THE ACOUSTICAL METROLOGY PROGRAMME AT THE NATIONAL PHYSICAL LABORATORY (UNITED KINGDOM)

1.0 Introduction

The Report provides a summary of research related to Acoustical Metrology currently being undertaken at the National Physical Laboratory (NPL). The work at NPL is organised in three-year Programmes whose content has been developed through extensive consultation and input from the user community. The 2004 – 2007 is currently in progress, and key technical highlights of the first year of the Programme, from October 2004 – September 2005, are presented within this Report.

1.1 Programme rationale

Measurements of acoustical quantities are made very widely, by companies in manufacturing and service industries, authorities responsible for occupational and environmental health, hospitals and clinics, and by defence services, for many different applications. Examples include the noise emitted by sources such as aircraft and industrial machinery, the noise exposures of workers in their occupational environment and the general public where they live, individual persons' hearing sensitivity, the ultrasonic sound energy produced by medical therapeutic and diagnostic equipment and by industrial devices such as ultrasonic cleaning baths, and the sound fields radiated or received by underwater acoustical systems. The purposes of the measurements include the collection of information for product specifications and contracts, demonstration of compliance with regulations, access to markets, assessment of public nuisance, comparison with safe exposure limits, ensuring accurate diagnosis and effective therapy, and enabling accurate underwater positioning, mapping and detection.

The objectives of the programme are to:

- provide and develop national measurement standards in the field of acoustics, noise, underwater acoustics and ultrasonics, at a level consistent with the current and future needs of UK industry, national and local government and the health service, and make them accessible to customers in as practical and economic a form as possible

- ensure that UK measurement standards in acoustics are harmonised with those of the UK's trading partners, through comparisons and collaborative research leading to mutual recognition

- develop innovative new methods of measurement for sound, noise and ultrasound to meet identified UK private and public sector needs, and promote international standardisation of these methods to ensure consistency in practical measurements, especially where these are used for regulatory or trading purposes

- promote knowledge transfer from the programme and the adoption of good measurement practice, and to provide technical support and advice to UK organisations and individuals undertaking acoustical measurements.

1.2 Programme structure

The programme is comprised of five main themes. There are three themes dealing with the core measurement standards, a fourth dealing with research, including the long-term research and a fifth covering cross-theme Knowledge Transfer (KT).

The five core Themes are:

Theme 1: Standards for Airborne and Audiological Acoustics
This theme provides for the realisation of primary standards of sound pressure within and beyond the audible frequency range; the calibration and verification of microphones, sound calibrators, ear simulators, and digital hearing aids.

Theme 2: Standards for Underwater Acoustics
This theme covers standards for underwater acoustics, providing for: the realisation of primary standards of acoustic pressure at frequencies below 1 MHz; the calibration/testing of hydrophones, projectors and underwater acoustical systems; and including the calibration at hydrostatic pressures and temperatures corresponding to real ocean conditions.

Theme 3: Standards for Medical and Industrial Ultrasonics
This theme covers standards for medical and industrial ultrasonics, providing for: the realisation of standards of acoustic pressure and power at frequencies above 1 MHz; the calibration of hydrophones, ultrasonic power meters and measurements of the acoustic output of medical ultrasonic equipment; standardised measurements of tissue heating caused by medical ultrasound; and measurements of acoustic cavitation relevant to both medical and industrial ultrasonics.

Theme 4: Acoustical Standards Research
This theme covers acoustical standards research for acoustic emission, and both machinery and environmental noise. It also covers work on 'sound quality' and new innovative methods for noise measurement. Most importantly, this theme covers the application of optics to acoustical measurement and a proposed new initiative on the development of a new generation of acoustical measuring instruments.

Theme 5: Knowledge Transfer
This theme covers cross-theme knowledge transfer aimed to promote the take-up of the outputs of the programme, and the adoption of good measurement practice, and to provide technical support and advice to UK organisations and individuals undertaking acoustical measurements.

2 THEME 1: STANDARDS FOR AIRBORNE AND AUDIOLOGICAL ACOUSTICS

2.1 Primary measurement standards for sound in air

This project provides primary measurement standards appropriate for the wide range of acoustical measurements in air. These standards support sound pressure measurements for manufacturing and product QA, health, safety and hearing conservation, environment noise measurement and monitoring, and many other applications. Dissemination of the measurement standards is undertaken to a degree through NPL's own calibration services, all of which are underpinned by this project. However the support provided to UKAS laboratories by this project is also vital for their effective operation, enabling traceability to be spread far more widely than NPL could manage alone. The facilities require continual incremental development to keep pace with (or even drive) the understanding of the physics underlying the calibration process and embodied in specification standards. From time to time the facilities also need significant re-development to keep pace with changes in IT and to replace instrumentation before it becomes obsolete.

Highlight

The laser pistonphone has returned to full operational again and an NPL reference microphone has been calibrated in the frequency range 1 Hz to 31.5 Hz to validate its performance. Results for this microphone fit well with the model for the expected response based on a non-adiabatic thermodynamic process within the microphone and for the effect of the microphone's equalisation vent. However a more comprehensive validation requires some form of international comparison with other NMIs, which has never been attempted, but is the subject of CCAUV.A-K2. As well as providing the basis for a service for low frequency calibration of microphones (and other pressure transducers), the laser pistonphone is being considered as a solution for the pressure calibration of non-standard pattern microphones, including MEMS microphones.

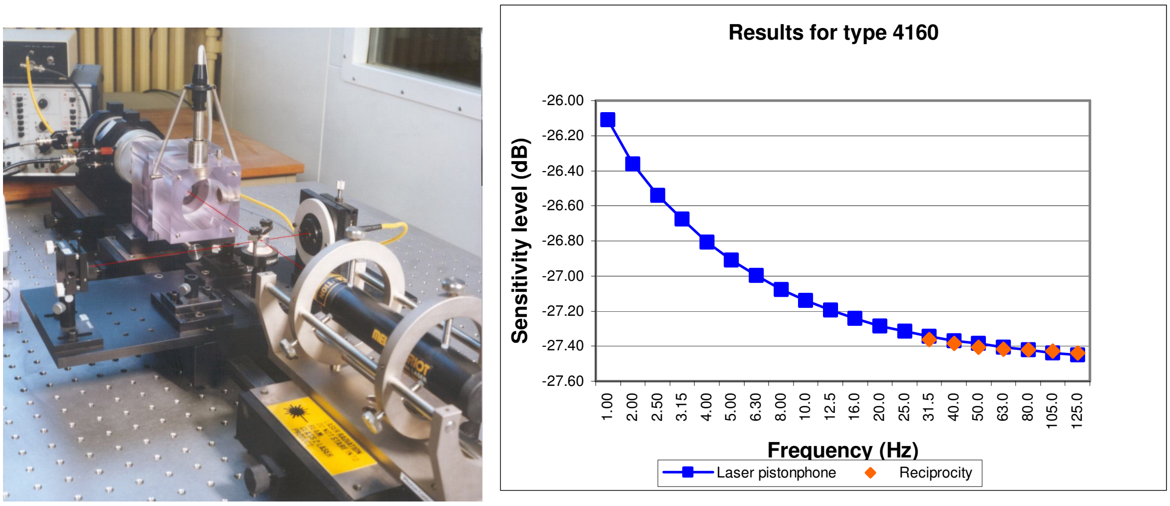

Figure 1: NPL laser pistonphone and typical frequency response of LS1 microphone to 1 Hz

2.2 Project 1.2 Working standard microphones

Secondary calibration of working standard microphones can offer the most direct and cost-effective traceability path for sound-in-air measurements. However, there is a growing call for these methods to cover microphones having a non-standard pattern. Free-field calibration is currently heavily resource-dependent and requires specialised facilities. There is therefore a need to simplify the process and embody this in international standards, enabling secondary laboratories to develop such facilities. Associated with this is the requirement to qualify the performance of free-field rooms. However, microphone calibration is only one application where this is necessary. Others include sound power measurement of machines and hearing aid testing. An international standard is therefore required dedicated specifically to the testing of free-field rooms and enclosures, that can be referred to where other applications require such specifications.

Highlight

In the omni-directional sound source work a new method of evaluation of sound source directivity has been developed. Non-perturbing sound field measurements using the acousto-optic effect (whereby local changes in the refractive index of the medium are detected using laser vibrometry) have been achieved for the evaluation of sound source directivity (see Figure 2). This is a significant technical achievement since it allows the rapid measurement and evaluation of sound source directivity, independent of the room. The emerging technique of acousto-optic measurements has a wider impact and could be used for source and field characterisation, device perturbation and the technique will be disseminated as part of this project. Work will now focus on the development of the omni-directional sound source for airborne measurement, which will require collaboration with a suitable UK industrial partner.

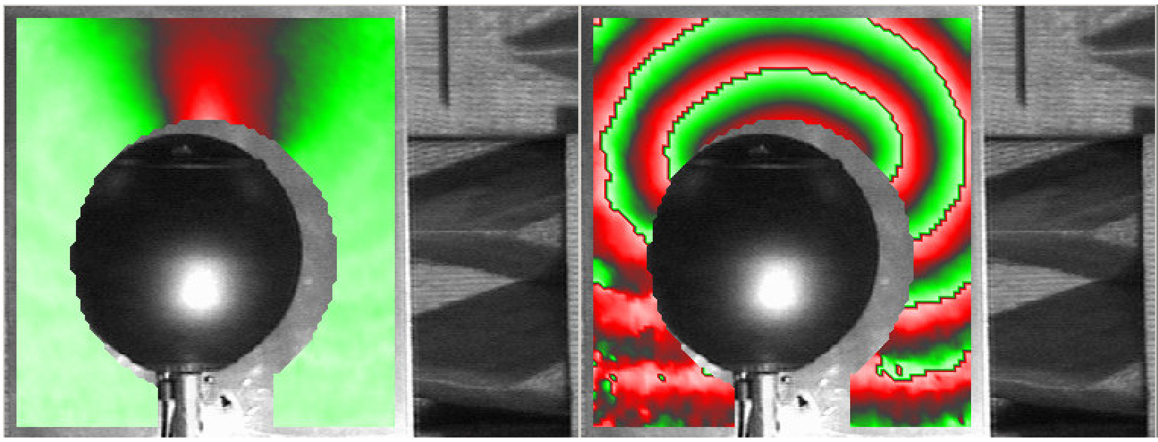

Figure 2*:* Magnitude and phase plot of acoustic field radiating from a ball loudspeaker measured using the acousto-optic effect

2.3 Sound level meters and calibrators

Sound level meters are the most commonly used instrument for sound-in-air measurements and the use of sound calibrators is the simplest way of providing traceability for such instruments. Consequently, calibration and periodic verification of the performance of these devices is important for a vast number of users. It is therefore vital that the UK plays an active role in specification standards in this field. Given the versatility in functionality of sound measuring systems (of which sound level meters can be considered a sub-set), and in the applications for which they are used, there is a need for best practice guidance on a number of aspects, such as verification of FFTs, checks on filters, or general frequency response measurement. Also advice is needed on the type of calibration and level of uncertainty appropriate for particular applications, such as sound power measurement. There is also a need to make recommendations on the level of calibration or verification appropriate for low-grade instruments, commensurate with their cost.

Highlight

NPL has continued to actively participate in IEC TC29/WG4 Sound level meters. Detailed comments on the CDV of IEC 61672 Part 3 'Periodic tests' were compiled, sent to BSI, discussed with other UK WG members, and the final version of comments submitted by BSI to IEC. The WG4 meeting was attended at the end May and the comments on the CDV of Part 3 were discussed and resolved. The FDIS draft of Part 3 has also been reviewed at the request of the Convenor. It is now expected the document will be published in Spring 2006. The writing of Part 3 has highlighted some necessary clarifications to Part 1 and hence to Part 2 of IEC 61672. A list of these was made at the WG meeting and the Convenor will circulate this to the WG. The revisions of Parts 1 and 2 started in February 2006, although it was agreed it was essential not to change the basic specifications.

2.4 Ear simulators and hearing aid testing

Measurements of hearing by pure tone audiometry are made traceable through the calibration of ear simulators. However, new techniques such as oto-acoustic emission and evoked response audiometry, while they may have been around for some time, are now seeing routine use in screening and diagnosis of hearing defects, and revolutionising hearing measurement on a national scale. The appropriateness of traditional methods of ear simulator calibration therefore needs to be reviewed and adapted to suit these newer applications. Indeed, the question of whether the ear simulators themselves, which pre-date the measurement methods to which they are being applied, are still fit-for-purpose needs to be addressed and the outcome embodied in IEC standards as appropriate. Going one step further, it may be time to consider the possibility of direct measurement of the in-ear sound pressure, thereby eliminating the need for ear simulators in the longer term.

Aside from audiometry, ear simulators are used in many other applications, including audio measurements for telecommunications. Bringing traceability to these measurements requires the development of new calibration methods and targeted knowledge transfer.

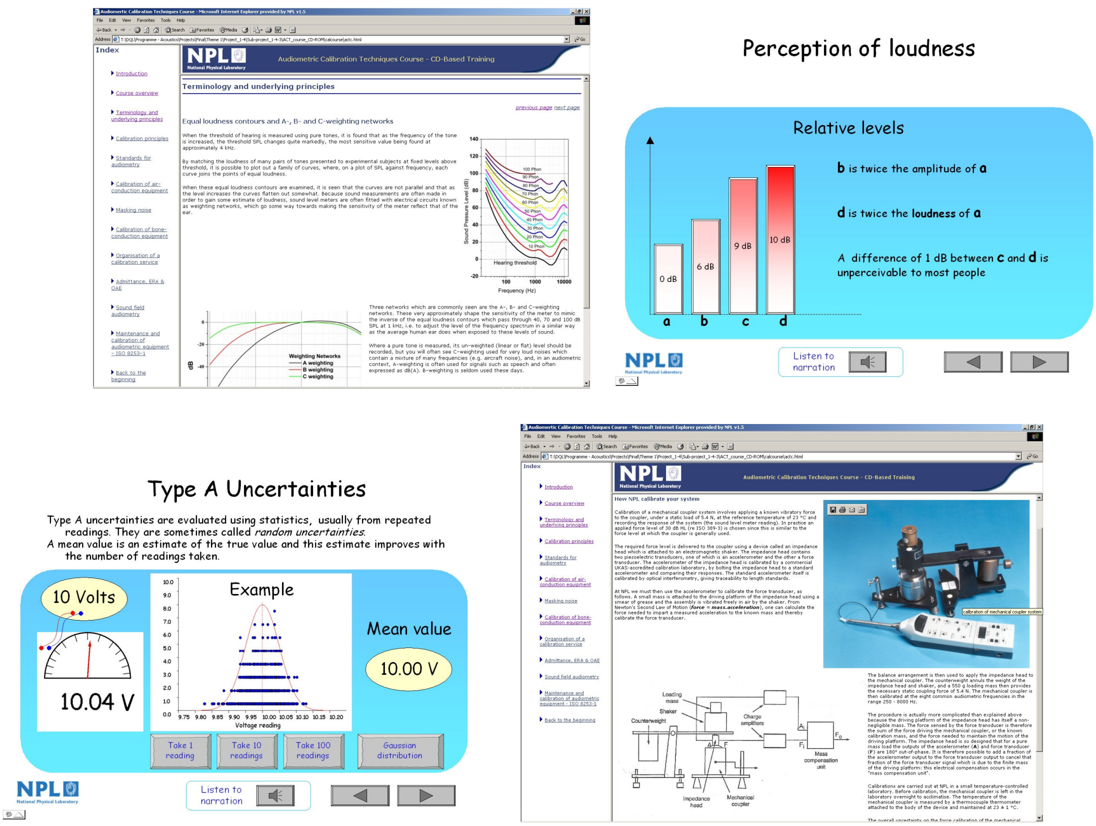

Figure 3: Screen shots from the Audiometric Calibration Techniques CD-ROM

Highlight

Interactive CD-ROM based training material has been produced on audiometric calibration techniques. The CD-ROM provides ten training modules covering calibration basics through to specific details of calibration methods for advanced audiometric methods. Full use has been made of the medium's potential by including a range of interactive demonstrations and numerous diagrams, photographs and sound clips to enhance the training material. The CD-ROM received very favourable comments after it was reviewed by a small number of leading calibration technicians (see Figure 3)..

A NPL-led EUROMET project to develop a test method for the acoustical impedance of an artificial ear, and generate normative data for IEC 60318-1, has begun. NPL has already gathered a significant amount of data, so our main contribution to the project has been to investigate and report on refinements to the measurement configuration, such as the influence of various microphone grid configurations on the performance of the device up to 16 kHz. These have been completed. Results from the project are being fed into the review of IEC 60318-1 that specifies the artificial ear. Publication of the revised standard will allow testing laboratories to verify that the ear simulator has the specified acoustic impedance, thereby improving the quality of information that accompanies a calibration.

The feasibility of an approach to measuring the impulse response of the artificial ear and occluded ear simulator has been established and a facility set up. The first measurements of an impulse response have been made, and further refinements to the method are in progress. This is important work because tests using impulsive stimuli are becoming more widespread. For example such methods are the basis for the Universal Neonatal Hearing Screening Programme. It is therefore vital that the equipment used is subject to appropriate calibration rather than extrapolating previously available data. The first step in this process is to understand the difference between the steady-state and impulsive responses of the ear simulators used to calibrate the transducers used for testing.

3 STANDARDS FOR UNDERWATER ACOUSTICS

3.1 Underwater acoustical standards for hydrophone calibration

This work of this project underpins the provision and dissemination of standards in underwater acoustics in the frequency range 20 Hz to 500 kHz. The basis of free-field primary standards in the frequency range 1 kHz to 500 kHz is the calibration of laboratory-standard hydrophones by the three-transducer reciprocity method (IEC 60565), the coupler reciprocity technique being used for the calibration of standard hydrophones at frequencies from 20 Hz to 1 kHz. An improved understanding of the sources of error in these primary standards is vital if long-term improvements are to be made to the methodology.

These standards are disseminated either by direct calibration using the primary method, or by comparison with a calibrated reference hydrophone. NPL's free-field calibration service provides industry (including UKAS laboratories) with traceability to national standards. Free-field measurements are undertaken at ambient temperature and hydrostatic pressure in two open tanks, the largest being 5.5 m diameter and 5 m deep, and the smaller tank being 2 x 1.5 x 1.5 m deep. The tanks are equipped with precision positioning systems enabling accurate positioning and orientation of acoustic transducers under computer control enabling full characterisation to be undertaken of sophisticated sonar transducers. A calibration raft on an open-water site at Wraysbury reservoir is also routinely used to disseminate these standards widely to users in the frequency range 1 kHz to 350 kHz. This facility has the potential to be used for dissemination of standards at frequencies below 1 kHz.

The aim is to extend the capability of these services to provide the best match with industrial requirements possible, and to disseminate the results of the work to a wide audience by the most appropriate routes (direct measurement services, scientific papers, web-based information sheets, etc). Extending the capability will include:

- improved dissemination of the standards at frequencies less than 1 kHz where currently the provision is weakest
- establishment of a reference phase calibration capability for hydrophones so that the full response of the device can be determined
- developing an improved understanding of the sources of error in calibration
- harmonization of standards through appropriate comparison exercises.

Highlights

Significant progress has been made with the work to extend the frequency range of calibrations for the open water facility at Wraysbury. This activity will substantially improve the provision of traceable free-field hydrophone calibrations. Successful calibrations have been undertaken at frequencies as low as 250 Hz with the expected "flat" receive response obtained (Figure 4). The measurements use improved signal processing to analyse the acquired waveforms, and utilises new mounting brackets to enable transducers to be used at greater depth. Measurements at lower frequencies are currently limited by poor signal-to-noise ratio, and strategies to improve this are currently being investigated.

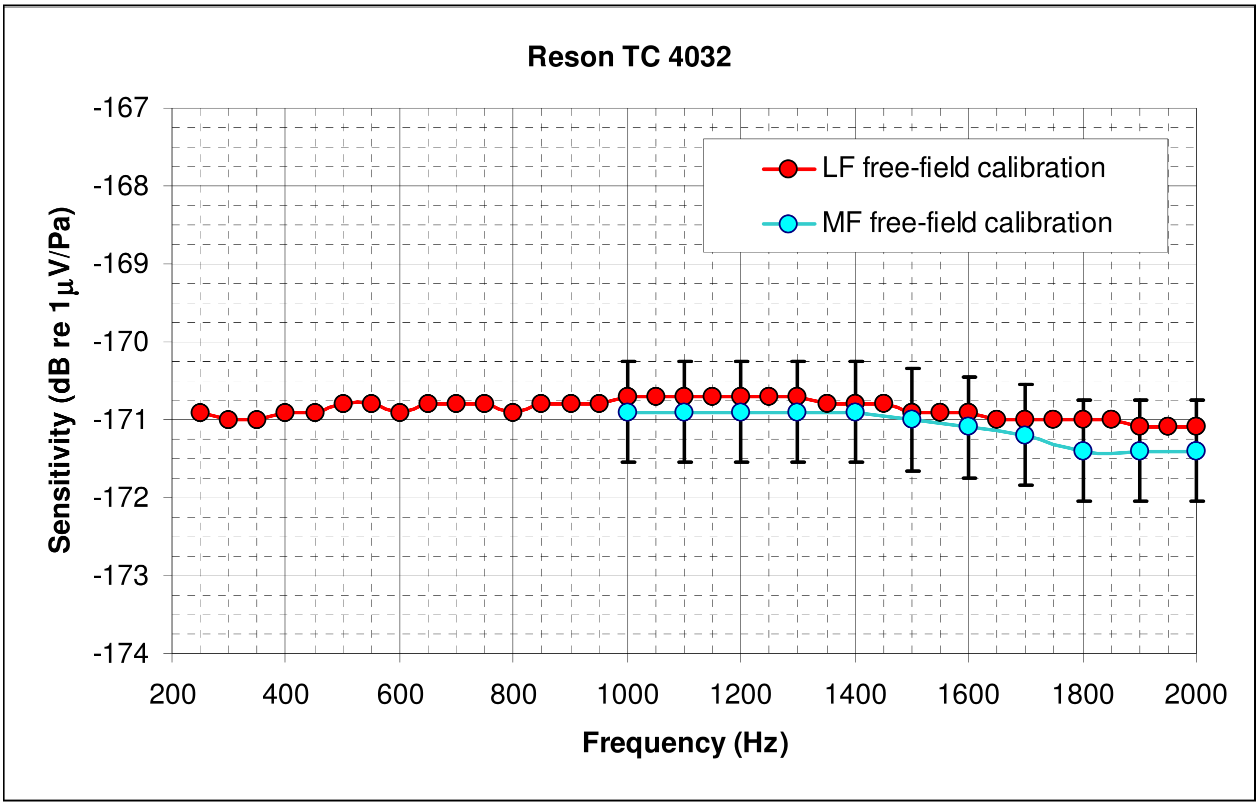

Figure 4: Example of a low frequency free-field calibration of a Reson TC4032 hydrophone undertaken at the Wraysbury open-water facility. A comparison is made with a standard mid-frequency calibration for the same hydrophone

A new method for calculating the correction for electrical loading on hydrophones from long extension cables has been derived using a standard two-port electrical network. The method requires the measurement of both the open and short circuit impedance of the cable at each frequency. The method has been successfully validated against experiment.

3.2 Underwater acoustical standards for acoustic field characterisation

This project incorporates a range of activities that are best described by the term acoustic field characterisation. This includes the extension of the use of near-field measurement techniques which can be applied to assessing large high frequency transducers and arrays in laboratory tanks, both to determine the far-field response and the acoustic distribution at the transducer surface, an excellent monitor of performance for individual array elements. The use of optical techniques may provide long-term benefit in this area.

As described above, underwater noise is of increasing importance both in its impact on marine life and its influence on the performance of other acoustic equipment in the vicinity (e.g. acoustic positioning systems which are crucial for accurate location and navigation in deep water). Before specification standards can be prepared, agreed methods of measuring the noise are needed which are rapid, flexible and sufficiently accurate. Such methods will enable financial savings to be made by industry since they will not require the use of expensive noise ranges.

Many users of high frequency sonars (including multi-beam echo-sounders) report the need for new guidelines for their *in-situ* testing, in particular for the provision of standard targets with improved performance compared to those recommended in current standards (e.g. in IHO S44).

Improvement in the knowledge of hydrophone response in the presence of sediment will benefit users in the oceanographic community studying sediment transport processes, important for studies of coastal erosion, and mine-hunting in shallow-water ports and harbours. In addition, studies of sediment are important for mine counter measures, environmental oceanography, seabed characterisation for the offshore construction and extractive industries, and for marine habitat mapping.

Finally, knowledge transfer provides an important part of this project. NPL has already provided technical guidance sheets and web-pages which have been highly valued by the user community. The further development of this dissemination route will allow guidance to be provided on additional topics such as the technical specification of acoustic equipment (not always clearly and unambiguously provided), the correct use of terminology and units for acoustical quantities (a source of considerable confusion in the past) and other issues that are raised in consultation with the user community.

Highlights

Nearfield measurements have been made of the field generated by an High Frequency (HF) sonar array operating at 330 kHz and 500 kHz using both planar scanning using a miniature hydrophone, and using a scanning optical vibrometer to measure the surface vibration of the array. The data have been used to compare the results of the two scanning methods when used with the plane-wave angular spectrum method of propagating acoustic fields. Figures 5,6 and 7, give examples of the technique in use.

An invited paper was presented describing the planar nearfield work at the *Underwater Acoustic Measurements 2005* conference in Crete. The paper was a joint paper and was presented by Prof. Victor Humphrey of the Institute of Sound and Vibration Research (ISVR), and was well received. The conference was attended by 200 people from 28 countries and had 4 parallel sessions.

(a) (b)

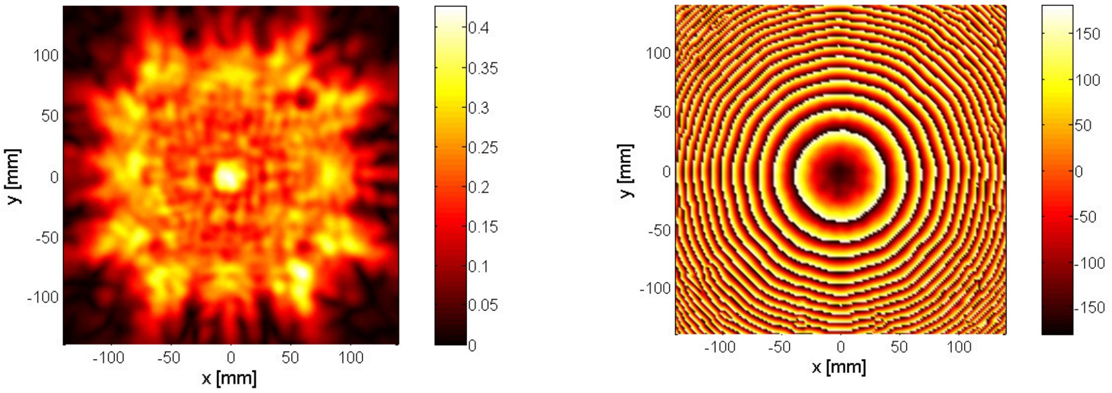

Figure 5: Measured pressure amplitude on a linear scale (a) and wrapped phase (b) in scan plane at a range of 106 mm from Transducer B at 375 kHz

(a) (b)

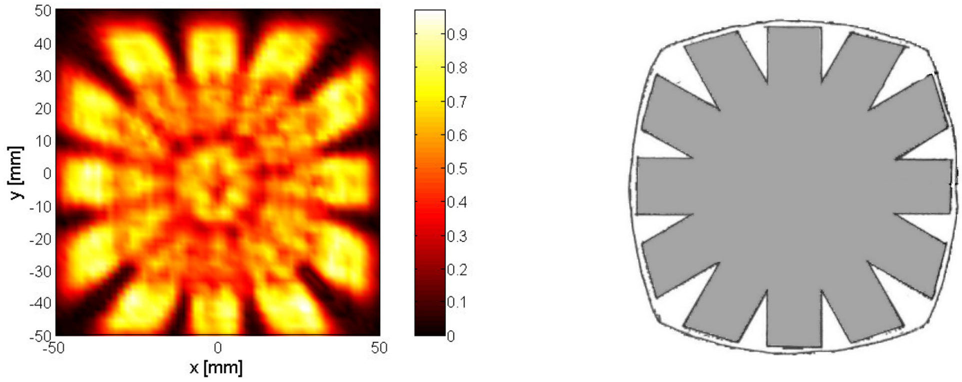

Figure 6: (a) Pressure amplitude (on a linear scale) for Transducer B calculated by back propagating the field distribution from 106 mm to 10 mm; (b) the electrode pattern on the array

(a) (b)

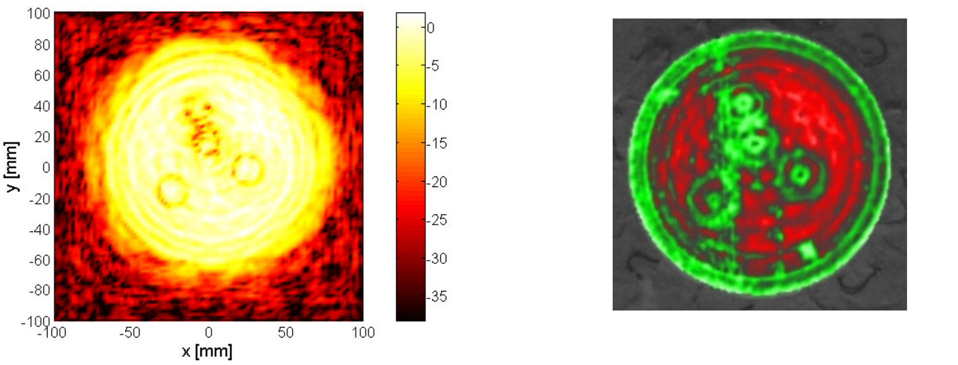

Figure 7: Results for Transducer C showing: (a) pressure amplitude (on a dB scale) calculated by back propagating field from 200 mm to 10 mm; and (b) direct measurement of the surface velocity using scanning laser vibrometry

3.3 Project 2.3 Underwater acoustical standards under simulated ocean conditions

This project provides standards for acoustic transducer testing and free field materials evaluation under simulated ocean conditions by use of the NPL Acoustic Pressure Vessel (APV), and disseminates those standards by operating measurement services. The results of the characterisation of commercial hydrophones will be disseminated to industry to act as guidance of the use of these devices.

The environmental conditions within the APV can be modified to simulate ocean depths down to 700 m (hydrostatic pressure from atmospheric to 7 MPa) and temperatures from 2 ^{o}C to 35 ^{o}C. With the APV, NPL provides a valuable facility which is unique within Europe, a fact recognised by the UK underwater acoustic industry.

As noted earlier, the APV provides a cost-effective alternative to sea-trials which is an order of magnitude less expensive. To maximise savings to industry, it is therefore of considerable importance to be able to maximise the usefulness of the facility in terms of the technical capability. Novel methods will be investigated to increase the frequency range over which measurements may be made in the APV, with particular emphasis on the difficult low frequency range below a few kilohertz.

The materials used in underwater acoustics often have an important influence on the transducer performance, especially if the material properties vary with temperature and depth of immersion (for example for viscoeleastic materials). Methods of characterisation of these materials have been undertaken in the NPL APV, but there is a need to further extend the frequency range of the measurements down below the current limit of 5 kHz.

Highlight

Improvements have been made to the signal modelling method to combine simultaneous multi-frequency analysis with models that include the first few reflected signals. Wavelet techniques have proven to be able to provide a successful estimate of the echo-arrival times without a priori information. The improved methods have provided significantly improved estimates of TVR for high Q projectors in the APV. The work is being undertaken in collaboration with the Mathematics and Scientific Computing Group in the Division for Enabling Metrology at NPL.

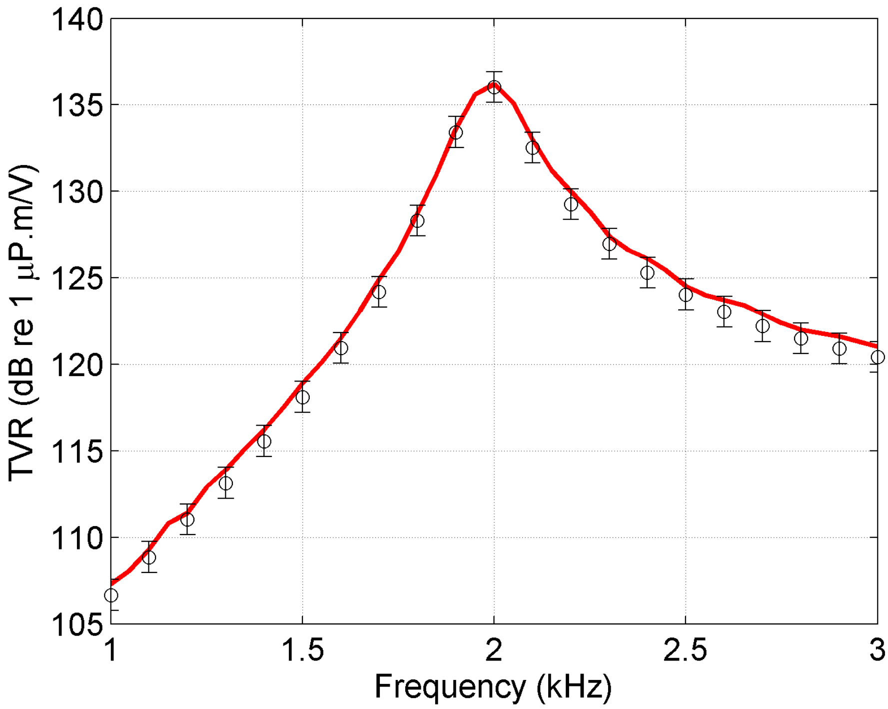

Figure 8: Results of calibration of a high-Q low-frequency projector in the APV using the signal modelling method (circles) and a comparison with a free-field measurement undertaken at the Wraysbury open-water

4 STANDARDS FOR MEDICAL AND INDUSTRIAL ULTRASONICS

4.0 Background

The aims of this theme are:

- provision of calibration and testing services for the area of ultrasonic metrology, providing traceability to both the industrial and hospital community
- undertaking leading-edge metrological research and, through it, to develop, validate and disseminate novel instrumentation to meet the requirements of the UK user community
- dissemination of the research through a variety of means: peer-reviewed publications; exposure of key results on the *www* and contributing to, and influencing, the development of international specification standards to the benefit of the UK
- promotion of the benefits and impact of the metrological take-up by the user community, through the coordination of targeted Knowledge Transfer events, including workshops addressing issues of measurement at the user level.

Ultrasound is an exceedingly common form of medical imaging, with almost all pregnancies with the UK being subject of at least one ultrasound imaging scan. It also has a growing range of therapeutic uses. In obstetric applications in particular, where the developing foetus is exposed to an applied ultrasonic field, quality control of equipment and assessment of safety are paramount. Hydrophones, used for determining acoustic pressure, and radiation force balances, used for measuring acoustic output power, remain pivotal to these measurements. Over the years, UK companies, some of them SME’s, have been at the forefront in terms of designing and manufacturing high quality measurement devices. Through NMS funding, the measurement infrastructure has been established providing a range of industrial and hospital users with the ability to undertake traceable, absolute measurements of key acoustical quantities in order to meet the requirements of international safety and performance standards. Medical ultrasonic applications, both diagnostic and surgical, continue to proliferate from an innovative UK community. With the need to meet the exacting measurement requirements posed by this emerging equipment, there is a requirement for new measurement techniques to be developed and for existing capabilities to be extended to ensuring safe, effective and optimised application of medical technology.

High power ultrasound is used extensively throughout industry within a variety of applications from ultrasonic cleaning and sonochemical processing to ultrasonic welding. In the former two applications, acoustic cavitation is the agent responsible for physical and chemical changes generated within a medium, and there has been a long-standing need to develop standardised methods of measurement for both cavitation, and ultrasonic cleaning itself. Establishing this capability will allow the harnessing of the processing capability provided by high power ultrasound and enable difficult issues, such as industrial scale-up, to be addressed. It will also allow processes to be optimised, ensuring energy savings, and equipment designs to be refined. The improved understanding of cavitation dynamics and measurement will also impact on medical applications, where (as a non-thermal mechanism) cavitation is considered an important potential source of hazard in diagnostic and surgical applications. Cavitation may be especially important in newer applications, where contrast agents are being used to improve image quality and to deliver therapeutic treatment.

4.1 Ultrasonic pressure standards

The NMS primary standard for hydrophone calibration, a laser interferometer, will continue to be provided, and in response to an increasing industrial demand, the feasibility of extending its operating frequency range up to 100 MHz will be investigated. New hydrophone calibration services will be developed to keep pace with the continued development of the membrane hydrophone as reference wide band-width measurement devices. A new calibration service will be established providing higher frequency calibrations up to at least 40 MHz. A feasibility study will be completed to establish the upper working frequency range of the primary standard laser interferometer, in response to a growing need to develop such a measurement capability. Medium and long-term provision of Measurement Services will be assured through detailed evaluation and commissioning of hydrophones for use as replacement devices for the existing, ageing and non-replaceable, Marconi gold-standard hydrophones.

Highlight

Early calibrations above 60 MHz have been carried out utilising a nonlinear model for propagation of ultrasound in water. A review of theoretical methods for hydrophone calibration using nonlinear propagation has been completed and extensive discussions held with Professor Victor Humphrey (ISVR), who has considerable experience in this technical area. The review has shown that the KZK equation is the most appropriate model to use, and indeed has been applied by workers in the field attempting calibrations at high (>50 MHz) frequencies. First calibrations using acoustic pressure data generated using the KZK code for a focused axisymmetric transducer and measured output voltage were carried out for one of the NPL high frequency reference hydrophones. The characteristics of the transducer were obtained by optimisation to match the low-amplitude experimental data obtained with a 5 MHz transducer with focus at 60 mm. The velocity of the face of the transducer is then adjusted so that measurements of the fundamental at higher drive levels agree with the KZK prediction at 60 mm, 75 mm and 90 mm from the source. An up-dated optimisation of results yielded sensitivity values between 50 MHz and 100 MHz for the hydrophone/amplifier systems investigated.

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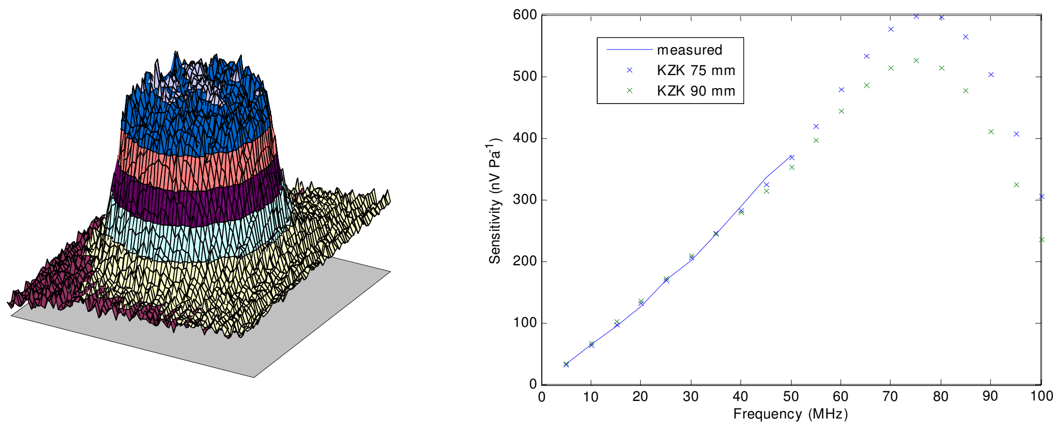


Figure 9: a) 2-dimensional scan undertaken 6 mm from face of 5 MHz focussed transducer of focal length 60 mm, showing the approximately uniform pressure over aperture of transducer and its cylindrical symmetry. The scan has been completed using a 9 µm coplanar hydrophone. The transducer is being investigated as a reference source to generate a nonlinear acoustic field and frequency components in excess of 100 MHz; b) initial calibration results for one of NPL reference hydrophones, IP901. The results are obtained by predicting the ultrasonic field of the focused source using the KZK model and by measuring the output voltage of the hydrophone/amplifier combination at two axial positions in the field around the focal region of the transducer (75 mm and 90 mm away from the source)

4.2 Ultrasonic power standards

Services for hospitals and industry, relating to calibration of radiation force balances for determining ultrasonic output power, will continue to be provided and extended to include power determination at human body temperature. These services will be improved through the commissioning of an ultrasound therapy-level Portable Power Standard which will be made available to UK manufacturers and hospitals for use as a QA tool. Further theoretical and experimental evaluation of a novel (solid-state) pyroelectric-based technique for monitoring and determining ultrasound power will be undertaken. To address the needs of emerging medical ultrasound technologies, collaborative projects will be established with hospitals and academia for the development of new underpinning measurement techniques. This includes the development of standardised techniques for determining essential properties of HIFU fields used within cancer therapy, and the extension of ultrasonic power measurement capability from the current upper limit of 20 W to at least 150 W.

Highlights

Spring 2005 saw the completion of a 3½-year European Community project to develop transfer standard devices for physiotherapy-level ultrasound power measurements. The outcome of the project is a high performance Portable Power Standard (PPS), which consists of a driver unit, five transducers and a Cavitation Detector (see Figure 10).

The project included testing of the PPS by invited third parties, whose feedback and data contributed to design enhancements and a detailed international comparison of results.

The PPS has been characterised over an 18 month period, and is sufficiently stable over the power range 1 W to 15 W to be used as an internal transfer standard and is currently calibrated quarterly;

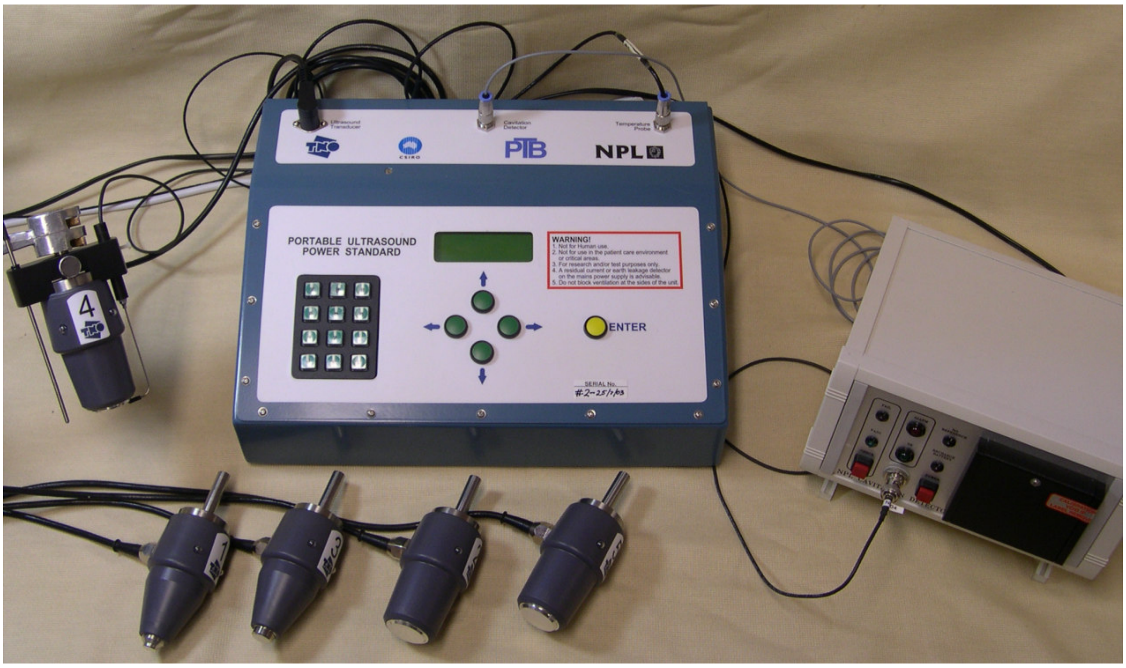


Figure 10: The complete set-up of the Portable Power Standard (PPS). In the centre is the driver, on the right the Cavitation Detector, on the bottom and left the five transducers and to the left is the transducer holder including the temperature probe fixture and the Cavitation Detector sensor

4.3 Ultrasonic characterisation, field measurements and quantification of dose

Services provided to industry, including rapid acoustic output determination for UK manufacturers of medical ultrasonic equipment, and specialist testing services, requiring the application of unique hydrophones, will continue to be provided and extended in key areas. The uncertainty of acoustic output measurements provided by a range of Measurement Services will be improved through the implementation of deconvolution techniques. Services providing reference measurements of the ultrasonic properties of materials, and the assessment of heating caused by medical ultrasound equipment using tissue equivalent Thermal Test Objects, will be maintained. For compliance with recent International Standards, a service will be established for use by industry for the measurement of surface heating generated by diagnostic equipment and this will include a detailed evaluation of uncertainties. As a long-term look at the future requirements for ultrasound metrology in assessing the imaging performance of diagnostic ultrasound equipment, an assessment will be undertaken of the needs for calibration and characterisation services.

Highlight

The major highlight has been the approval of the Draft Technical Specification 623206 - Test objects for determining temperature elevation in medical diagnostic ultrasonic fields. This document refers to the thin-film thermocouples and thermal test objects which have been developed at NPL and funded by the NMS programme. Approval was unanimous and the final version, following editorial revisions, has been sent to IEC Central Office for publication.

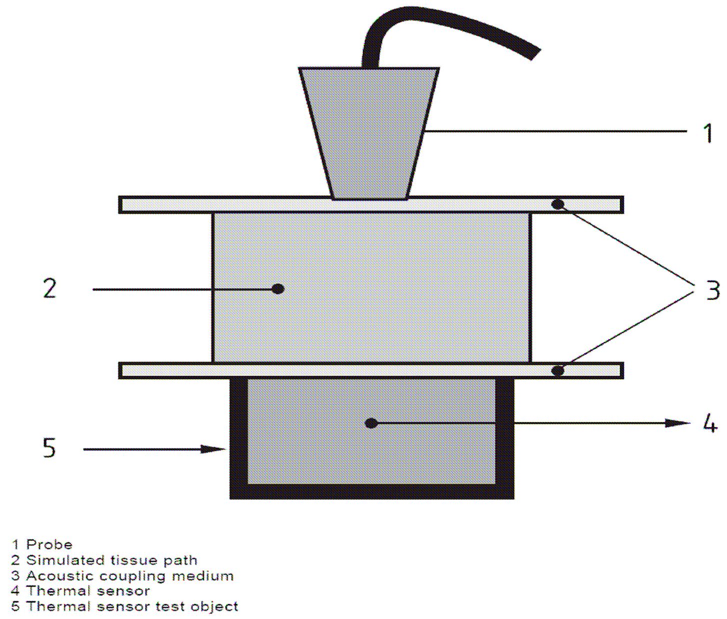


Figure 11: Schematic representation of a thermal test assembly, taken from the future Technical Specification IEC 62303

A prototype thin-film thermocouple for the measurement of transducer surface temperature has been constructed and tested. This worked successfully although it had a limited life due to the lack of a protective parylene coating. A multielement thin-film thermocouple (16 elements with a spacing of 1.5 mm) has been constructed and a multiplexer purchased to interface the sensor with the rest of the Thermal Test Rig. Several batches of the tissue-mimicking material given as an example material in 60601-2-37 have been made and their acoustic properties evaluated. These are now being monitored for their longer term stability. An infra-red camera belonging to DEPC has been used to measure transducer surface heating in air (Figure 12). Programmes have been written to capture timed sequences of images and to analyse and present the results. Thermal resolution is approximately 0.05°C and, spatial resolution approximately 0.2 mm. Measurements of surface temperature have already been made for one manufacturer seeking CE marking. The measurements involved the use of an infra-red camera and a tissue-mimicking phantom and were broadly similar to those specified in IEC 60601-2-37.

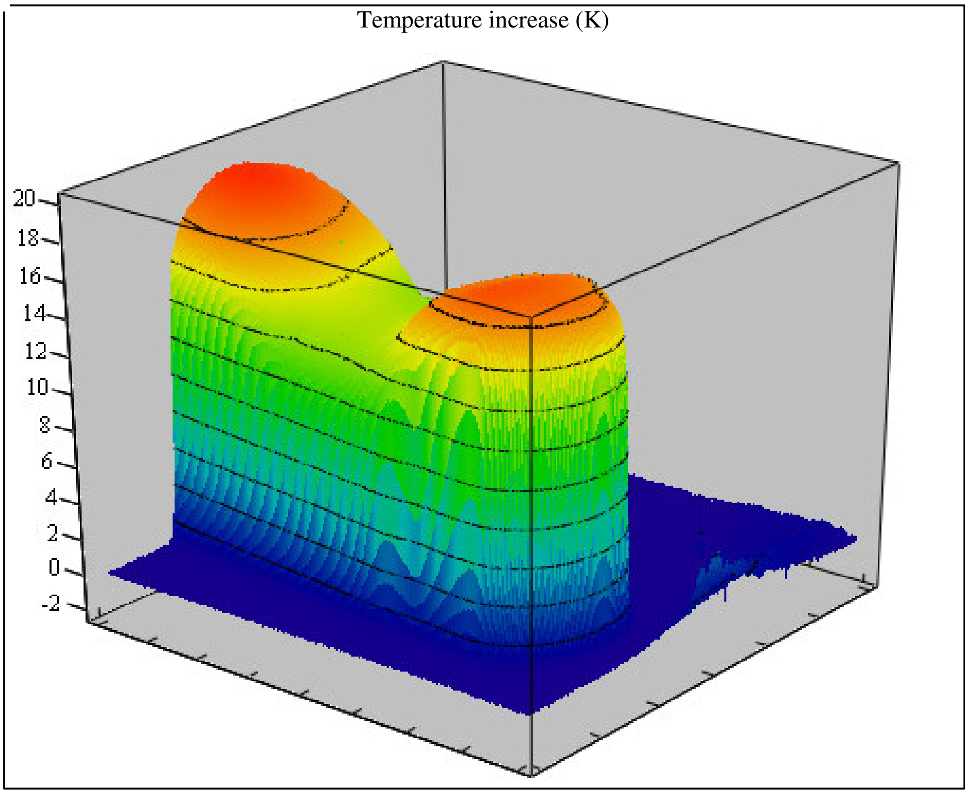


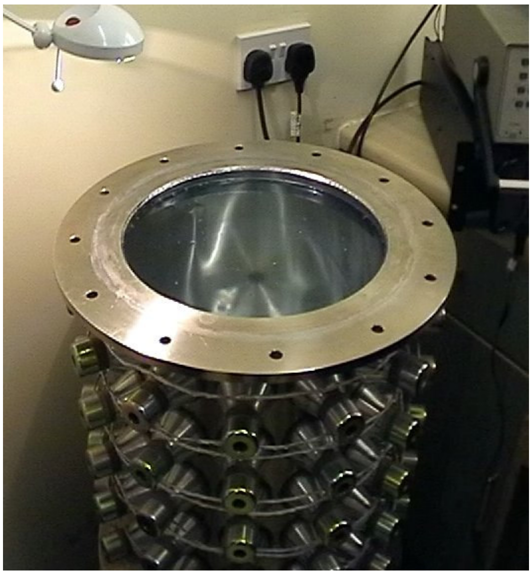
Figure 12: Surface temperature map of a prototype mechanical sector transducer radiating into air measured with an infra-red camera. The ultrasound crystal is near the front of the image; the rear temperature peak is caused by the motors which rotate the crystal

4.4 High power ultrasound and acoustic cavitation

Leading-edge research investigating the development of new measurement and monitoring techniques for determining the degree of acoustic cavitation within industrial high power ultrasonic fields, will continue. A key component of this will be the further evaluation of NPL's novel patented cavitation sensor technology, to establish a better understanding of the stability, lifetime and performance of the devices. This will be undertaken through collaboration with universities and industry and further exploitation of the technology, for higher frequency applications potentially extending up to 1 MHz, will be investigated. Collaboration, both with industrial and academic partners, constitutes a key feature of this project, and will be used to carry out a feasibility study of standardised methods for assessing the cleaning performance of ultrasound cleaning vessels, with the long-term aim being to develop simple, easily applied methods, appropriate for implementation at the industrial level.

Highlights of first year

For the first time, measurements of the spatial distribution of cavitation activity within the reference vessel have been completed. This has generated a number of key results regarding the capability of the NPL cavitation sensor, some of which have been fed into a technical paper and presentation produced for the World Congress in Ultrasound / Ultrasonics International meeting held in Beijing and the IEEE Ultrasonics Symposium held in Rotterdam. Whilst the results are extremely encouraging, they have shown the sporadic detrimental influence of high frequency noise during scans, which will have to be addressed in future.



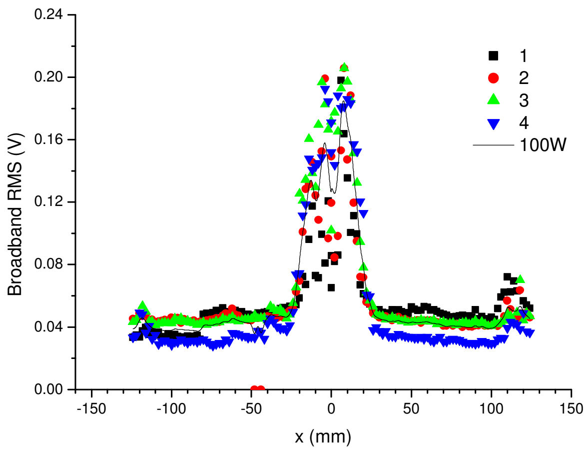


Figure 13: Top: photographic image of a cylindrical sonochemical reactor very similar to the one being developed at NPL as a reference system for investigating cavitation monitoring techniques. The reference reactor has ten inward-looking 25 kHz transducers disposed around the periphery of a cylinder, generating a strongly focused acoustic field; Bottom: early measurements of the spatial distribution of cavitation activity generated with the vessel, determined using the NPL cavitation sensor, for a nominal operating power of 100 W. The results of four consecutive repeat runs are shown.

5 THEME 4: ACOUSTICAL STANDARDS RESEARCH

5.0 Background

Unlike other themes, this theme concentrates on research topics, many of which have common features and span the main technical themes. Topics include:

Acoustic emission;
Optical techniques for acoustical measurement and calibration in air and water;
New science and technology based on silicon MEMS technology and wireless communication;
Machinery noise measurement, including sound quality;
Environmental noise measurement.

5.1 Project 4.1 Acoustic emission

5.1.1 Background

This project addresses the need for national measurement standards for acoustic emission. Key components will be:

- development of a robust traceable source for in-situ calibration, to replace the pencil lead break
- sensor calibration and characterisation, including optical fibre-based devices
- modelling of acoustic emission systems
- dissemination of key outputs.

Acoustic emission (AE) measurement is widely used in industry to monitor the condition of safety-critical and production-critical systems such as pressure vessels, engines and high-speed machinery. It can prevent the need for unnecessary and expensive early shut down of plant, as well as providing the means to minimise expensive, and often dangerous, failures. Recently, there has been more interest in the use of AE as an in-service condition monitor and as an on-line process-monitoring technique. Examples of its use cover a wide spectrum, from monitoring of large pressure vessels, storage tanks, and large structures such as bridges and aircraft structures, to studying tool wear and composition of liquids.

5.1.2 Rationale

Acoustic emission measurement is potentially a very important technology for the future, with the recent increase in computer processing capability providing the opportunity for more sophisticated methods of data analysis. One factor hindering the greater use of AE technology is the lack of traceability. This is particularly important for safety critical and highly regulated industries, such as aerospace and off-shore industries. In discussions, representatives of these industries in the UK cite this lack of traceability as a major obstacle in implementation and adoption of these valuable techniques. Indeed, a leading aircraft engine manufacturer has indicated it is unable to employ AE as an NDT certification technique due to this lack of traceability.

The project in this three-year programme builds on the work of the 2001–2004 Acoustical Metrology Programme, a previous INTErSECT project on acoustic emission, and on a small co-funded project between NPL, Lloyd's Register of Shipping and Airbus UK.

Under the 2001-2004 Acoustical Metrology Programme considerable progress has been made in starting to address key areas of concern to industry and to provide solutions that meet their current needs. One of the major issues is their requirement for a more robust traceable reference source for in-situ calibration of AE measurement systems, to replace the flawed pencil lead break and its associated problems of repeatability and traceability. Full characterisation of sensors in terms of in-plane and out-of-plane displacement sensitivities is also vital if informed decisions on transducer selection are to be made. This programme will build on the current work, collaborating with industry to ensure that the developed reference source is suitable for use in the field, and that calibration services meet their requirements. In the longer term optical sensors based on fibre technology may provide attractive alternatives to current day AE sensors, but it is essential that these devices are suitably characterised and calibrated. NPL will collaborate with industrial partners to research and develop suitable methodologies.

Knowledge of the type of excitation and how the sensor responds to such an excitation is key to understanding the signal produced by an AE sensor, and the current programme has investigated the potential for modelling small reference systems. These techniques will be extended to incorporate larger and more complex structures, and investigate the possibility of using molecular modelling techniques to model fracture type events in engineering structures. If successful this would provide an extremely useful and very powerful tool for industry.

Close links with industry, together with raising awareness, consistency and improved measurement practice among the user community are key to the development of acoustic emission as a recognised technique. These issues will be addressed by a number of knowledge transfer exercises, including an acoustic emission forum, input to standardisation committees and various web-based initiatives.

Highlights

A conical transducer has been loaned to Cardiff University and initial tests have been performed to explore performance and design requirements for a reference source.

The most significant technical achievement of the year has been the successful measurement of in-plane displacement for a shear wave using the existing NPL AE interferometer. A stepped block was used to measure the displacement horizontal to the surface of the block and the block dimensions allowed separation at frequencies above 500 kHz of the longitudinal and shear wave modes which propagate at difference speeds. The displacements measured with the interferometer were also detected using a number of commercial AE sensors, producing typical output levels from the sensors. The shear wave was generated by a commercial non-destructive testing normal incidence shear wave transducer.

5.2 Project 4.2 New generation of acoustical measurement standards

5.2.0 Background

The main aims of this project are to:

- develop optical techniques as the basis of new measurement standards for the calibration of airborne and water-borne measuring instruments

- establish proof of feasibility for photon correlation as a primary standard for airborne sound

- develop optical vibrometry as the basis of a new primary standard for underwater acoustical calibration above 1 kHz

- establish an increased understanding of the acousto-optic interaction for applications of cross-beam vibrometry to: 2D/3D beam profiling, non-linear focused fields and in the near field.

The reciprocity method has become the standard method for calibration of microphones or hydrophones.

For sound in air, the calibration method that has become recognised internationally is coupler reciprocity, where calibration is undertaken essentially in a closed coupler. This is a simple calibration technique that has been developed and refined over many years to realise the pascal to an accuracy unsurpassed by any free-field technique, and it is the basis of UK NMS primary standards, see Theme 1. Traceable calibrations of devices such as microphones, sound calibrators and sound level meters are mainly achieved by pressure-based techniques using a calibrated reference microphone. However, the calibration of non-standard microphones is not easily accommodated by these methods because of coupling considerations, and this is quite a restriction and an inhibitor to the introduction of new technology. Furthermore, calibration of miniature array microphones or MEMS sensors is also not possible. These limitations would be overcome if free-field calibration techniques could be implemented more easily, and this could be achieved using optical techniques as they offer the ability to realise an accurate determination of the pascal at a point in a sound field.

For sound in water at kilohertz frequencies, primary calibrations of hydrophones and transducers are currently based on free-field reciprocity techniques (see Theme 2). The headroom between the primary standard and the typical uncertainty provided in calibration services is relatively small. In order to meet the most demanding industrial and traceability requirements, the primary standard must be realised with improved uncertainties. As with sound in air, it would be preferable to realise the primary standard by basing it on the determination of a fundamental acoustic quantity at a point of interest in the sound field. Again, this can be achieved using optical techniques and pilot work undertaken as part of the NMS Quantum Metrology Programme has shown that optical vibrometry applied to a thin pellicle in water is the way forward.

5.2.1 Rationale

For sound in air, photon correlation methods have been developed to the point at which a prototype system can now be developed as a method of improving the accuracy of primary acoustical standards, thereby enabling them to be more accurate and directly traceable to SI base units. Scattering of light from natural particles in the air as they pass through a fringe pattern established by two intersecting laser beams will be used. There will be a need to undertake research studies on particle size and concentration, signal-to-noise and photon correlation signal analysis techniques. Implementation and testing of a pilot facility in the small anechoic chamber at NPL will be the ultimate objective.

For sound in water, it is proposed to implement, test and validate a specially developed laser vibrometer based on optical fibre technology as the basis for a new primary standard for underwater acoustical calibration above 1 kHz.

A key issue for all optical methods is achieving an understanding of the relationship between the optical signal received and the sound field disturbance. This is especially important in situations where the acoustic field is highly complex, for example in focussed fields, non-linear fields or in the near-field of transducers, where the field is far from plane-wave. It is well established that the interpretation of the optical signal in a plane progressive wave and the optical beam is parallel to the acoustical propagation direction. In more complex fields, it is vital that the physics of the acousto-optic interaction is thoroughly understood in order for the measured data to be correctly interpreted, and considerable further work is required before a complete understanding is gained. This is important as the foundation for future wider application of optics for acoustic measurement. In the long term, optical techniques have the potential for 2D/3D acoustic field mapping in the Acoustic Pressure Vessel.

Highlights

The collaboration with Loughborough University on the optical work has continued, with their Polytec scanning vibrometer being provided on loan for several periods during the year. Measurements have been made of the field emerging from an HF sonar operating at 330 kHz and 500 kHz using the acousto-optic effect with the scans undertaken transverse to the field. The scans were undertaken both by scanning the transducer (single beam mode) and using the scanning capability of the vibrometer. The results will provide input to a proposed tomographic reconstruction of the field, and will be compared with the surface scans.

The NPL long-path difference interferometer has been used to detect the field of highly focused ultrasound transducers. The interferometer is a homodyne interferometer which is configured to measure velocities up to 100 m/s and with a bandwidth of 100 MHz. It therefore has the potential for measuring high intensity focused fields which are difficult for commercial devices due to their limitations on bandwidth and dynamic range. The measurement configuration is currently not ideal since the light is delivered through optical fibres and a emerges at an angle through a lens system and must be reflected back from a mirror. However, by directing the acoustic field at only one of the beams (the incident or return beam) it has been possible to obtain velocity waveforms showing many harmonics. Now that the feasibility of the technique has been shown, the interferometer optical delivery system will be reconfigured to produce a single beam system.

5.3 Project 4.3 New generation of acoustical measuring instruments for sound in air

5.3.0 Background

The main aims of this project are to:

- develop a new generation of acoustical measuring instruments for sound in air based on silicon MEMS technology and wireless communications
- achieve a matchbox-sized wireless device with on-board microphone and temperature sensor
- evaluate the performance of the new sensor against conventional acoustical instruments
- work towards the next stage of multi-variable sensors capable.

For over 40 years, the condenser microphone has been the laboratory and working standard measuring device for airborne acoustics. Hence, microphones, sound calibrators and sound level meters have become the centrepieces of acoustical metrology. The limitations of these systems are that they are expensive, difficult to deploy in large numbers and physically quite large. The inability to deploy a larger number of measuring devices often leads to larger measurement uncertainties in many machinery noise, environmental noise and room acoustic measurement situations. Many of these modern acoustical measurement challenges could be overcome if small, cheap, remotely deployable and easy to use measuring instruments were available.

5.3.1 Rationale

The development of a new generation of acoustical measuring instruments based on silicon MEMS technology and combining these with wireless communication to a central console would overcome many of the current limitations. Typical performance characteristics would be:

- Small (button-sized) silicon-based acoustic sensor (MEMS) integrated with on-chip signal processing capability;
- Performance properties suitable for acoustic measurement;
- Remote operation - wireless communication;
- Multi-channel capability;
- Additional sensing of particle velocity and other parameters such as temperature, atmospheric pressure etc.;
- Cheap, robust and easy to use.

Whilst this is a formidable list of characteristics, to make progress, not all of these need to be achieved in the first instance. It is proposed to undertake the development of MEMS-based sensors in two main stages:

Highlights

A feature of this flagship project has been the early and full involvement of industrial partners. A Forum to discuss potential applications of MEMS sensors in acoustical measurement, and to inform the wider acoustics community about the project, was held at NPL in March 05. This was a very valuable event in many respects. In particular, it made it clear that there are a large number of possible multi-parameter devices of roughly equal importance. Due to this range of options, it was felt that it would be advisable for the latter stages of the project to concentrate on networking issues rather than to attempt to define the functionality of a multi-parameter device. The meeting also meant that the capabilities of the devices could be prioritised, ensured that many potential problems and issues were raised (with some being resolved) very early in the project, and identified some key contacts in the field.

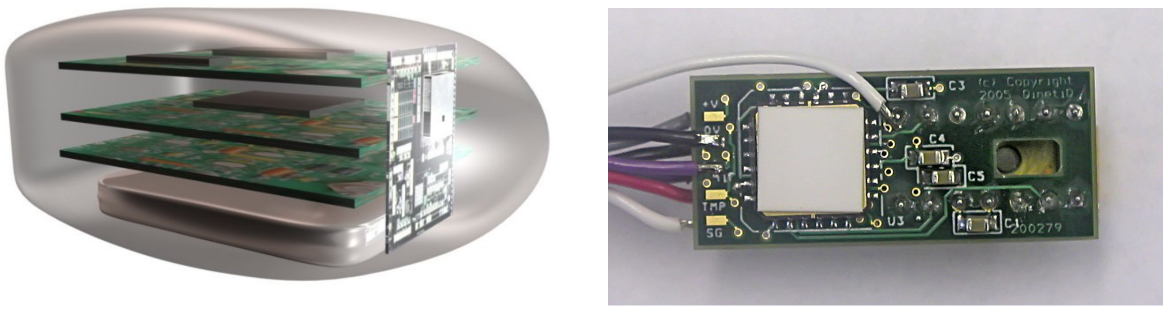


Figure 14: NPL conceptual artwork and the first QinetiQ prototype microphone board (15mm x 35 mm), delivered to NPL early in 2006

5.4 Project 4.4 Improved methods for quantifying noise emission from machines and products

5.4.0 Background

The aim of this project is to improve methods for quantifying noise emission from machines and products by delivering both short to medium term solutions as well as driving the development of new measurement technology and striving to eventually resolve many of the issues posing barriers to industry. The expected outcome will firstly benefit UK industry offering more efficient, accurate, and reliable measurement techniques enabling improved noise emission diagnosis and low noise design, but the benefits will then extend further. The UK workforce and community will in future benefit from reduced machine and product noise emission levels, leading to improved health and safety conditions and quality of life.

There is an increasing global awareness that the effects of noise can be hazardous to health and impact significantly on quality of life. In the UK, an extensive body of regulations, many of which implement the requirements of EC Directives, are in place to control noise, imposing limits on the noise emission levels from specific sources such as vehicles, industrial machinery, and domestic products. Most commonly noise emission measurement is required to protect the health and safety of the workforce and public, but it is also necessary to enable improvements in product design, and to provide data for noise immission prediction and assessment.

The Physical Agents (Noise) Directive, due to be implemented as UK regulation in 2006, to replace the Noise at Work Regulations 1989 with more stringency, sets out the requirements for employers to manage risks arising from noise, stipulating the need for noise assessment. A number of EC Directives (e.g. 89/392/EEC, 2000/14/EC) require manufacturers to make measurements in accordance with international specification standards such as the ISO 3740 and ISO 9614 series so as to provide information on sound power level of their products as evidence of compliance with health and safety requirements. Furthermore, it is a requirement that noise labels are affixed to many machines and products showing the guaranteed sound power level and that a declarations of conformity are issued. Measurements to obtain this information are a prerequisite for placing the machine on the market. Where the noise levels generated by a machine are unacceptable, non-standard diagnostic measurements will often be required to determine comprehensively, the noise emission characteristics of the machine, to enable effective implementation of noise reduction techniques and to improve product design. Low noise level and ‘sound quality’ are known to be an important issue for consumers and effect the overall decision of purchasing a product.

5.4.1 Rationale

The process of consulting with many sectors from UK industry confirmed that measurement of noise at source continues to pose problems in practice. The complexities associated with measuring noise emission from machines and products in real situations can lead to uncertainty and concern over accuracy. The increasing pressure placed on industry to make noise emission measurements to meet the requirements of EC Directives and UK Regulations is causing industry to question current measurement methods and technology available.

Compliance testing in accordance with regulations using measurement methods set out in current specification standards, and the recognised importance of low noise and sound quality design in product development, add to production and operational costs, placing an economic burden on UK industry. Efficient and accurate methods of measurement are essential for UK industry to operate competitively. Existing methods such as sound pressure and sound intensity can lead to large uncertainties for certain situations, particularly large sources. There are practical difficulties where for example extraneous noise can be a problem with the measurement result contaminated by unwanted contributions from other component noise sources. Particular concerns about accuracy and the amount of measurement effort required, using current techniques, need to be addressed, both in the short and long term.

The research proposed supports this principle of developing new technologies and solutions for the reduction of noise emission, delivering both short term solutions to the practical measurement issues as well as the drive for development of new measurement technology, which will eventually resolve many of the difficulties posing barriers to industry.

There is an ongoing desire for simplification of noise emission standards, and a long-term vision that selection of a measurement set-up should be less restrictive. Initial steps are currently being made to evaluate uncertainties associated with various methods. With further endeavour the principle of floating uncertainty could be realised where the user of the standard would have information on the level of uncertainty and accuracy for a given measurement configuration. Information needs to be fed directly into the improvement of the existing international specification standards benefiting industry obliged to use the methods.

It is important that industry have available, accurate and efficient source characterisation technology to encourage innovative solutions to further reduce the noise output of machines and products in line with EC noise policy. Research proposed will examine the validity of using existing airborne noise emission measurement methods for characterising a range of industrial sources. Practical measurement problems and the current state of knowledge with regards dominant sources of uncertainty will need be considered. The output of the work will identify priority research and development support needs.

Research will be conducted to investigate new and more adequate measurement techniques to improve upon current methods for characterising complex industrial noise sources. Consideration will be given to the unified approach of quantifying airborne, structure-borne, and fluid-borne noise to characterise emission processes inherent with real machines. The feasibility of using alternative measurement techniques (e.g. Microflown particle velocity sensors, and laser vibrometry) and technologies will be investigated.

Acknowledging the growing employment of sound quality techniques in product design, an element of this research will be to expand on the work done so far under the current NMS on sound quality metrics, paying attention to validity of currently available objective sound quality measuring equipment, as well as demonstrating the benefits of employing psychoacoustic techniques in industrial product design.

Figure 15: Machinery noise work at NPL

Highlight

A web-based survey designed to elicit the views of a wide variety of industries on problems and issues associated with conducting noise emission measurements of products and machinery noise, including those for regulatory and diagnostic reasons has been started. Information on the survey has been e-mailed to over 100 organisations so far, covering the following industry supply sectors: lawn, garden and agricultural equipment; earth moving equipment; power generation equipment; heating, ventilation and air conditioning systems; power tools; paper industry equipment; manufacturing machinery; construction equipment; industrial cleaning; pumping and air compression equipment; lifting and handling equipment; other organisations involved with noise emission and sound power measurement.

5.5 Project 4.5 Improved methods for quantifying airborne noise immission

Lead Scientist: Mike Goldsmith

5.5.0 Background

The aim of this project is to ensure methods used for quantifying noise levels in the environment are reproducible and robust, recognising the importance of the decisions made at Government level on the basis of the measured and predicted results. A significant effort will be to establish the potential for the application of new techniques and technologies to improve noise immission measurements, to benefit both the UK community and economy.

Awareness of the effects of noise immission has increased in recent years, especially since "The Green Paper on Future Noise Policy" (1996), which identified that about 80 million people are exposed to noise levels considered unacceptable because they lead to sleep disturbance and other adverse health effects and that the annual economic cost of noise to society is more than 12 billion Euro. According to the Chartered Institute of Environmental Health, local authorities in England and Wales reported receiving FIVE times as many complaints about noise in 2001/2002 than in 1982/1983.

The Green Paper proposed a framework for action to substantially reduce environmental noise, based on the principle of shared responsibility at national, regional and local levels, involving target setting, monitoring of progress and measures to improve the accuracy and standardisation of data to help improve the coherency of different actions. The most significant realization to date has been the approval of the Directive on the Assessment and Management of Environmental Noise (2002/49/EC). This has resulted in considerable activity throughout Europe, primarily focussed on the production of strategic noise maps for all major agglomerations. The maps will in future years be linked with other models including transport, air pollution, and health models and used for strategic decision-making enabling Government to take greater account of noise.

5.5.1 Rationale

Consultation with UK professionals involved in environmental noise has identified a variety of concerns about current methods and technology available to facilitate the measurement and prediction of noise immission.

An aspect of noise immission, which undoubtedly requires attention, is the measurement of low frequency noise in buildings, where views were received that current measurement techniques are unreliable, with poor repeatability and reproducibility. Such concerns are noteworthy, considering the recent changes to the Building Regulations, which introduced the need to measure and assess noise at lower frequencies. Whilst no specific work is planned on this topic, the development of the MEMS-based acoustical measuring instruments, see 4.3, will provide new methods of measurement by allowing a large number of measurements to be made over the volume of the room, say by the use of sensors placed on space frames.

Having historically received less attention than transportation sources, there is a need to assess the quality and validity of industrial noise prediction methods currently used in practice to assess how a new development or installation will impact on the local surrounding environment. Consideration is needed with regards uncertainty of the prediction methods, the reliability of algorithmic implementation in software, and the representation of frequency content, complex emission characteristics and acoustic features. The work will help to establish the potential for improvements in the techniques to predict accurately and reliably.

Highlight of first year

A project advisory board was set up, with the following organisations represented:

Acsoft
Birmingham City Council
Casella Stanger
DTI NMSD
Environment Agency
Environmental Acoustics
Hoare Lea
IoA
NPL

Two meetings of the board were held and these, and further face-to-face discussions with its members ensured that the project plan was optimised, that all relevant parties were either represented or consulted, that practical benefits were maximised, that the work has not and is not being carried out elsewhere and that all possible co-funding sources were explored. Hoare Lea completed an overview of the range of technical and practical issues associated with current and possible future noise modelling techniques. The findings of the review identified 3 key elements of current practice that may contribute to uncertainty and risk: 1 The ability of different mathematical algorithms to accurately predict sound propagation.; 2 The implementation of mathematical algorithms into widely adopted proprietary modelling software ; 3. The application of predictive modelling, encompassing both the construction of the models and the use of their outputs without fully understanding the limitations of the model.