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FREE-FIELD/PRESSURE SENSITIVITY DIFFERENCES FOR LABORATORY STANDARD MICROPHONES

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1. INTRODUCTION

The growing importance of quality schemes is placing a greater emphasis on the calibration of equipment. In many acoustical measurement situations this may simply mean the application of a sound calibrator to the microphone of the measurement system to establish the *pressure* sensitivity of the microphone at one or more frequencies. For the most accurate free-field measurements however, it is important to know the *free-field* sensitivity of the microphone as a function of frequency. This can be obtained relatively simply by comparing the output of the microphone with that of another whose free-field sensitivity is already known, when the microphones are exposed successively at the same point in a free sound field. Alternatively a known pressure/free-field sensitivity difference for that microphone type could be applied to the pressure sensitivity of the microphone obtained from a reciprocity or electrostatic actuator calibration. However both these approaches relate back to some form of *absolute* free-field calibration. For example in the first method a reference microphone with a known free-field sensitivity must be available and in the second the free-field/pressure sensitivity difference values must have been determined.

IEC 486[1] and IEC 655[2] published in the 1970s specify the method of free-field calibration and values for the free-field/pressure sensitivity difference for IEC type LS1 (one-inch) microphones. However no data are available for the type LS2 (half-inch) microphones which are today used for the majority of acoustical measurements. This is being addressed by the IEC with the drafting of new Standards to provide the necessary data. This paper describes the research that has been undertaken at NPL to develop facilities for the absolute free-field calibration of laboratory standard microphones to support these new Standards.

2. THE RECIPROCITY METHOD

The reciprocity method has been standardised by the IEC for the pressure calibration of type LS1P and LS2P microphones[3] and the same principle can be applied to free-field calibration. The essence of the method is that the sensitivity product of two microphones can be found by using one as a sound source and exposing the other to the field produced by it. For two microphones coupled in this way, having sensitivities M_1 and M_2 respectively, the sensitivity product is given by

$$M_1 M_2 = \frac{1}{Z_a} \frac{U}{i} \tag{1}$$

where Z_a is the acoustical transfer impedance coupling the two microphones, U is the open-circuit output voltage of the receiver microphone and i is the current driving the transmitter microphone. Note that the quantity U/i is an electrical impedance, or more correctly a transfer impedance because the current and voltage are measured at different locations. By introducing a third microphone with sensitivity M_3 it is possible to determine M_1M_3 and M_2M_3 by the same process and therefore derive M_1, M_2 and M_3 separately. The calibration thus requires the two factors in (1) to be found for the three pairwise combinations of microphones. Normally the acoustical transfer impedance is based on theoretical calculations while the electrical transfer impedance is measured.

When a free sound field couples the microphones the acoustical transfer impedance at a frequency ω is given by

$$Z_a = \frac{\rho\omega}{4\pi d} e^{\alpha d} \tag{2}$$

where ρ is the density of the air, α is the air attenuation coefficient and d is the distance between the acoustic centres of the two microphones. The notion of an acoustic centre, being a virtual point source equivalent to the microphone, is required because (2) has been derived for a point source and point receiver located in a free field. Since the microphone has a finite size, the acoustic centre is in general located at some position away from the diaphragm of the microphone and the factor d cannot be taken as the physical distance between the microphones. This presents one of the major difficulties in determining Z_a.

The electrical measurements also present some problems primarily because the microphone is an inefficient transducer. The sound pressure produced at the receiver microphone, and consequently the microphone output voltage, are very small and the effects of noise and cross-talk become formidable.

3. PRACTICAL IMPLEMENTATION OF THE RECIPROCITY METHOD

A new free-field chamber was built to provide the acoustical environment for the calibrations. It is a free-standing design mounted on anti-vibration supports and constructed from double-skinned steel panels filled with a dissipative material to add damping. These panels are more commonly used to build machinery enclosures in noise control applications, so overall the chamber has good sound isolating characteristics. The interior of the chamber is lined with polyurethane foam wedges. These have a total length of 400 mm giving a theoretical low-frequency limit for the chamber of about 300 Hz. The internal dimensions of the lined chamber are 2.4 m × 2.4 m × 2.6 m high. Two long cylindrical mounts for the microphones extend from the floor and ceiling of the chamber aligned vertically along an axis slightly offset from the centre line. The mounts are the same diameter as the microphones and designed to be semi-infinite rods.

The noise isolation performance of the chamber has been tested[4] and found to exceed 40 dB over the working frequency range. The free-field performance was also assessed by the method proposed by Delany[5] and the r.m.s. deviation from the inverse pressure-distance law in the chamber was found to be less than 0.1 dB. These results illustrate the level of performance that can be achieved with this type of chamber construction.

Given that the chamber provides the necessary free-field environment, the remaining tasks during the calibration were to measure the electrical transfer impedance U/i and determine the positions of the acoustic centres.

Comparing the electrical transfer impedance directly with a known electrical impedance would seem a logical approach. Such a method was first described by Koidan[6] and modified by Torr and Jarvis[7] making it amenable to computer control. In simple terms this requires a voltage, equal to the open-circuit output voltage of the microphone U, to be developed across a resistor placed in series with the transmitter microphone. Since this resistor also has the driving current i flowing through it, the electrical transfer impedance is given by its resistance. This method provides an elegant means for measuring the electrical transfer impedance with minimal requirements for the traceability and accuracy of the instrumentation.

Implementing the reciprocity method in a free sound field places two important constraints on the above technique, both being a result of the very small voltage yielded by the receiver microphone. The first is that it must be possible to measure this signal amidst a noise level that can be orders of magnitude greater than the signal. This signal detection problem is tackled by employing lock-in amplifiers. Such instrumentation is quite uncommon in acoustical measurements but is often employed in optical applications where similar problems of low signal-to-noise ratio exist. The lock-in amplifier consists of a phase sensitive detector coupled to a low-pass filter with variable roll-off rate as shown in Figure 1.

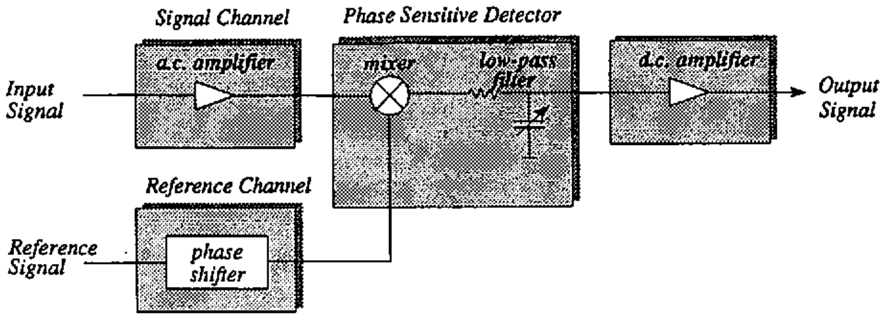

Figure 1. Elements of a lock-in amplifier.

The signal to be measured is mixed with a synchronous reference signal, adjusted so that the two are exactly in phase, resulting in a dc signal proportional to the signal to be measured. This is then low-pass filtered and measured with a suitable time constant which controls the filter roll-off rate. The combined effect is that of a very narrow band filter centred at the frequency of the signal being measured. For example a 1 second time constant is equivalent to a filter with a bandwidth less than 1 Hz.

The second consequence of the low value of the receiver microphone signal is that the value of *U/i* becomes small to the point where it is difficult to find an electrical impedance of sufficiently low uncertainty with which to compare.

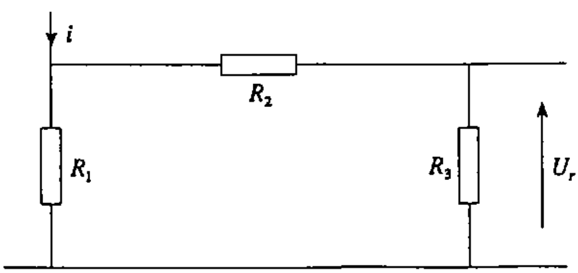

Figure 2. Resistor π-network

An alternative is to use a π-network as shown in Figure 2, where the current passes through one arm and the voltage is measured across the other. The transfer resistance R_π of this network can be defined as

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$$\frac{U_r}{i} = \frac{R_1 R_3}{R_1 + R_2 + R_3} \tag{3}$$

By making R_2 large compared to R_1 and R_3, the majority of the voltage across R_1 is developed across R_2 and the transfer resistance can be made small. With suitable choice of resistor the transfer impedance of the π-network can be as low as 0.01 Ω.

With the means available to measure the necessary electrical signals and to establish a suitably low reference impedance, it becomes possible to implement the free-field reciprocity procedure. Calibrations are performed at the preferred third-octave centre frequencies between 1 kHz and 20 kHz for type LS1P microphones and between 2 kHz and 40 kHz for type LS2P microphones. At lower frequencies, the free-field sensitivity is assumed to approach the pressure sensitivity so that any difference is negligible.

To enable the acoustic centre to be accounted for, the experimental procedure has been designed so that measurements are made at many known physical microphone separations. From (1) and (2) the resultant data can be expressed in the form

$$\frac{\rho\omega}{4\pi}\frac{1}{(U/i)e^{\alpha d}} = \frac{1}{M_1 M_2} d \tag{4}$$

Now if the value taken for d is the distance between the acoustic centres of the microphones then the quantity on the left-hand-side of (4) when plotted against d will result in a line that passes through the origin. However, at first d is taken to be the physical microphone separation and does not account for the acoustic centres. The plot will then not be of the form indicated by (4). The value of d is therefore adjusted and the data are made to pass through the origin. The amount by which d is altered is the sum of the acoustic centres of the coupled microphones. More importantly the gradient of the resulting line, having corrected d, gives $1/M_1M_2$.

A complete calibration requires the measurement of three microphone pairs each at fourteen frequencies and twenty microphone separations. Due to the averaging times necessary to measure the electrical signals the procedure takes approximately six days of continuous measurement to complete.

4. RESULTS AND CONCLUSIONS

Figure 3 shows typical pressure and free-field sensitivity responses for a type LS2P microphone. The curves are derived from independent absolute calibrations of the appropriate sensitivity, in both cases using the reciprocity method.

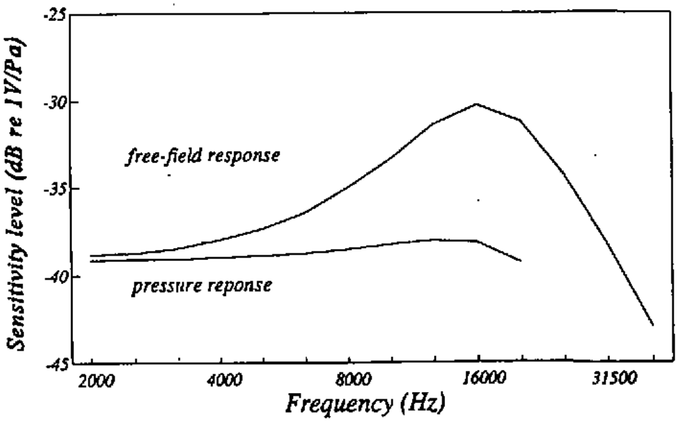

Figure 3. Typical reciprocity calibration results for type LS2P microphones.

By performing such calibrations on a representative sample of microphones of the same type it is possible to calculate the mean difference between the free-field and pressure sensitivity for the group of microphones. The mechanical and acoustical specifications of laboratory standard microphones have been defined[8] so the mean values derived from the measurements should be characteristic of all microphones of that type. This is fortunate given the effort required to derive the values. Having determined the free-field/pressure sensitivity differences for laboratory standard microphones, these can then be used as reference devices to determine the sensitivity of all other types of microphone by comparison.

To conclude, a new facility for free-field reciprocity calibration has been developed at NPL and is being used to determine values for the free-field/pressure sensitivity difference of laboratory standard microphones. This will enable the UK to contribute to the drafting of a new IEC Standard which will specify such data.

5. REFERENCES

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