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Development and performance of a multi-point distributed environmental noise measurement system using MEMS microphones

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ABSTRACT

The first round of noise mapping exercises, required by the European Noise Directive, are now completed, and have shown a preference towards prediction with modelling software. A possible criticism of this approach expressed by some researchers across Europe, is the lack of measurement validation in the process, which often neglected because of its intrinsic costs. This leads potentially to a reduced confidence in the final data, which is crucial for the success of the resulting action plans. DREAMSys is a measurement system that has been developed to address this problem in the future. This paper describes the development and testing of this MEMS microphone-based measurement system, under both laboratory conditions and outdoors. Results of the laboratory evaluations include key microphone parameters such as free-field frequency response and dynamic range, as well as sensitivity to environmental conditions such as temperature, atmospheric pressure and vibration. Outdoor evaluation then extends these to consider the effect of wind, rain, extreme cold and sunlight. For the first time the potential for MEMS microphones to be used in general measurement applications and for outdoor noise monitoring has been thoroughly evaluated.

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1. BACKGROUND

MEMS technology now yields a multitude of devices that have found their way into everyday products and high tech applications alike (for example in Apple's *iPhone* and Sony's *Playstation*, to use in medical robotics and energy harvesting). M-E-M-S is an acronym for micro-electro-mechanical systems; techniques originating in the micro-electronics industry are used to fabricate devices in materials such as silicon. It was recognised early on that the technology lends itself well to the production of microphones[1,2], and the potential for miniaturisation led the hearing aid industry to pioneer the development of MEMS microphones. However opportunities from high volume consumer products, especially mobile telephones, soon saw manufacturers addressing these markets also[3]. Consequently, and amidst a strongly competitive environment, MEMS microphones developed rapidly, leading to a selection of commercial products being available today. MEMS microphone have two significant features; they are very low cost, and they have a very small form factor. The technology is also very new, so further improvements in performance and miniaturisation are to be expected in the course of time. Amidst these developments, the National Physical Laboratory (NPL) saw a role for such devices in *measurement*, an area that no manufacturer appeared to be considering. At a time when the National Measurement System strategy was under review in the UK, MEMS microphones naturally featured strongly in the vision for significantly advancing measurement technology in the airborne acoustics field.

Meanwhile, a completely separate initative was underway in Europe. EU Directive (2002/49/EC)[4] requires that noise maps be produced for all agglomerations, roads, railways and civil airports, to inform strategic planning for noise control. The approach mandated in the directive makes exclusive use of modelling to predict noise levels. However, out of necessity due to issues of complexity, these rely on over-simplified assumptions and exclude vital features such as temporal variation, leading to data that is at best indicative. Now that the first implementation of the directive has been complete, many authorities across Europe are finding it impossible to use noise maps for further action planning or as part of a noise reduction strategy. The problems include lack of confidence in the output data reflecting reality and lack of any temporal variation. Such issues could be resolved by including a role for measurement in the process, but this is prohibitively expensive with instrumentation currently available.

NPL was therefore well positioned to recognise that MEMS could have a significant part to play in improving noise mapping exercises and enhancing the impact and effectiveness of this socially important process. This application was therefore chosen to drive the development of a new MEMS microphone-based measurement system, but with the realisation that such a system could be readily deployed in a much wider range of noise measurement situations.

2. REMIT FOR A NEW TYPE OF MEASUREMENT SYSTEM

A measurement system for noise mapping needs to be capable of aquiring noise data at distributed locations simultaneously. The low cost of MEMS microphones removes a significant barrier in considering such a system. Furthermore the cost of operating the system is greatly reduced by enabling data to be collected remotely, using wireless technology.

Such a system would also need to be fully weather-proofed and be able to operate unattended for prolonged periods of time. The system would also have to be well-characterised in order for the measurements to be considered reliable. Traditionally, this is achieved by demonstrating conformance to a specification standard such as IEC 61672[5] (specifying industry standard performance requirements for *class 1* and *class 2* sound level meters) or its predecessors (which referred to *type 1* and *type 2* instruments). However, in this instance, reaching one of these levels of performance was not deemed necessary because the accuracy of Class 1 or Class 2 instruments exceeds that actually required for characterising the majority of noise problems sufficiently for action planning. In addition, the data from a distributed measurement is likely to be more informative than data of better accuracy but limited to a few locations

Taking this remit, a consortium of NPL, Castle Group, QinetiQ and Hoare Lea Acoustics, set out to develop and demonstate a **D**istributed **R**emote **E**nvironmental **A**rray **M**onitoring System – DREAMSys.

3. DEVELOPMENT OF DREAMSys

The consortium aimed to develop a novel, low-cost, distributed wireless noise monitoring system, known as DREAMSys, to enable measured noise data to be used to enhance strategic noise maps, bringing significant improvements to their accuracy in key areas and increasing their overall value. DREAMSys consists of a large number of individual measurement devices. Up to one hundred will be used in this specific project, but the total number necessary depends on the application. Two types of MEMS microphone are used. The majority of units use a commercially available MEMS microphone, while around 10% of the devices will be fitted with a bespoke MEMS *measurement* microphone, developed specifically by the DREAMSys project to have an improved level of performance over commercially available devices. During the proof-of-concept stages, the system will also include a Class 1 sound level meter as a means of validating the system, but one objective is to show that this is unnecessary in the longer term.

Microphone developments are being undertaken by QinetiQ. The following key features were specified for the new MEMS measurement microphones.

- Acoustic dynamic range greater than 75 dB(A) (self generated noise <25 dB(A) and limit of distortion >100 dB(A))
- Acoustic frequency range from 20 Hz to 20 kHz
- Membrane resonant frequency greater than 30 kHz
- On-chip temperature measurement accuracy of better than 1°C
- Operating voltage from 3.3 V to 5 V with <0.1 dB change in microphone sensitivity for 1% change in voltage
- Operating current less than 5 mA
- Analogue output voltage range of 1V full scale

Prototype microphones have already been tested, but development of the final version of the microphone is still underway.

The remainder of this paper will therefore focus on the development and performance of the rest of the hardware and specifically the data acquisition unit, which is the main responsibility of the Castle Group, assisted by AVI Limited, within the DREAMSys project. The key requirements for this unit were:

- On-board power supply capable of continuous operation for at least 15 days
- Weather proofing to IP66
- Data storage capacity for at least 15 days of measurements

- Wireless data transmission for remote data collection (using GSM)
- An wireless link fail or not be available.
- Dynamic Range of greater than 70 dB (30 dB(A) to 100 dB(A))
- Frequency weighting A- & C- and time weighting F according to IEC 61672-1, class 2
- Calculation of L_{Aeq}, L_{Ceq} L_{max} plus 3 user-defined L_N levels in contiguous programmable time periods (10 minutes typically)
- Overload and under range indicators
- Data automatically corrected for microphone specific temperature effects
- Time stamped data and synchronous timing between all the devices.
- Device and location identifications
- Indication of operational and battery status
- Calibration mode for periodic alternative direct digital link to allow data collection/ interrogation, should calibrations at 1 kHz

Efficient use of power was a key consideration in designing the electronics. For this reason a processor was avoided, and all calculations are performed with a floating-point-gate-array implementing the simple arithmetic to calculate the L_{eq} values.

The GSM network has been used to provide the wireless functionality. Each unit is fitted with a data SIM card and is capable of transmitting its stored data via SMS.

To address the issues of mounting the microphone at height and away from nearby perturbing objects, it was decided to adopt a two-box approach, where the microphone and acquisition circuit are housed separately from the modem and power supply. Such an approach also provides for a range of mounting options, two of which can be seen in Figure 1.

Figure 1: Tripod and post mounting options for DREAMSys masthead and battery/modem units. The microphone is seen here fitted with a hydrophobic wind shield and bird spike.

4. DEVICE TESTING

NPL has responsibility for testing devices both during their development, and following production. This includes extensive acoustical and electrical laboratory tests on the chosen commercial MEMS microphones, on prototype QinetiQ microphones and on the DREAMSys electronic units.

For the microphones these tests include:

- Absolute pressure sensitivity and frequency response in the range 125 Hz to 10 kHz
- Free-field sensitivity and frequency response in the range 125 Hz to 10 kHz and in a number of mounting configurations
- Determination of self-generated noise
- Linearity and distortion thresholds
- Dependence on ambient temperature, pressure and humidity
- Dependence on vibration, wind, condensation and frost

A selection of typical results for a given microphone can be seen in Figure 2.

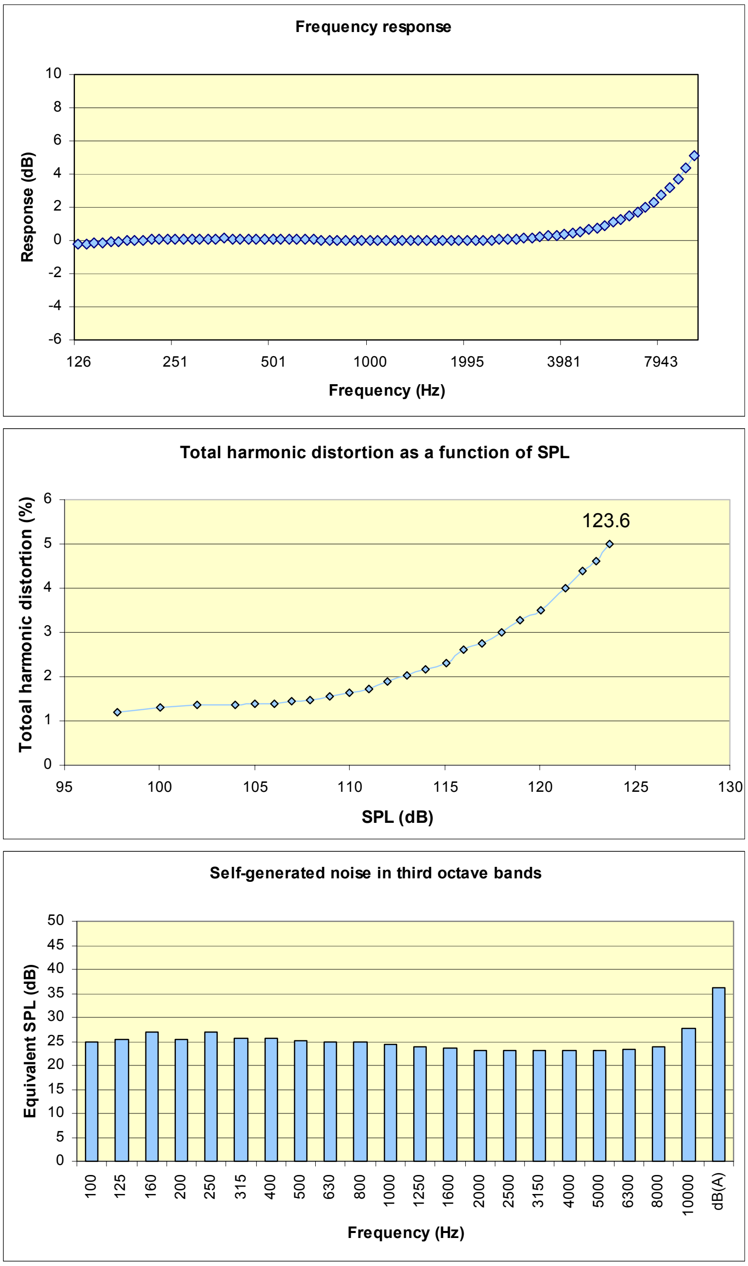

Figure 2: Typical results from laboratory testing of commercial MEMS microphones. Over one hundred microphones have been tested; results typically span a range of approximately ±1 dB.

Laboratory testing of the electronic units focussed on:

- Electrical tests of the frequency weighting and networks
- Dynamic range of the electronics
- Validation of the accuracy of the electronics
- Functionality under extreme environmental conditions

In addition to these studies, a series of acoustical tests investigated the free-field performance of housings for the microphone and data acquisition electronics, as well as the effects of the wind shield and bird spike elements. These acoustical tests were also used to optimise the design in these areas.

Further laboratory tests have been carried out on fully assembled units. This provides a validation of the earlier tests of individual components, post-assembly and prior to the deployment of the units outdoors.

Since DREAMSys consists of a completely new set of equipment, and represents the first attempt at deploying MEMS microphones for measurement, it has been essential to gain some experience of its use outdoors.

A number of units have therefore been set up around the NPL site, which provides an opportunity to investigate the performance of some units under controlled conditions. For instance it has been possible to site two units very close together, but where one is well sheltered from the weather, and the other is not. Another has been placed in the outlet of HVAC ducts and therefore exposed to an almost constant flow of air and an elevated temperature, while a nearby unit is free of such influences.

Five of the units are also accompanied by a type 1 sound level meter-based logging system enabling a ready comparison of DREAMSys with proven equipment in a real noise measurement situation. Figure 3 shows a DREAMSys unit and the type 1 data logger installed near the NPL site boundary, adjacent to a busy road and bus stop, and Figure 4 shows a sample of data from these two units.

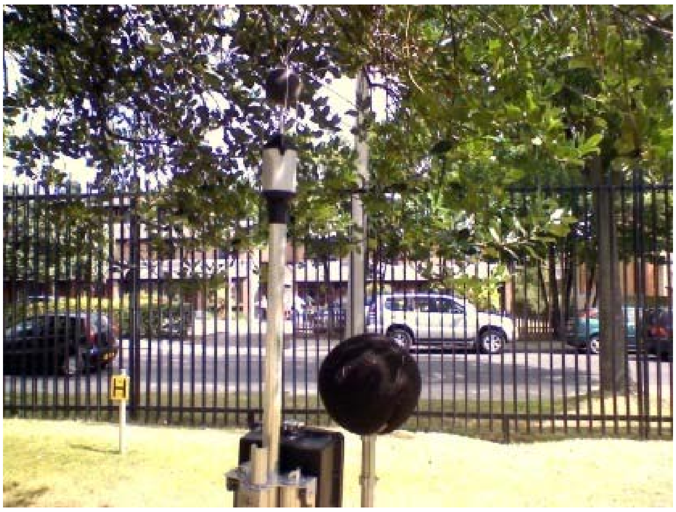

Figure 3: DREAMSys and a SLM based data logger sited close to the NPL roadside boundary

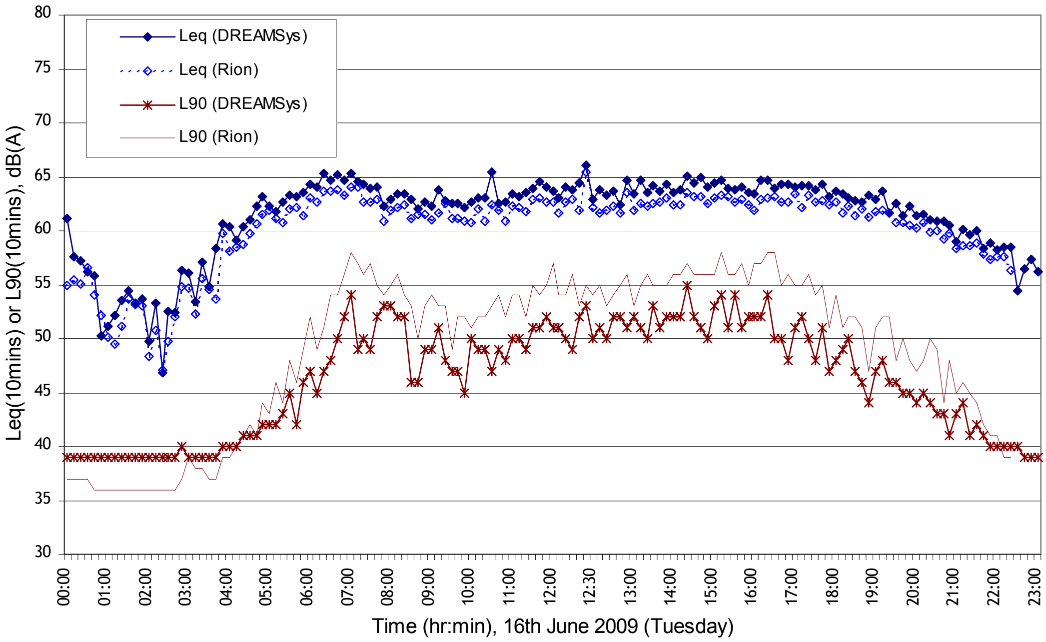

Figure 4: Sample of 10 minutes L_{eq} data from DREAMSys unit and type 1 SLM (Rion).

These outdoor tests have been invaluable in completing the final stages of development of the system. The GSM communications have been particularly problematic with the network, the service provider and the modem all contributing to performance issues, despite the units testing positively in the laboratory. During the trials so far, weather conditions have ranged from heavy precipitation, very high temperatures (above 30°C), strong sunlight, and high winds, all of which have been coped with well.

The outdoor tests will remain in progress for some months as they provide valuable experience not only in setting up the system, but also in its operational longevity.

5. CONCLUSIONS

The development of a new noise monitoring system called DREAMSys has been described. The system has been conceived as a cost-effective solution to the distributed measurement of noise over a widespread area. Components of the system have been thoroughly tested and calibrated in the laboratory, and initial results of testing outdoors indicate a high degree of consistency with conventional equipment.

Furthermore, DREAMSys offers advantages over conventional equipment, by greatly expanding the coverage offered by the measurement system, enabling a large number of measurement points to be installed and used to continually monitor the area over prolonged periods of months or even years.

With the development of DREAMSys completed, the next stage is to embark on a number of field trials around the UK. Hoare Lea, as environmental noise consultants, engage in this phase of the work alongside NPL. Planned field trails include the mapping of an area of land adjacent to City Airport, earmarked for residential development and a study at a wind farm in Scotland. Other trials in the UK and Europe are also under discussion.

Ultimately these trials are intended to explore the role of measurement in the strategic noise mapping process. It is not intended that the DREAMSys array replaces prediction entirely. It is rather the case that both approaches will complement each other, with the measurements being made in areas carefully selected on the basis that action plans would be significantly enhanced as a result.

Progress in the project can be followed at www.DREAMSys.org

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