PERFORMANCE OF A NEW MEMS MEASUREMENT MICROPHONE AND ITS POTENTIAL APPLICATION

R Barham National Physical Laboratory, Teddington, Middlesex, UK
M Goldsmith Teddington, Middlesex, UK

1 INTRODUCTION

In deciding how to determine the sound level of a particular environment or source, the selection of microphone is frequently a limiting factor. In the area of environmental noise monitoring, for example, it would be ideal if arrays of low-cost transducers were continuously available for periods or many months. It would then be possible to obtain multi-point measurements of the noise fields of, for example, roads, railways, factories or streets which would include diurnal and seasonal variations at all likely listener positions[1]. In the measurement of the sound fields due to particular machines and installations – especially large ones like air-conditioning systems or pump installations - an array of low-perturbation transducers spread over an enveloping surface would also be ideal[2]. A third example is that of condition monitoring, where small, low-cost, robust transducers could be permanently installed in vehicles or domestic products, and be used to check on changes in acoustic signature which would indicate degradation of performance.

In reality, the microphones and associated equipment currently available are highly unsuitable to such tasks, being expensive, large, somewhat perturbing and not particularly robust. Furthermore, their relative instability compared to other measuring devices means that an in-situ calibration is required (in the form of, for example, a sound calibrator).

The difference between desirable measurement instruments and real ones is so significant that completely different approaches are taken to determining noise levels. Thus, predictive noise modelling is used for noise mapping, often not constrained by measurement at all (but on, for example, traffic flow predictions for road noise) – temporal variations are modelled or ignored. Similarly, sound power measurement of large machines or installations employs a range of compromises and simplifying assumptions, while condition monitoring by acoustic measurement is rarely used.

The enormous increase in recent years of the number of cell phones led to an immediate and unprecedented demand for low-cost, robust microphones. This was met by the rapid development of microphones constructed on silicon chips, so called MEMS (MicroElectroMechanical Systems) microphones[3,4]. The cost of these transducers is a tiny fraction of that of conventional condenser microphones.

If it were possible to use MEMS-based microphones in place of current measurement microphones, the reduction in cost alone would allow enormous improvements in noise measurements, and their small size and robustness would also be very significant advantages.

The problem with this is of course that cell phone microphones are not intended to be used as measurement devices, so there is no guarantee of their stability (over time or over environmental conditions, in particular temperature). Also, they are required to function only over a narrow frequency range.

The question therefore arises: is it possible to design and build a MEMS-based microphone which could produce more useful results than current measurement systems and/or predictive approaches?

To answer these questions, a number of collaborative projects led by the Acoustics Group of the UK National Physical Laboratory have been undertaken, funded both by the DTI/DIUS NMS and Technology Programmes. The remainder of this paper will describe elements of this work.

2 TEAM

There have been two main phases to this work; the first running from October 2004 to September 2007, and involving NPL with QinetiQ and Strathclyde University, the second running from October 2007 to September 2010 with a team comprising NPL, QinetiQ, Castle and Hoare Lea Acoustics. The first project designed and built experimental prototype transducers exploiting technology available at QinetiQ[5] and tested them in laboratories, while the current one is producing enhanced transducers, installing them in prototype measuring devices and testing them, both in laboratories and as arrays in real environments.

3 TRANSDUCER DESIGN

The key design targets associated with the MEMS microphone (see Figures 1 and 2) are:

Diaphragm resonant frequency, which should be significantly higher than the required upper frequency limit (20 kHz in this case). For this project, >30 kHz was specified.

Mechanical Q-factor of the membrane. This was chosen to be 0.5 in this project.

Microphone sensitivity (1 mV/Pa here).

The minimum detectable A-weighted sound pressure level. This relatively challenging parameter is determined by the noise from the microphone, the bias resistor and the associated electronics as well as the microphone sensitivity. The original target set for this was 45 dBA, reduced to 30 dBA for the next phase of the project.

The maximum sound pressure level that the microphone can measure within a set limit of total harmonic distortion. Target for this application was 110 dB. The difference between this and the minimum detectable A-weighted sound pressure level defines the acoustical dynamic range of the microphone. (In practice the electrical dynamic range may be less than this and may define the actual dynamic range of the microphone)

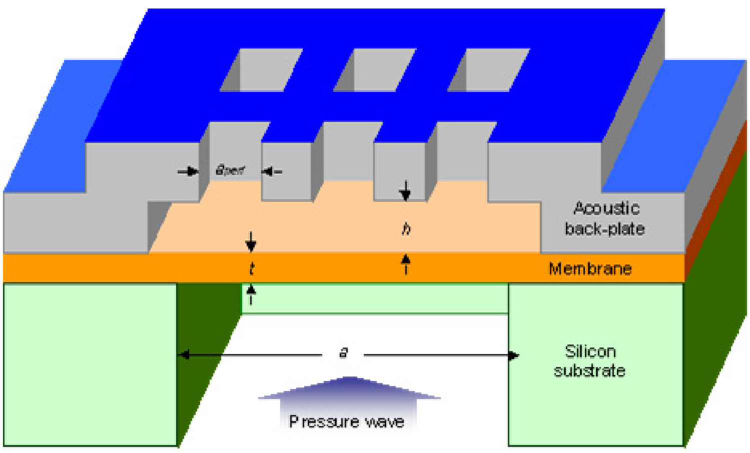

Figure 1: Schematic view of microphone design (QinetiQ copyright image)

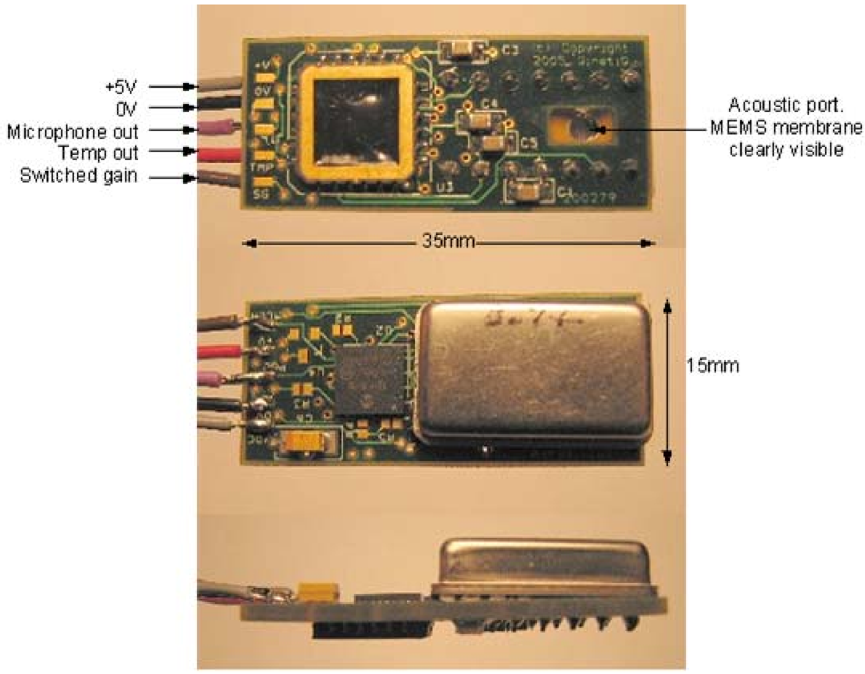

Figure 2: General view of prototype transducer (QinetiQ copyright image)

4 LABORATORY TESTS

Aside from the design and fabrication of the MEMS microphones, a significant element of the project was to develop a suite of calibration and testing facilities to enable the electroacoustic performance of both bespoke and commercially available MEMS microphones to be fully evaluated. This was considered to be a key project development, as no similar facilities or corresponding data have been reported in the literature on MEMS microphones.

Facilities and techniques have therefore been developed at NPL to evaluate the following parameters;

- Pressure sensitivity in the range 31.5 Hz to 20 kHz,
- Free field sensitivity at normal incidence and 90 degrees incidence in the range 100 Hz – 25 kHz,
- Signal-to-noise ratio (and hence noise floor) in the range 20 Hz to 20 kHz
- Total harmonic distortion,
- Dynamic range

These facilities were employed to test the prototype MEMS microphones produced by QinetiQ. Results for representative devices are reported below. Some comparison measurements of a Commercial Off-The Shelf (COTS) MEMS microphone, designed for mobile phone use, were also made. Comparative reference data for Brüel and Kjær eighth-inch (4138), quarter-inch (4135) and half-inch (4133) microphones are also shown.

4.1.1 Free field frequency response

These tests were carried out in the NPL full anechoic chamber. A comparison method adopting a substitution approach was used. A reference microphone (Brüel and Kjær type 4180) was first used to establish the sound pressure at the point of calibration. The MEMS microphone under test was then substituted into this sound field and its response to the known sound pressure determined. Comparison calibrations were conducted in the frequency range from 100 Hz to 25 kHz.

Figure 3 shows the response of a QinetiQ microphone and is compared with an equivalent response for a commercially available device.

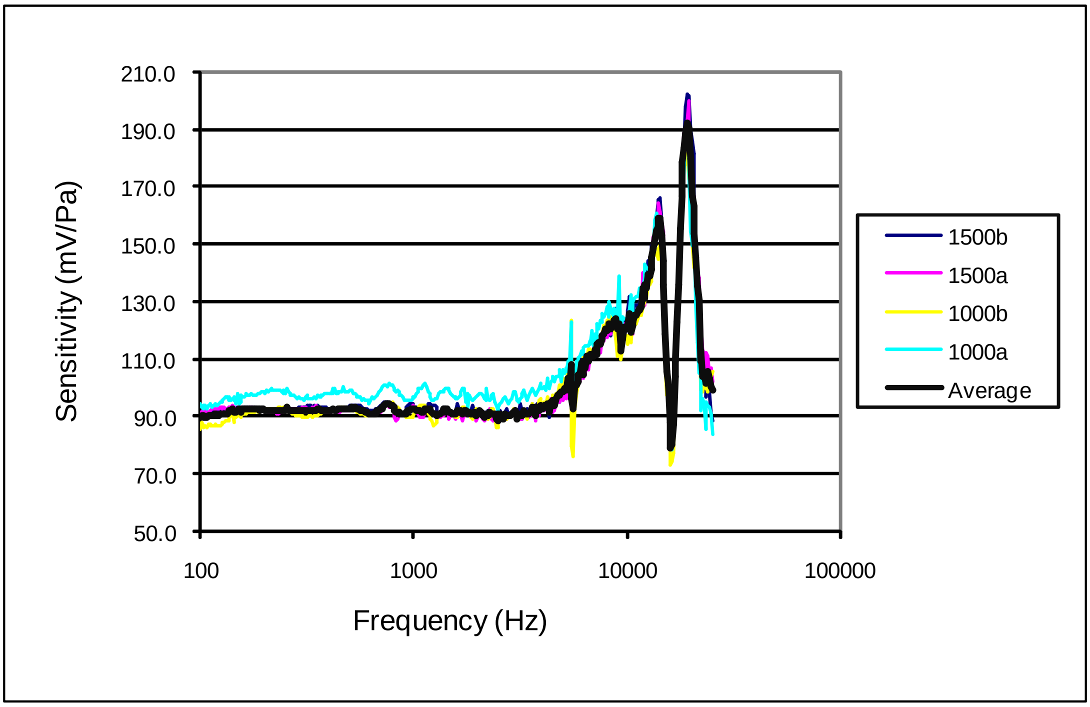

Figure 3: Free-field response of QinetiQ microphone (line labels include measurement distance in mm and test sequence identifier)

The ripple in the frequency responses and the spikes observable around 6 kHz and 9 kHz are almost certainly due to imperfections in the free-field performance of the room, mainly arising from the use of a pure tone test signal.

A comparison of free-field responses of the COTS microphone with the QinetiQ one shows that, as hoped, the high-frequency increase in sensitivity seen in the response of the COTS device is much reduced in the QinetiQ microphone (Figure 4).

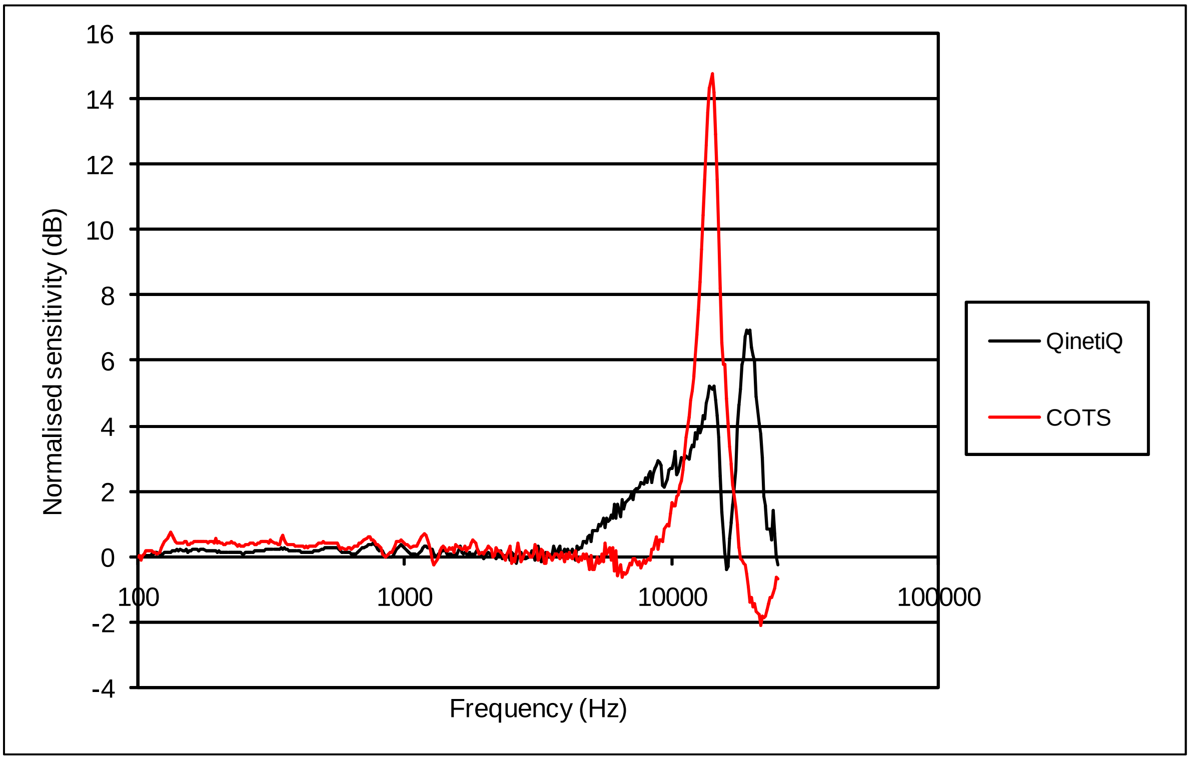

Figure 4: Free-field responses of bespoke and commercial MEMS microphones compared

The general rise in sensitivity with frequency of the QinetiQ device is due, at least in part, to interaction of the acoustical field with the microphone assembly. This is the same effect that gives rise to a free-field correction for conventional measurement microphones and is investigated further below.

4.1.2 The influence of mounting geometry on microphone sensitivity

A number of experiments were conducted on the effects of different mountings on the microphone sensitivity variation. Space limitations preclude the inclusion of full details here, but it is clear that, despite the small size of the microphone itself, the packaging geometry has a significant impact on the frequency-dependence of the sensitivity, due to diffraction effects, and that, in designing MEMS-based acoustic sensors, the optimum geometry would be one in which the diaphragm is mounted on the end of a rod of the same circumference, thus reducing the frontal area to a minimum. Alternatively, in designing microphones in the future it would be necessary to consider an appropriately controlled damping mechanism that can be used to compensate for the enhancement effect of the geometry. This is the approach taken to produce conventional measurement microphones having a flat free-field response, despite the diffraction effects that results due to their size. However replicating the approach at the MEMS level may present significant technical challenges.

4.1.3 Noise floor

MEMS microphones typically have significantly higher noise-floors than conventional devices, but can in principle be accurately "tuned" at the design phase to have relatively low noise floors albeit at the expense of reduced frequency bandwidth.

The noise floors of the MEMS microphones were determined by simply removing any sound from the environment as far as possible, and measuring the persisting output from the microphone, which was then assumed to be the self-noise of the device. The NPL hemi-anechoic chamber was known to have an acoustic background level below 0 dB SPL, so this was used as the test environment for determining the noise floor. Before proceeding, the actual background noise was established using a very high sensitivity microphone system. See Table 1 for results.

4.1.4 Total harmonic distortion (THD)

Distortion in MEMS microphones results when the deflection of the membrane becomes sufficiently large that it can no longer be considered small compared to the gap size between the membrane and backplate (such an assumption is required to linearise the analytical model of the membrane dynamics). Indeed this is true of all microphones, but in MEMS devices the gap size is itself already very small (c. 1 µm).

The THD of the MEMS microphones was measured by placing the devices within a closed pressure driver, along with a calibrated WS3 microphone. The WS3 microphone was used to monitor the sound pressure level within the pressure driver, while a frequency analysis of the MEMS microphone output was carried out: the levels of the fundamental (1 kHz) and the first six harmonics, were measured directly from the analyser and used to calculate THD. The process was repeated with 1 dB increases in the sound pressure level until the THD reached around 5%, where the tests were terminated to avoid damaging the MEMS devices. However, a COTS device was tested to much higher levels, to investigate whether these devices actually fail at some point.

It is noticeable that the distortion of the QinetiQ device, in the upper range of sound pressures to which it was exposed, is less than that of the COTS transducer. See Table 1 for numerical results.

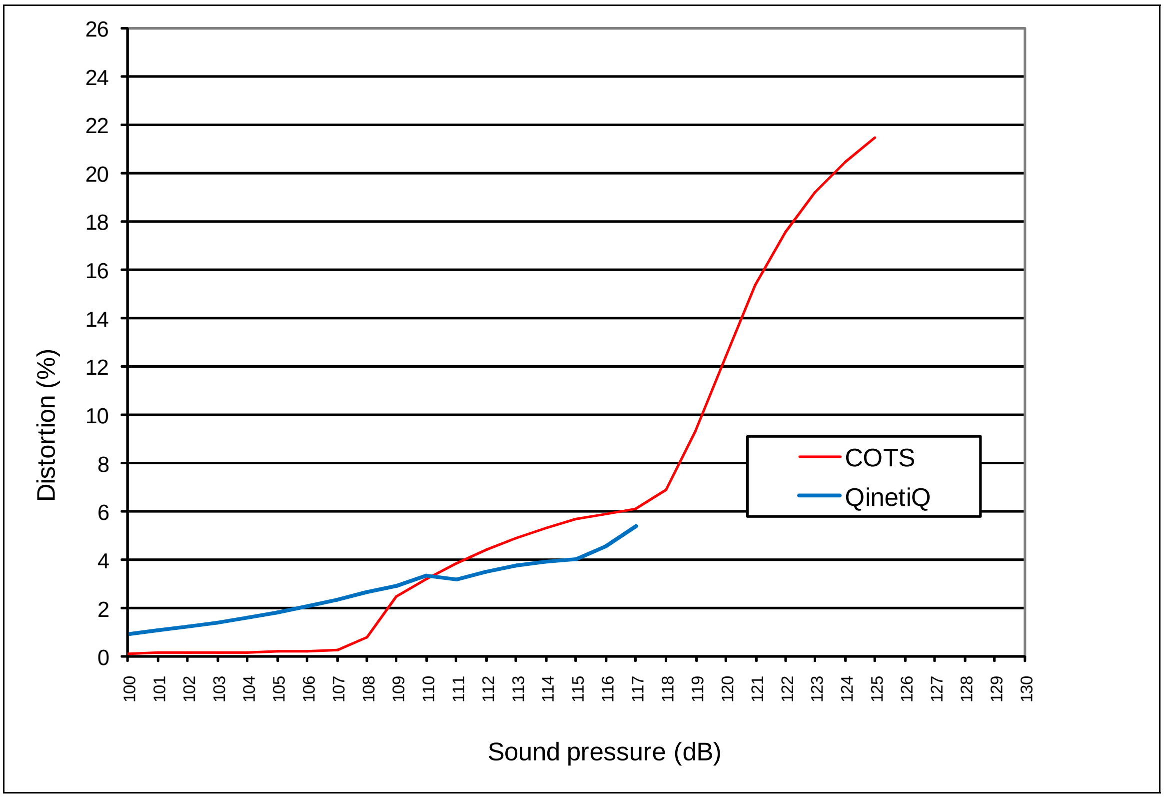

Figure 5: Distortion tests

4.1.5 Dynamic range

The dynamic range is defined here as the difference between the A-weighted noise floor and the SPL required to produce a distortion of 5% at 1 kHz. The data measured in the tests described above have been used to determine the dynamic ranges given below

Device	A-weighted noise floor	SPL at 5% THD (dB)	Dynamic range (dB)
QinetiQ	51.2	116	65
COTS	42.4	113	71
B&K 4138 ⅛"	56	174	118
B&K 4135 ¼"	39	170	131
B&K 4133 ½"	26	161	135

Table 1: Dynamic ranges

5 NEXT STEPS

The next phase of the project will aim to illustrate the potential impact of MEMS measurement microphones using a specific application to drive the technological developments required. The selected application involves the use of MEMS microphones in the development and testing of an innovative approach to the validation of strategic environmental noise maps. However such developments will be readily applicable to a wide range of other applications. The approach involves the deployment of DREAMSys, an array of approximately 100 wireless sensor devices containing MEMS-based microphones, including enhanced versions of the type reported above which are planned to have significantly lower noise floors. The remainder will be low-cost commercial devices of lower performance. The array will be tested for one year at a specially selected site, and the results used to validate a predictive noise map of that site. The information and knowledge gained from this field trial will lead to guidance on the adoption of a new approach to noise mapping and validation based on a mix of measurement and prediction. The array-based system will be available for use for future mapping projects.

6 ACKNOWLEDGEMENT

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