541, and a large acoustical duct. Measurements in the duct proved not to be practical because of the difficulty of aligning the microphones with the required accuracy on a wave front. The Brüel & Kjær pressure-residual intensity index testing device does not excite the rear of the microphone so is only suitable for some highly specialised microphones which have a very high attenuation of pressure applied to the vent. The most practical device was the laser pistonphone, though any device which can contain the whole microphones (and any parts of the pre-amplifiers necessary for the correct venting of the microphones) and generate a uniform sound pressure in the cavity would probably be suitable.

4. PROCESSOR REQUIREMENTS

The processor is tested in the same fashion as most electroacoustical measuring instrumentation, but the requirements have particular regard to the determination of sound power in one-third octave bands.

The unique feature of the processors amongst electroacoustical instrumentation is the ability to measure a small phase difference between sound pressure signals and to present this as an intensity. To test this facility the processors are presented with two electrical signals with a phase difference calculated to give a specific intensity when the processor is set to a given microphone separation. The pressure-residual intensity index of the processor is measured and limits placed on this quantity determine the operating range.

The Standard allows processors to provide A-weighted results, phase compensation for probes and autoranging, but does not *require* any of these facilities.

5. CALIBRATOR REQUIREMENTS

The Standard gives requirements for three types of calibrators for use with sound intensity instruments. A sound pressure calibrator and a pressure-residual intensity index testing device are necessary for the field calibration checks described in the Standard, and a sound intensity calibrator is optional.

A sound pressure calibrator must comply with IEC 942[4].

A pressure-residual intensity index testing device subjects both microphones of an intensity probe to an identical pink noise input. The Standard requires that the phase difference between the two ports of the device should be less than a few hundredths of a degree.

A sound intensity calibrator simulates a sound intensity by applying two pressure signals, p_1

and p_2, with a known phase difference, β, to the two microphones. The simulated sound intensity level is given by

$$10 \lg \frac{p_1 p_2 \sin\beta}{2\pi f dr\, 10^{-12}} \text{ dB}$$

where f is the frequency of the sound and dr is the spacing between the microphones set on the processor. Hence a sound intensity calibrator can be calibrated, for a nominal microphone spacing, by measuring the pressure at each port and the phase difference between the two ports.

6. PERIODIC VERIFICATION

The tests described above are to be applied to a representative sample of a type of probe or processor to demonstrate that the design meets the requirements of the Standard. The Standard specifies a sub-set of these tests to demonstrate that individual instruments comply with the requirements. Processors are subjected to all the tests, but at a reduced number of measuring points. Individual probes do not need to be tested in either the plane wave or standing wave environments, but are inspected for damage, the microphones are calibrated with actuators or multi-frequency sound calibrators and their pressure-residual intensity index is measured. Calibrators are tested as in the type tests.

7. FIELD CHECKS

The Standard requires that each time a sound intensity instrument is used, checks are made to ensure that it is operating correctly. After warming up, a sound pressure calibrator is applied to each channel, and the pressure-residual intensity index is measured to confirm that the instrument is within requirements. In addition, a sound intensity calibrator, if available, is used to check the sound intensity indication.

8. CONCLUSIONS

Sound intensity instruments are much more complicated to use than sound level meters. This is partly because a probe and processor may be supplied by different manufacturers and the user then has to decide how to configure a processor and a probe to work together, and partly because the probes have to be constructed from a kit with many small parts that can be neglected or assembled wrongly so that the probe is not used in the same configuration as that in which it was tested. While probes and processors may be type tested separately the Standard implies that a verification test should be performed on a whole instrument, which will give the testing authority the ability to specify how a particular probe should be used with a particular processor and so reduce the possibility of operator error.

9. REFERENCES

[1] International Standards Organisation, (to be published). Acoustics – Determination of sound power levels of noise sources using sound intensity – Part 1: Measurement at discrete points. ISO 9614–1.

[2] International Electrotechnical Commission, (to be published). Instruments for the measurement of sound intensity – Instruments which measure intensity with pairs of pressure sensing microphones. IEC 1043.

[3] Barham R G, 1990. The NPL laser pistonphone. Proc. Inst. Acoustics **12** part 1, 923–926.

[4] International Electrotechnical Commission, 1988. Sound calibrators. IEC 942.