PRIMARY STANDARDS FOR SOUND PRESSURE – FACILITATING TRACEABILITY

J E M Avison
Centre for Acoustics and Ionising Radiation
National Physical Laboratory
Teddington

1. INTRODUCTION

Recent times have seen an increased public awareness of noise both as an environmental nuisance and as a hazard to hearing. Technological advances have led to a greater number of noise producing activities and at the same time stricter regulations on working conditions and noise exposure have come into force. An ever broadening range of social and commercial activities as well as medical and legislative requirements necessitate noise measurements. If these measurements are to have any technical validity, good measurement practice requires that they be traceable to a physical reference quantity or primary standard. The UK's National Measurement System (NMS) is a defined measurement infrastructure through which primary standards are disseminated to end users nationwide. The role of developing and maintaining the primary measurement standards on which the system is founded, is fulfilled by the National Physical Laboratory (NPL). The primary quantity for acoustics is the pascal but it is usually expressed in decibels (dB) relative to a reference pressure level of 20 µPa. The internationally agreed method for realising this primary standard is through the use of microphones calibrated by the reciprocity technique. These microphones can then be used to calibrate other instruments and thus provide transfer standards.

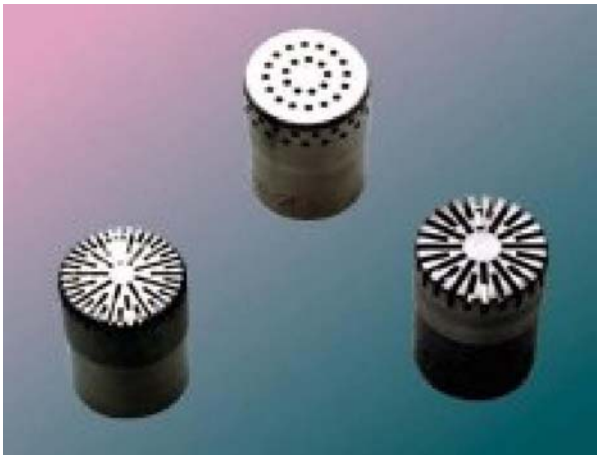
2. RECIPROCITY

Measurement microphones are classified in IEC 61094-1, according to their design, either as Laboratory Standard (LS) or Working Standard (WS). Both classifications refer to capacitor (condenser) microphones. LS microphones are designed to have a simple geometrical shape with an exposed diaphragm to suit the requirements of calibration, but are not usually appropriate for practical measurements. WS microphones are more robust and fitted with a protective grid. Different sizes of microphones are classified as type 1, 2, 3 or 4, which were formerly known as 'one-inch', 'half-inch', 'quarter-inch' and 'eighth-inch' respectively. In addition, the frequency response characteristics are declared by adding P, F or D to the specification, denoting microphones having a nominally flat pressure, free-field or diffuse-field frequency response. For example, a Laboratory Standard half-inch pressure microphone is denoted as type LS2P.

The reciprocity technique for determining the absolute pressure sensitivity of microphones is defined in IEC 61094-2. The method is suitable for calibrating LS1 and LS2 microphones. Some working standard microphones can be converted to this configuration by replacing the protective grid with an adaptor ring and can also be calibrated by the reciprocity method.

The calibration method relies on the fact that the operation of the microphones is reversible, so that it can be used as a transmitter or receiver of sound, and that its sensitivity is the same in both modes. In reciprocity, measurements are made on three microphones, usually of the same type, enabling the sensitivity of all three to be deduced. Two of the microphones are used at a time and are placed in a small cavity, known as an acoustical coupler, which is designed to create a simple cylindrical geometry between the diaphragms of the microphones. One of the microphones is then driven electrically to act as the source of sound, and the other responds to the pressure generated in the coupler, producing an output voltage. With this arrangement it can be shown that the sensitivity product of the coupled microphones is given by the ratio of electrical and acoustical transfer impedances. The electrical transfer impedance, being the ratio of the input current to output voltage produced at the receiver microphone, is measured in the calibration procedure. The acoustical transfer impedance, the ratio of the sound pressure at the receiver microphone to the input volume velocity, is deduced from transmission line analysis. Having determined the sensitivity product for one pair of microphones, the process is repeated with the other two possible pairwise combinations. The set of three sensitivity product measurements then allows the individual microphone sensitivities to be deduced. The main traceability of the calibration comes from a reference electrical impedance against which the electrical transfer impedance is compared. Measurements of the environmental parameters pressure, temperature and humidity are also made throughout the calibration and used in the final calculation of microphone sensitivity so the instruments used must also have fully traceable calibrations. The coupler dimensions are also used in the calculation of the acoustic transfer impedance.

Laboratory standard LS1 and LS2 microphones



Working Standard WS2 microphones with their protective grids fitted

NPL has developed a calibration facility to implement the reciprocity method for laboratory standard microphones. LS1 microphones can be calibrated over the frequency range from 31.5 Hz to 10 kHz and LS2 microphones have an extended range up to 20 kHz. The emphasis in reciprocity calibration is the stability and reliability of the measurements. Therefore tests are conducted, at discrete third-octave frequencies covering the range. The best measurement uncertainty achievable for these calibrations is 0.03 dB increasing to 0.09 dB and 0.18 dB at the highest frequency for type LS1 and LS2 microphones respectively. These are expanded uncertainties for a coverage factor $k = 2$, providing a level of confidence of approximately 95%.

The reciprocity technique has its limitations. It is time consuming and provides a level of uncertainty that is smaller than necessary for many practical applications. It is also limited in the range of microphones that can be calibrated and these microphones are of little use for practical measurement applications where working standard microphones are more appropriate. For the calibration of these and other instruments there is clearly a need for other calibration techniques traceable to the primary standard.

3. PRESSURE COMPARISON

To enable the calibration of a wider range of microphones, a comparison technique has been developed. This involves the test microphone being compared with another laboratory standard microphone that has previously been calibrated by the reciprocity method. In the approach adopted by NPL, measurements are made with the two microphones simultaneously exposed to the same sound pressure, while the ratio of the voltage outputs are compared. Since the ratio of the sensitivities is the same as the ratio of the output voltages under these conditions, knowing the sensitivity of the reference microphone allows the unknown sensitivity to be determined. The method is suitable for all working standard microphones, provided the microphone’s protective grid can be removed. This is necessary because the definition of pressure sensitivity requires the pressure to be applied uniformly over the diaphragm of the microphone. With a grid in place, one cannot be certain of the actual pressure distribution under the grid, particularly at high frequencies, so making a determination of the pressure sensitivity impossible. The grid is therefore removed during calibration.

There are two stages to the calibration involving two different measurement configurations because neither can successfully cover the full frequency range. In the first stage, measurements are made with the microphones positioned in an active coupler. In the second stage the microphones are placed inside a miniature anechoic chamber, referred to as the acoustic ‘egg’, and positioned with the use of a jig assembly.

Two microphones positioned in the active coupler held on a clamp stand

In the acoustic coupler the test microphone and the calibrated laboratory standard microphone are positioned face to face with their diaphragms approximately one millimetre apart. The microphones are held firmly in place by rubber ‘o’ rings within the coupler. Since the test microphone must be calibrated with the diaphragm unobstructed by a grid, there must be some way of protecting it from damage when placed in the active coupler. One solution is to fabricate an adaptor from another grid of the same design, where the central portion is removed, thereby exposing a majority of the diaphragm. However, even this approach presents limitations as will be seen below.

A WS2 microphone with a cut away grid fitted (left)
and another with the protective grid removed altogether (right)

The active coupler has two integral sound sources (coving different parts of the frequency range) which are designed to introduce an acoustical signal into the small cavity between the two microphone diaphragms. A pink noise test signal is used, the microphone responses being analysed over the whole frequency range simultaneously. This part of the calibration can therefore be performed quite quickly. During the test, it is assumed that the microphone diaphragms are spaced sufficiently close together that there can be no difference in the sound pressure applied to each of them. This is a valid assumption over the lower part of the frequency range. However, at higher frequencies, the different microphone geometries, and particularly the presence of the cut-away grid, causes the applied sound pressure to reach the microphones through different impedances, causing each microphone to experience a slightly different sound pressure eventhough they remain closely spaced. For this reason, this method is only used up to 2 kHz, if a cut-away grid is employed.

The anechoic ‘egg’ with two microphones positioned on a jig assembly

To cover the remainder of the frequency range, measurements are made inside the anechoic egg, again with any protective grid removed from the test microphone. The diaphragms of the two microphones must be positioned coaxially and within a millimetre of each other so that they are both exposed to the same sound pressure. This is particularly important at high frequencies where the wavelengths are shorter. The acoustical signal is generated by a loudspeaker situated in the lid of the anechoic ‘egg’. In this case sine waves are used rather than noise because some microphones exhibit a very rapid change in sensitivity at high frequencies and their response to band limited noise may differ from that of single frequency excitation, for which results are normally quoted.

A close up of two microphones as they are positioned within the anechoic egg.
On the left is an LS2 which has been reciprocity calibrated and
on the right is the test microphone, a WS2, with the protective grid removed.

Locating the whole body of the microphone in the sound field for a pressure calibration introduces a new problem. Microphones sense pressure both from the front of their diaphragms and at the rear (inside the microphone) via the equalisation vent. At higher frequencies the vent is effectively closed, but as the frequency reduces, the vent becomes more active. While the two microphone diaphragms can be placed close together within the anechoic egg, it would be physically impossible to simultaneously position the two venting holes close together. Since the two vents are positioned some distance apart they experience different sound pressures and this causes misleading results at low frequencies. Results from the jig measurements are therefore used over the high frequency range of 2 kHz to 12.5 kHz making the total frequency range covered by this comparison technique 63 Hz to 12.5 kHz. This is a slightly smaller range covered by reciprocity, but further research aims to extend this to 31.5 Hz to 20 kHz in the future. The best uncertainty attained by this method is 0.07dB for a coverage factor $k = 2$, providing a level of confidence of approximately 95%.

The major advantages of this service are its speed, which allows it to be relatively inexpensive, and the range of microphones it can cater for, that is, any LS2 or WS2 with a removable grid. In principle jig measurements can also be carried out on type 1 and type 3 microphones but the active coupler is designed to accommodate only type 2 microphones.

4. FREE-FIELD COMPARISON

Comparison measurements can be made sequentially as an alternative to simultaneous methods such as described above. In order to do this the sound field must be spatially and temporally stable during subsequent measurements. Therefore a stable sound source is essential and a fixed positioning system is needed for both the sound source and the measurement microphone. This approach is taken for free-field calibration of microphones at NPL. Sequential measurements are performed first on a LS1 microphone that has a known free-field sensitivity, obtained by applying free-field correction values to a measured pressure sensitivity, and then on the test microphone.

In a free-field calibration we are interested in the response of the microphone to a plane progressive wave incident from a specified direction. In order to achieve these conditions specialist rooms are usually required. In the NPL calibration facility, the majority of the measurements are made in a free-field room where the plane wave requirement can be met by positioning the microphone at a large distance from a point source. The free-field chamber is lined with sound absorbing wedges, the length of which define the lowest frequency at which the room produces a free field. The NPL chamber has a low frequency cut off point at 250 Hz.

For to lower frequencies, a plane wave duct, terminated by a suitably long wedge, is used. This is driven at one end by a loudspeaker and is operated at frequencies where a plane wave is able to propagate. This is determined by the dimensions of the duct cross-section, which must be less than half the wavelength of the highest frequency of interest. The duct is used for measurements from 250 Hz down to 31.5 Hz. The calibration as a whole then covers frequencies from 31.5 Hz to 12.5 kHz and has a typical expanded uncertainty of 0.2 dB with a confidence level of approximately 95%. The process is very time consuming and requires specialist facilities. It has the advantage that it can be applied to almost any measurement microphone and in many cases a free field calibration is more suitable for the customer than a pressure calibration because the customer is using it to make measurements in the open.

5. TRACEABILITY FOR OTHER MEASURING EQUIPMENT

Microphones that have been calibrated by these methods can be used to provide traceability to other types of acoustical measuring equipment. Sound calibrators and pistonphones are widely used to provide a reference level for setting up many types of measuring instruments. They are designed to produce a steady repeatable sound pressure at particular levels and frequencies. Most instruments provide only one frequency at one or two levels but multi-frequency devices are also available. The steady acoustical output can be measured with a calibrated measurement microphone thus providing traceability for any measurements subsequently made using this calibrated level as a reference.

NPL also provide calibrations of ear simulators. Again a calibrated measurement microphone is used to provide traceability. Hospital technicians use the calibrated ear simulators to calibrate audiometers, which are in turn used by clinicians to conduct hearing tests on patients. This is just one example of how the primary standard is propagated by a chain of calibrations to the intended measurement application.

Ideally every absolute acoustic measurement should be traceable through a similar chain to a primary measurement standard.

Selection of instruments used for acoustical measurement

6. ACKNOWLEDGEMENT

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