Overview of Acoustical Metrology Research being undertaken at the United Kingdom National Physical Laboratory (NPL)

1 Introduction

This report provides a description of selected key research topics related to Acoustical Metrology currently being undertaken at the United Kingdom National Physical Laboratory. The work within Acoustics is now part of a larger government funded programme covering both Acoustics and Ionising Radiation.

2 Programme rationale

Measurements of acoustical quantities are made very widely within the UK, 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 principal objectives of the Acoustical Metrology Programme at NPL are to:

- provide, develop and disseminate primary acoustical standards for realising the pascal for sound in air and water;
- ensure that UK measurement standards in acoustics are harmonised with those of the UK's trading partners;
- develop innovative new methods of acoustic measurement to meet identified UK private and public sector needs, and promote international standardisation of these methods;
- promote knowledge transfer from the programme and the adoption of good measurement practice.

Peer-reviewed Journal publications since 2008 are given in Section 7.

3 Programme structure

The programme is composed of three principal Thematic areas dealing with the measurement standards and a fourth addressing cross-theme knowledge transfer. These Themes are:

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. Research is also carried out into novel noise measurement, for example, those enabled by MEMS microphone technology.

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 calibration at hydrostatic pressures and temperatures corresponding to real ocean conditions.

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 cavitation relevant to both medical and industrial ultrasonics.

4 Sound-in-air

The NPL reciprocity calibration has undergone upgrade to both hardware and software components. This has resulted in significant expansions to the scope of measurements that can be performed. The software was upgraded primarily to implement the requirements of the new issue of IEC 61094-2 :2009. Doing so has enabled two new capabilities: the calibration at extremely low frequencies, and primary phase calibration. Uncertainty estimates and traceability have been established in both areas, and NPL is ready to pursue ISO 17025 accreditation for primary phase calibration. The low frequency calibration capability compliments the existing NPL laser pistonphone. Alongside these developments, NPL was also pleased to support GUM, Poland to implement a similar upgrade to the facilities originally provided in 1998.

Figure 4.1: The NPL reciprocity equipment shown here being used to calibrate LS1P microphones, which are the subject of the proposed CCAUV.A-K5.

Secondary microphone calibration techniques have also been the focus of attention. After a period of being out-of-service, the NPL secondary free-field calibration facility was re-launched and immediately used to carry out measurements for a Euramet project on the free-field correction of sound level meters. Techniques for free-field phase calibration have also been investigated. The calibration of WS3 microphones has also been given consideration. There has been an opportunity to extend secondary pressure calibration to cover these devices and a novel phase calibration technique has been developed for these microphone, which will soon be submitted for publication. NPL has also been investigating multi-channel simultaneous calibration exploiting the homogeneous nature of a diffuse sound field. The intention is to have a capability to calibrate large numbers of microphones. A paper on this work has been submitted for publication.

NPL's involvement with the measurement of hearing focussed mostly on ear simulators. In response to the 2010 edition of IEC 60318-1 which was prepared by NPL, ear simulator calibration services have been extended to include verification of the acoustic impedance. Research on the calibration of ear simulator has also investigated the potential for determining the impulse response. However there appear to be severe limitations associated with the requirement to know phase responses at frequencies greater than 20 kHz. Work in this area will therefore continue, especially given the intention of the ISO WG on hearing to establish new hearing thresholds based on impulsive responses.

NPL has continued research in the optical measurement of airborne sound utilising photon correlation spectroscopy. Since the last CCAUV meeting, a number of acousto-optical systems have been designed and implemented; these aimed, firstly, to improve the efficiency of the measurements. Subsequently, the system was made robust enough to rely on almost no artificial seeding. Particle analysis revealed that the system's requirement on seeding was so small that it was comparable to natural air therefore not affecting the speed or properties of sound. The working frequency range was also established in the range 150 Hz - 2 kHz. At present, research work is also focusing on the development of a high speed (40 MHz) external hardware module to isolate photon pulses resulting from specific parts of the acoustic cycle that can then be auto-correlated and yield acoustic velocities. This approach is necessary in the development of the fully anechoic chamber implementation. In this case, the delivery optics are placed outside the chamber; the laser beams cross in the middle of the chamber and a collection system employing a Gallilean telescope with additional focusing lens and optical fibre captures and delivers the scattered light to the photo-multiplier tube that produces photon event sequences yielding acoustic velocities. A conference paper and presentation was also delivered at the 16th International Congress on Sound and Vibration 2009 in Poland.

NPL has maintained an international presence through engagement in committees such as Euramet, IEC and ISO. Invited presentations have also been given at major international conferences and meetings, including a talk on ‘Future trends in acoustical metrology’ to Danish industry, a keynote lecture on the future role of MEMS microphones to the Italian Congress on Acoustics, and a demonstration of our MEMS measurement microphone technology at EuroNoise 2009.

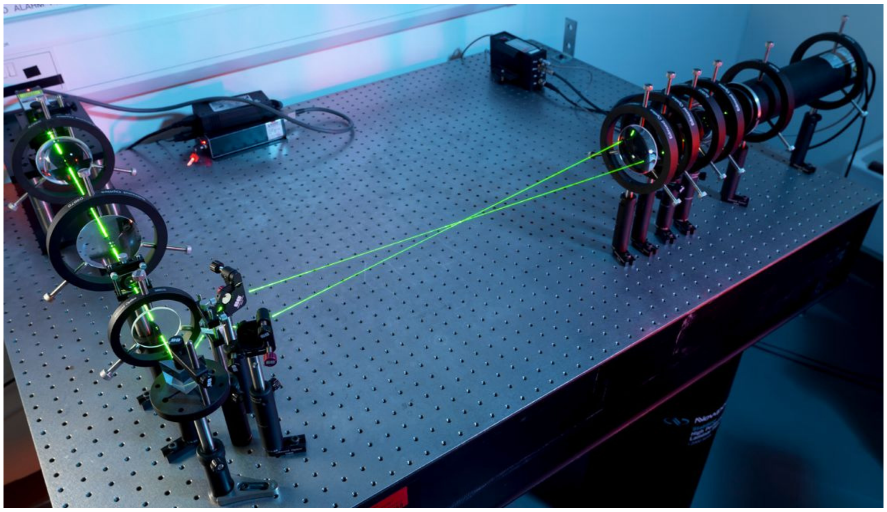

Figure 4.2: The upgraded bench-top optical system for acoustic particle velocity measurement.

The highlight of recent achievements has been the development of DREAMsys, the MEMS microphone based distributed noise measurement system pioneered by NPL and developed in collaboration with out industrial partners.

The concept of this project was to demonstrate the benefits and potential of MEMS microphones in measurement applications. To do this convincingly, NPL set out to demonstrate the system in real outdoor environments in response to an identified measurement need, augmentation of noise maps produced for the Environmental Noise Directive.

Having developed the instrumentation and completed an extensive series of laboratory assessments, some one hundred prototype units were manufactured ready for deployment at selected test sites.

Figure 4.3: A DREAMsys unit under test at NPL, illustrating the resilience of the system to harsh weather conditions.

Figure 4.4: Two of the forty DREAMSys units deployed at the site adjacent to London City Airport. The units monitored noise continually for a six month period, reporting data wirelessly.

These sites included the NPL open water facility used by the underwater acoustics group, where exposure to the weather was particularly harsh, a city centre location accessible to the public and an area close to London City Airport. Deployment covered the period from Apr-09 to Sep-10.

Details of the project findings and conclusions are the subject of an ongoing series of publications and progress can be followed on www.DREAMSys.org, however the most significant outcome is that proof-of-concept has now been established for the use of MEMS microphones in measurements.

Excellent agreement with conventional Class 1 sound level meters has been demonstrated. The equipment, and the microphone especially, has withstood the whole range of British weather conditions including wind and heavy rain, snow and frost, high temperatures and strong sunlight and electric storms (though we can't claim a lightning strike!). Indeed the MEMS microphones have proved to be extremely stable through all of this, with typical sensitivity changes being less than 0.2 dB over many months of operation.

The Euronoise 2009 Soundwalk Noisemaps

First, select the day that you attended the soundwalk from the list below. (You can also chose from a few averaging periods)

Then use the scroll bar at the bottom of the map to cycle through the noisemaps.

Change noisemap collection:

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Noise Futures demonstration: Sound walk, LAeq 2 minute, Wednesday 28th October 2009

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Figure 4.5: Screen shot from the web based noise data visualisation tool, developed with Google maps. Further examples of output from the DREAMSys project can be found at www.DREAMSys.org.

5 Underwater Acoustics

Underwater acoustical standards work at NPL has a number of key objectives. Firstly, NPL maintains primary standards, traceability and international consistency for the UK, and disseminates standards via UKAS-accredited calibration services to users. The work also aims to improve the ability of industry to conduct Environmental Impact Assessments for the effect of man-made noise on the marine environment; to improve the ability of industry, academia and government to assess the full performance of underwater acoustic systems over a range of environmental conditions by use of NPL's facilities such as the Acoustic Pressure Vessel and the open-water facility; and to support UK manufacturing industry in sectors such as offshore, ocean engineering and science, defence and marine renewables industries. NPL has an active research programme in underwater acoustical metrology, and the following are some of the highlights from the last two years.

Considerable effort in the last two years has been devoted to developing methodologies for the measurement and impact assessment of anthropogenic underwater noise. Of course, sound is a dominant feature of the underwater marine environment as a result of both natural sources (wind, waves, rain, biological sources, underwater earthquakes) and anthropogenic sound sources. The latter can be intentional sources of sound (sonar, geophysical surveying, echosounders, etc), or unintentional by-products of human activity (shipping noise, oil and gas platform noise, construction noise from marine renewable energy installations, etc).

The concern over the effect of anthropogenic marine noise has led to legislation, which in Europe is based around the EU Habitats' Directive 92/43/EC, and EC Directive 2001/42/EC. Here, man-made underwater sound is explicitly classified as a form of noise pollution, and Environmental Impact Assessments (EIA) are routinely required, with monitoring undertaken before and during the offshore activities, and attempts to predict the likely noise undertaken before commencement of work. A major driver in this area is the recent EU Marine Strategy Framework Directive MSFD (2008). This requires all EU Member States to achieve Good Environmental Status (GES) for their own coastal waters by 2020. One of the explicitly-defined descriptors of GES relates to underwater noise (classed as pollution). The MSFD states that to achieve GES, member states must ensure that the *"introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment."* Already work has begun to develop indicators which may be used as metrics for the GES noise descriptor.

Unfortunately, unlike the situation existing in airborne environmental acoustics, in underwater sound the basic metrology has a number of knowledge gaps and there are no widely used standards for measurement of underwater noise which can be used to underpin the implementation of the above Directives. In this area of underwater sound, the metrology is relatively immature, especially with regard to the measurement of difficult sources that must be measured in-situ (such as construction noise). In some cases, further work is required merely to achieve consensus on the proper definition of quantities, and the optimum method for their measurement. This is particularly true when considering the meaning of terms such as Source Level for difficult sources such as marine pile-driving. This latter source is of increasing concern since piling is a favoured method of construction for offshore windfarms, which are about to undergo a substantial expansion and, within the next decade, will be the most intensive engineering interventions in EU coastal waters.

Recently, NPL has undertaken work to develop improved methodologies for in-situ measurement of noise radiated by offshore marine piling, a loud impulsive sound source of some concern. This has involved characterising the source by measuring both the temporal and spatial variation of the sound field by use of calibrated hydrophones deployed from a survey vessel and from fixed recording buoys. The NPL work has shown that the acoustic output has a complex dependence on factors such as hammer energy, water depth, seabed penetration, and seabed properties. Figure 5.1 shows a plot of acoustic pulse energy flux density against energy setting on the hydraulic hammer during a soft start period where the hammer energy is the dominant factor. Also shown on the figure is a two-dimensional map of the noise field around a piling source, the noise map being produced by propagating the sound using a parabolic equation model which can account for range-dependence in the environmental parameters such as bathymetry (giving rise to an asymmetry in the field).

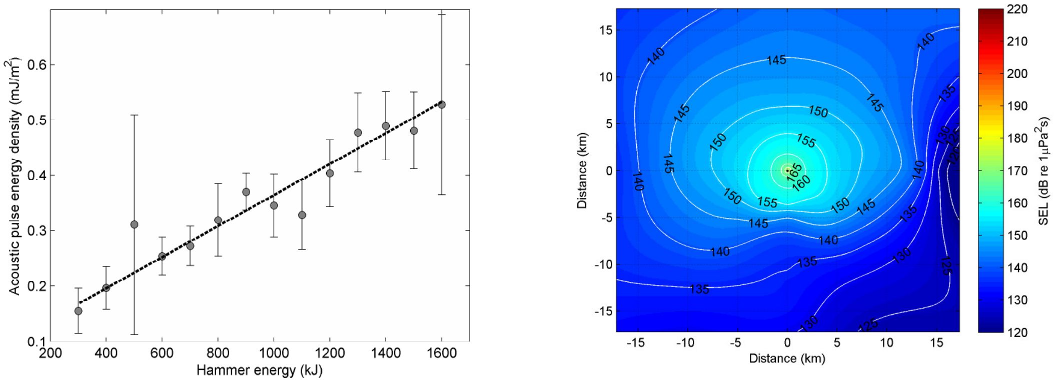


Figure 5.1: Left: Pulse energy flux density in mJ/m^2 plotted against hammer energy, recorded at a range of 1.5 km for a marine piling source. Right: Map of pulse Sound Exposure Level around the source.

NPL is also leading a project to determine the noise radiated by dredging for marine aggregate extraction. This project is funded by the UK Marine Aggregate Levy Sustainability Fund, with some co-funding from the UK National Measurement Office. So far, a total of 7 dredging vessels have been measured from the UK fleet in a variety of locations and modes of operation. Figure 5.2 shows some initial results, with the elevated levels at high frequencies during dredging being of particular note. This is believed to be because of the friction of the extracted sediment (gravel) on the extraction pipe.

NPL has worked closely with a number of collaborative partners on underwater noise, in particular with the University of Southampton (Institute of Sound and Vibration Research) and Loughborough University. Dr Paul Lepper of Loughborough University spent a three-month part-time secondment at NPL as a guest worker in 2009 to work closely on developing the capability for offshore noise measurement. A total of 7 joint papers have been presented at international conferences, including 3 of invited paper status. The latter included an invited paper on the requirements for measurement of marine piling at the international workshop *Assessing and managing the potential impact of marine piling noise within the evolving regulatory framework,* organised by Crown Estate and the UK Marine Science Coordination Committee in February, 2010.

Standards work in the area of underwater noise measurement is evolving and NPL makes contributions to a number of committees, both nationally and internationally. NPL sits on the Underwater Sound Forum of the UK Marine Science Coordination Committee and chairs the sub-committee on noise standards. NPL has also contributed to the development of the new ANSI S12.64 standard for measurement of noise from commercial shipping in deep water, and is represented on WG6 of SC2 of ISO TC8 (Shipping and Maritime Technology) which is responsible for drafting a new international standard on noise from commercial vessels. Finally, NPL is participating in a joint Anglo-Dutch-German informal collaboration to develop standards for measurement of noise form marine piling.

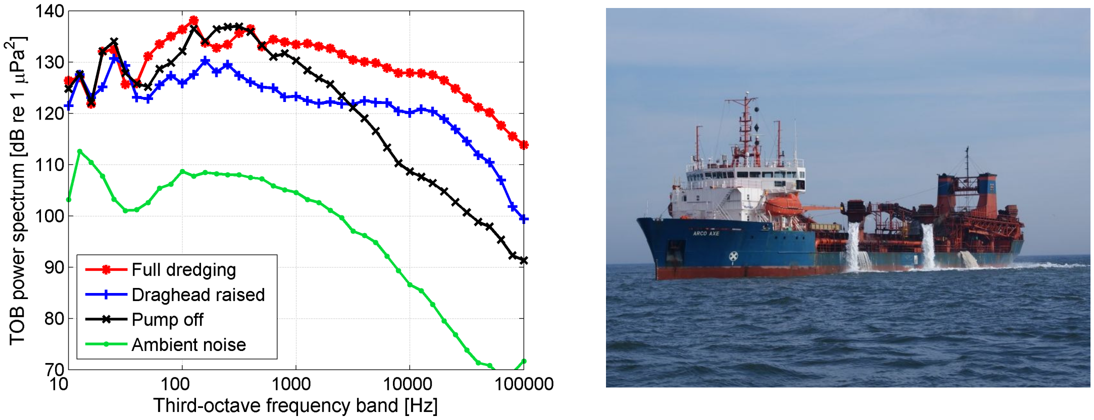


Figure 5.2: Left: Received third-octave band noise power spectra at 100 m from dredger for a variety of operational modes; Right: One of the dredgers measured under operation.

Another theme within the research is the use of optical techniques in underwater acoustic metrology. These techniques have been adapted for: (i) development of a new generation of primary standards to replace the traditional method of three-transducer spherical-wave reciprocity; (ii) measurement and mapping of the acoustic near-field of high frequency sonar transducers. Progress has continued with the development of the new primary standard, with a new heterodyne interferometer head now operational, and a new laser capable of delivering 60 mW into the water. This enables propagation to the centre of the tank and reflection from lower quality pellicle without compromising signal-to-noise ratio. Figure 5.3 (left) shows the interferometer set up in the small open tank facility at NPL. Analysis of uncertainties is now being carried out including comparisons undertaken between analogue and digital demodulation of the interferometer signal. For near-field mapping, NPL has sponsored a PhD student at the University of Southampton who has modelled the acousto-optic interaction and shown that the deleterious effect on near-field and surface scans is limited to high spatial frequencies, thus affecting accuracy of the side-lobe definition in measurements (but not the main beam on-axis).

The open-water facility remains our main dissemination routes for underwater acoustic free-field standards. In the last year, work has begun to upgrade the facility to provide extra functionality (extra trials facility, extension of frequency range, etc). The improved uncertainties of 0.9 dB achieved by the more detailed treatment of temperature variation in the reservoir have now been approved to ISO17025 and work continues to push the low frequency limit for calibrations down from 250 Hz to 50 Hz. Figure 5.3 shows the deployment of a large device at the upgraded facility.

Further work has been undertaken to improve the materials characterisation at simulated ocean conditions using the Acoustic Pressure Vessel by use of an array receiver, and the measurement service has been very active. A joint review paper was published in *Metrologia* on measurement and testing of the acoustic properties of materials (jointly with PTB).

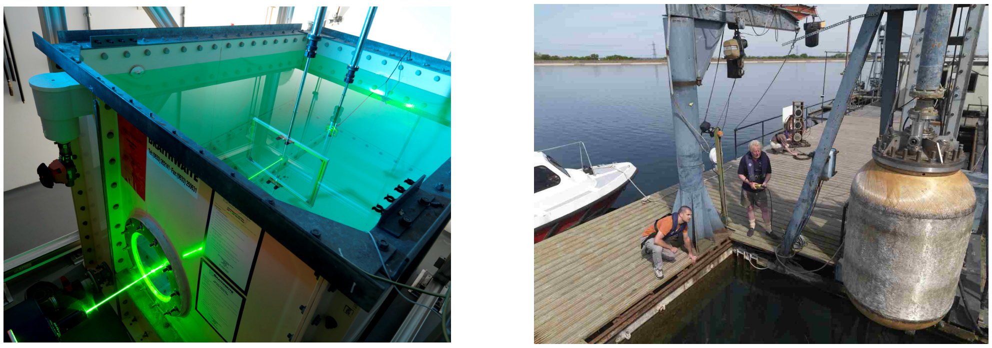


Figure. 5.3: Left: New primary interferometer in operation in the small NPL open tank facility; Right: Large device being deployed at the NPL open-water facility.

A number of journal papers have been published in the last two years (see Section 7.2). These include the paper with Dr Claude Leroy published in *J.A.S.A.* providing a new equation for the speed of sound in sea water as a function of temperature, depth, salinity, latitude (working for all oceans, and with fewer anomalies and better agreement with empirical data). The joint paper on prediction of acoustic radiation from axisymmetric surfaces with arbitrary boundary conditions using the boundary element method on a distributed computing system was also published in *J.A.S.A.*, as was a paper on absolute calibration of hydrophones immersed in sandy sediment (work described at the last CCAUV meeting).

6 Medical and Industrial Ultrasound

6.1 *Medical Ultrasound*

NPL has been employed in a collaborative project funded under the European Metrology Research Programme (EMRP) Joint Research Programme (JRP) 7, which is entitled External Beam Therapy. Other partners are PTB (Germany), UME (Turkey) and INRIM (Italy). The acoustic component of the project involves the development of standard methods of measurement to support the clinical exploitation of High Intensity Therapeutic Ultrasound of HITU clinical techniques which are increasingly being used for cancer therapy. One of NPL's roles has been an investigation of the calorimetric method which it has pioneered, as a means of measuring the elevated acoustic powers which this type of equipment is able to generate (>500 W).

The so-called buoyancy method for ultrasound power measurements has been the subject to a wider systematic study extending down to lower powers. It has been validated using conventional radiation force method up to 9.5 MHz and it has been established that powers as low sas 200 mW can be measured. The castor oil target has been re-designed and the measurement system improved through the use of a higher sensitivity balance. The estimated systematic uncertainty of the target and the measurement system is now ± 2.5 % compared to ± 3.4 % previously. The investigation of the method at higher frequencies has led to an improved understanding of understanding important characteristics of the target i.e. primarily heat loss at the acoustic entry window of the target (see Figure 6.1). Frequency-dependent heat loss occurs during and after an insonation and must be accounted for to avoid significant underestimates in the measured power. The mechanism of the heat loss and its effect on the measured power were studied both experimentally and through the application of mathematical modelling. Modelling-derived corrections for the heat loss were derived and applied to the measurement data. The application of the heat loss corrections and modified analysis methods led to an improved agreement with the radiation force method (see Fig 6.2) in an unfocused field.

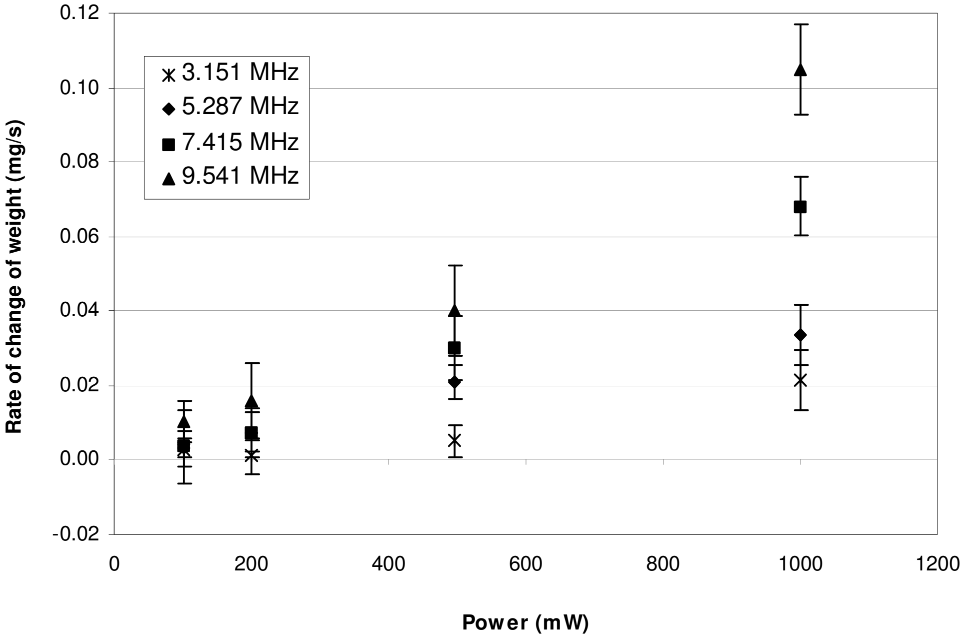


Figure. 6.1: Rate of change of weight of the buoyancy target immediately following an insonation as a function of frequency and power.

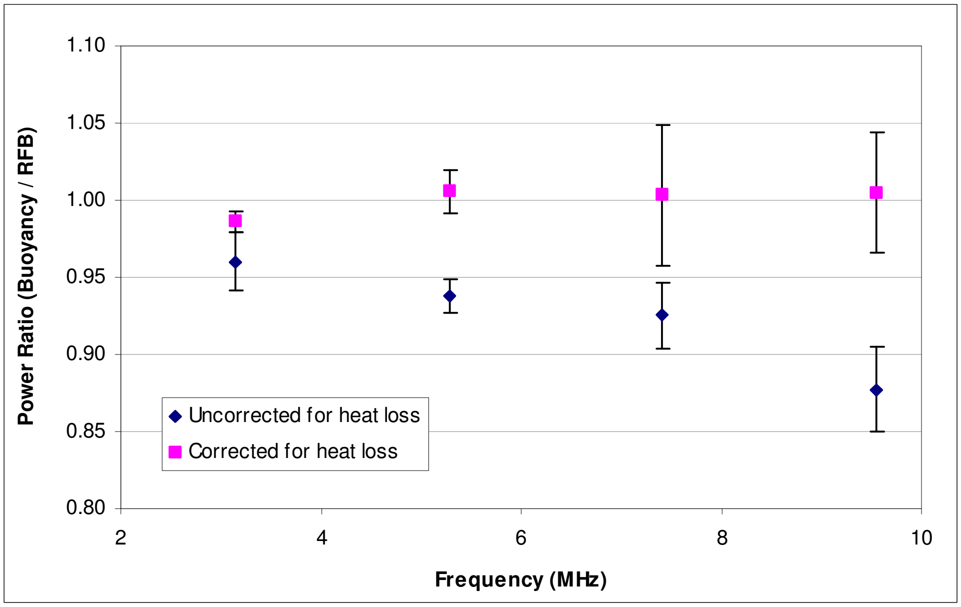


Figure 6.2: Comparison of ratios of power measurements made using the buoyancy method to radiation force methods both corrected and not corrected for heat loss.

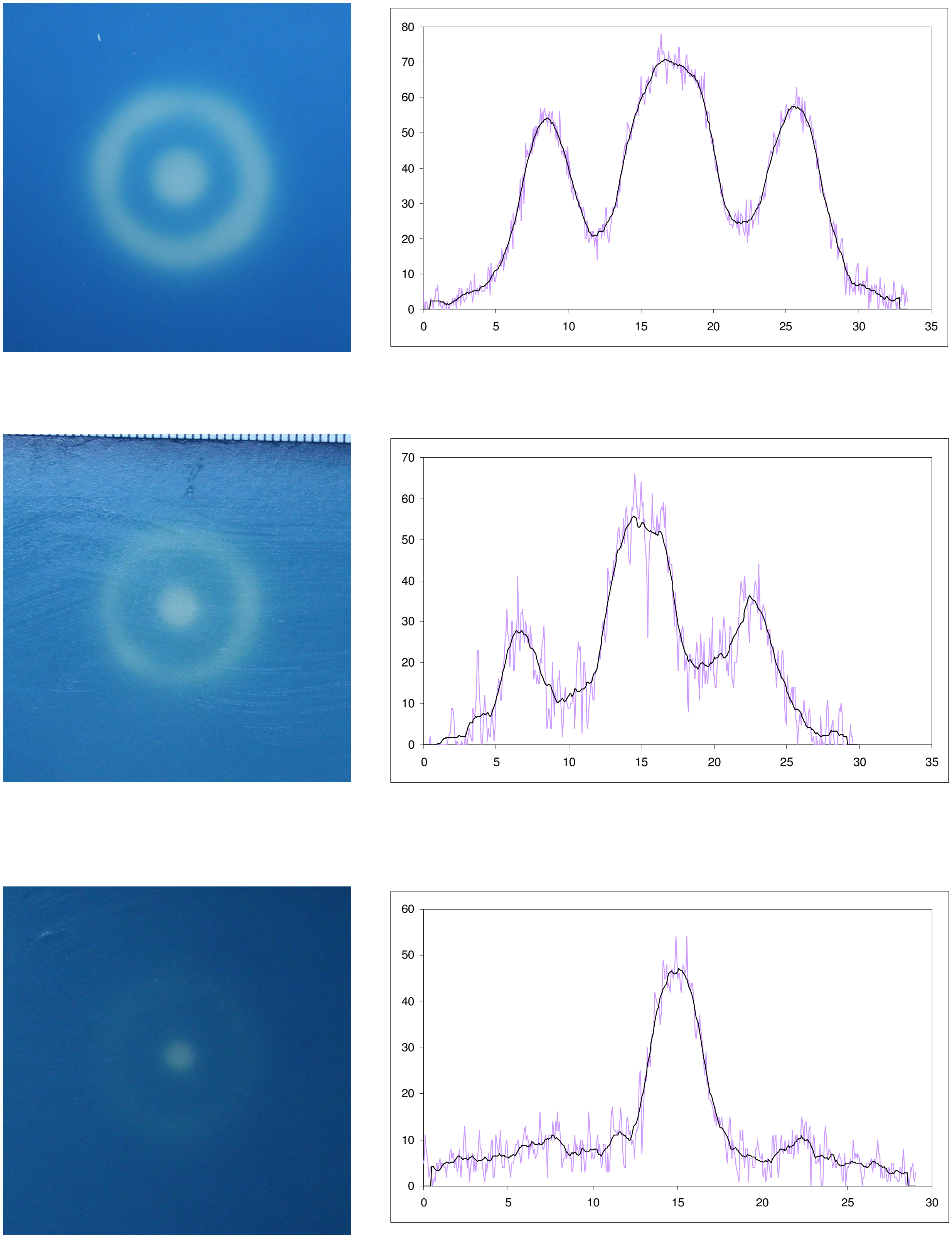
Thermochromic materials have been the subject of a number of studies of their use in providing a quick and easy way of ‘seeing’ the beam pattern of ultrasound transducers. Such materials have the potential to be used for Quality Assurance and safety purposes, such as checking for beam non-uniformities in therapeutic transducers, which could lead to areas of excessive heating in the patient.

So far, the application of thermochromic materials have provided qualitative information: providing an image of the beam pattern but no real quantification of the properties which allow comparison with manufacturers’ data, such as the Effective Radiating Area (ERA) or the Beam Non-uniformity Ratio (BNR) (defined in BS EN 61689:1997 / IEC 1689:1996: Ultrasonics – Physiotherapy systems – Performance requirements and methods of measurement in the frequency range 0.5 MHz to 5 MHz).

NPL has developed a novel of thermochromic tile design that has been tested with a number of transducers, in conjunction with common image analysis tools, the ‘thermochromic profile’ of the beam can be extracted (see Figure 6.3). Figure 6.3 illustrates what might be termed a ‘hot-spot’ transducer, where the acoustic intensity distribution within the acoustic field is characterised by a sharp on axis peak, of narrow spatial extent, meaning that this region of the beam generates high acoustic intensities with the resulting potential for tissue heating. The figure clearly shows the main lobe of the intensity distribution. With extended exposure times, conduction of heat away from the initial peaks, and the more general temperature rise caused by increased time exposure, the of the image of the subsidiary outer ring becomes clearly visible. It is hoped that this type of method could provide the physiotherapist with a rapid, visual, means of checking the that the treatment head is working correctly and has not become damaged (or even that it is working at all!). It is hoped to secure further funding to investigate whether more quantitative information (such as the BNR and ERA) can be derived from this technique. This might involve relating this thermochromic profile to the actual intensity profile of the transducer, potentially reconstructing the latter, by analysing a number of images resulting from testing at a range of switch-on times and/or a range of powers.

To determine the free-field acoustic pressure generated by their medical transducers, equipment manufacturers routinely use miniature membrane hydrophones. The measured acoustic pressure field is usually represented in terms of clinically relevant parameters describing the safety of a patient when exposed to such fields during diagnostic examinations. The short pressure pulses generated by the diagnostic equipment commonly undergoes distortion due to nonlinear propagation is the tissue. The peak rare-factional pressure of such pressure pulses is dominated by low frequency components. Therefore it is important to know the frequency response of miniature hydrophones below MHz region for accurate estimation of MI and TI. The relevant IEC standard describes methods for calibrating hydrophones in the frequency range 50 kHz to 1 MHz (IEC 62127-2). The current limitation in calibrating a membrane hydrophone below 300 kHz lies in reflections from the membrane ring due to broadness of the pressure field, as calibrations are commonly undertaken in the transducer far-field.

Figure 6.3: Photographic images derived using the Thermochromic tile developed at NPL, using a transducer operating at 3 MHz, and nominal intensity setting 1 W cm^{-2} for a time exposure (reading from top to bottom) of 10s, 7s and 5s. The *x*-axis is in mm and the *y*-axis is in arbitary units.



Currently at NPL, investigations are underway to overcome or at least reduce these limitations in calibrating a membrane hydrophone. A special ultrasound absorbing tile with an circular aperture at its centre is being used effectively as a "waveguide" to collimate the low frequency broad acoustic field generated by the transducer. The bounded acoustic beam is significantly narrower and a membrane hydrophone can be placed at the exit aperture of the collimating mask, thus reducing the effect of any acoustic reflections from the ring. FE modeling has been used to understand the effect that the absorbing aperture on the pressure distribution in the acoustic field, at frequencies in the range 100 kHz – 300 kHz.

Figure 6.4 shows a horizontal beam plot of the pressure distribution derived from a broadband *pvdf* transducer at a distance of 82 mm away from its face using a needle hydrophone both with and without the absorbing aperture. The calculated beam widths from the two profiles suggest that the use of the absorbing aperture narrows the unbounded beam by up to 50%. For a membrane hydrophone whose ring diameter is 80 mm, this indicates that the acoustic pressure at the ring will be –20 dB down when comparing the 'collimated' and 'uncollimated' pressure distributions.

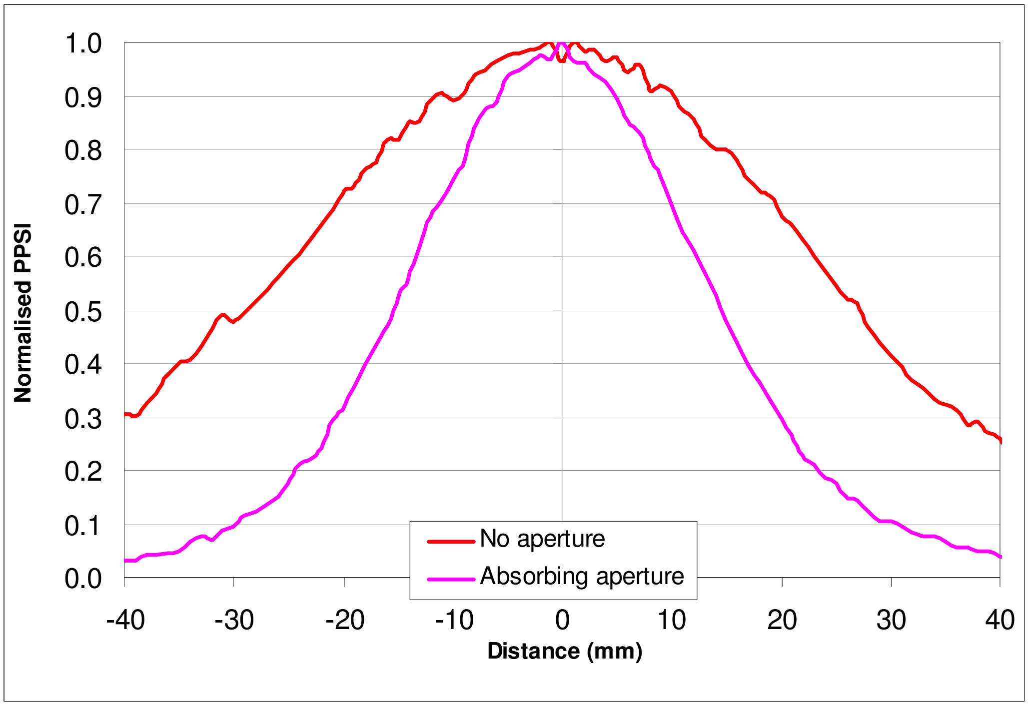


Figure 6.4: Horizontal beam profiles from a broadband *pvdf* transducer driven at 100 kHz and at a separation of 82 mm, both with and without the circular absorbing aperture in front of the transducer.

In order to understand the measurement method, ratios of the acoustic field magnitudes measured using a membrane and a needle hydrophone with the absorbing aperture in place, across a range of frequencies and different separations have been obtained. Simple models have been developed to identify the effect of various acoustic arrivals on the calibration. The ratios of voltages from the two hydrophones at frequencies of 200 kHz and above are independent of distance from the collar or aperture, indicating that the direct, plane-wave component, has been isolated, and is uncontaminated by diffraction from the aperture of the collimator, reflections from the hydrophone and any residual reflection or diffraction from the hydrophone ring. The situation is more difficult below 200kHz, as the longer wavelength means there are fewer cycles before the corrupting effects of the other acoustic influences become seen.

The aim of this research is to establish a substitution technique for calibrating the membrane hydrophone relative, potentially, to a second hydrophone which had been calibrated using a technique such as reciprocity. Work is underway to use the absorbing collar method to calibrate a membrane hydrophone using NPL's primary standard interferometer at the lower end frequency of 100 kHz. Once the absolute sensitivity of the hydrophone is determined it is then possible to calibrate hydrophones for customers using the absorbing collar method using the developed substitution calibration technique.

Significant progress has been made since the last CCAUV meeting in understanding and further developing the *pyroelectric* method for measurement of the output power generated by medical ultrasound transducers. It is a thermal-based measurement method involving the conversion of acoustic energy into heat. Energy within the ultrasound beam is absorbed within a layer of a special polyurethane rubber material, whose coefficient of absorption is sufficiently high to ensure energy deposition typically occurs within a mm or so of the ultrasonic wave entering the material. The *rate of change* of temperature at the absorber surface is monitored using the *pyroelectric* voltage generated from electrodes deposited either side of a thin (0.037 mm thick) membrane of *piezoelectric* polymer polyvinylidene fluoride (*pvdf*), intimately bonded to the absorber and sufficiently large to intercept the whole beam. The change in the *pyroelectric* voltage generated from the sensor at times immediately following Switch ON and Switch OFF of any transducer is proportional to the delivered ultrasound power.

Extensive studies have been undertaken to understand the measurement method which have pointed to the importance of the acoustic and thermal properties of both the absorbing backing layer and *pvdf* membrane in controlling the sensor response. Work has revealed several key features of the method: its excellent linearity, its high sensitivity, suggesting the possibility of instrumentation capable of measuring powers as low as a few mW. Indeed, an instrument, the NPL Pyrometer shown in Figure 6.5, has been developed with prototypes being successfully trailed within three UK Hospitals, indicating its ability to measure the acoustic output power of medical ultrasound scanners.

Additionally, it has been shown to have the potential as a device for directly measuring acoustic intensity, through the employment of a sensor whose active area is small in relation to the spatial extent of the acoustic pressure distribution. An example beam-plot is shown in Figure 6.6. Currently, acoustic intensity is measured by using a hydrophone to measure acoustic pressure, with intensity being derived using the plane-wave approximation. This work is being funded under an NPL Strategic Research Project.

Figure 6.5: Image of the prototype NPL Ultrasound Pyrometer developed to determine the acoustic power generated by medical diagnostic equipment.

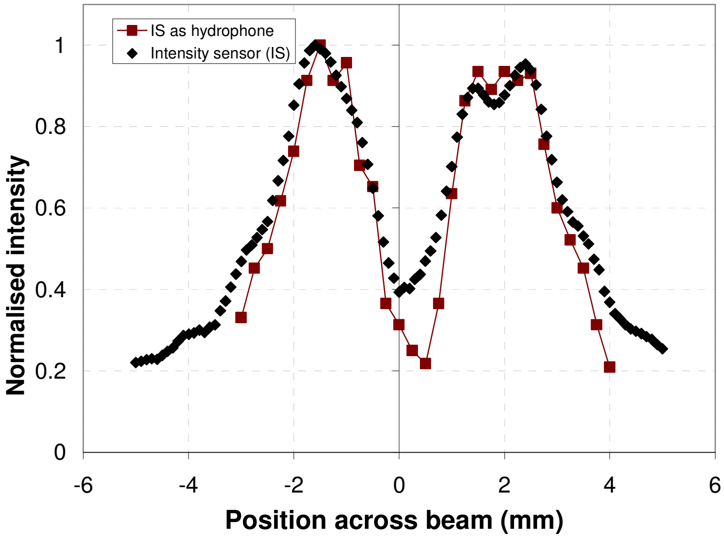


Figure 6.6: Beam-profile of the normalised intensity determined at the last-axial minimum of a focused 3.5 MHz plane-piston transducer, using the backed sensor both as a pressure measuring device and as an 'intensity' sensor (IS).

6.2 *Industrial Ultrasound*

Over the past three years, NPL has developed the capability to model multi-frequency reference vessels for cavitation – temperature-controlled sono-reactors – where the geometrical and temporal distribution of acoustic pressure can be predicted.

Research at NPL has progressed in parallel with the development of novel sensor technology to measure cavitation (namely the NPL cavitation sensor and CaviMeter^{TM}

– see Section 6.2.2), with the aim of providing a repeatable ’cavitation source’ to calibrate sensors over a wide range of frequencies.

This project builds on the first prototype of reference vessel RV-25 (working at 25 kHz and characterised at NPL over the period 2004 – 2007) and was aimed at extending its versatility to meet the growing needs of modern industry, where cavitation-based applications are no longer limited to the lower frequencies, but are increasingly covering the whole 15–130 kHz frequency range.

As a first step towards the development of a multi-frequency vessel, the limitations of RV-25 were thoroughly investigated. It was found, for instance, that under certain conditions, even small temperature changes (e.g. due to prolonged operation of the vessel at medium and high powers) could cause substantial variations (up to ±6 dB over 30 minutes) in cavitation activity at a fixed position, thus hindering its ability to function as a reference source. The underpinning reasons for this behaviour were determined following a detailed investigation into its mode of operation, with a complementary approach based on semi-analytical modal analysis (i.e. treating the vessel as a resonant cavity) and numerical finite-elements modelling. It was found that the RV-25 was sensitive to mode-hopping, because of the absence of a temperature control and the particular geometry of transducers.

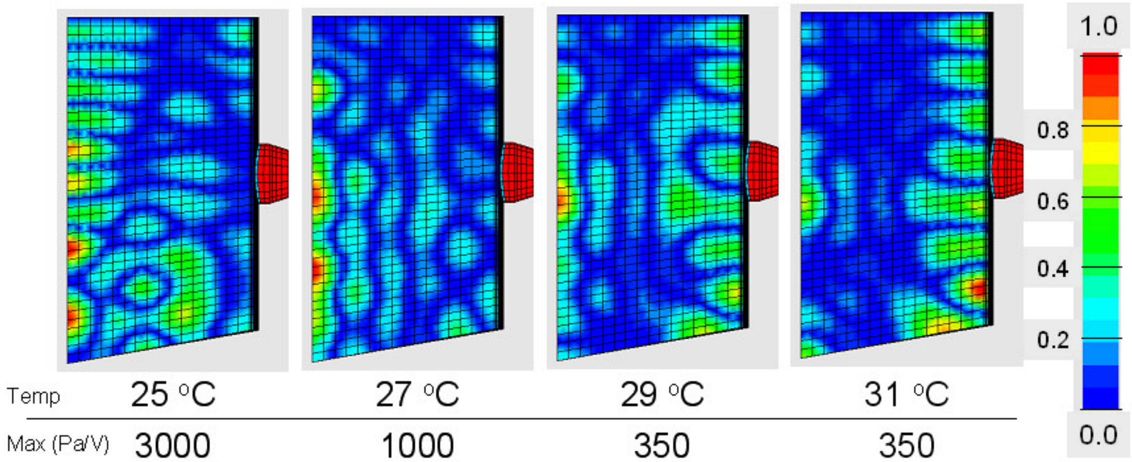
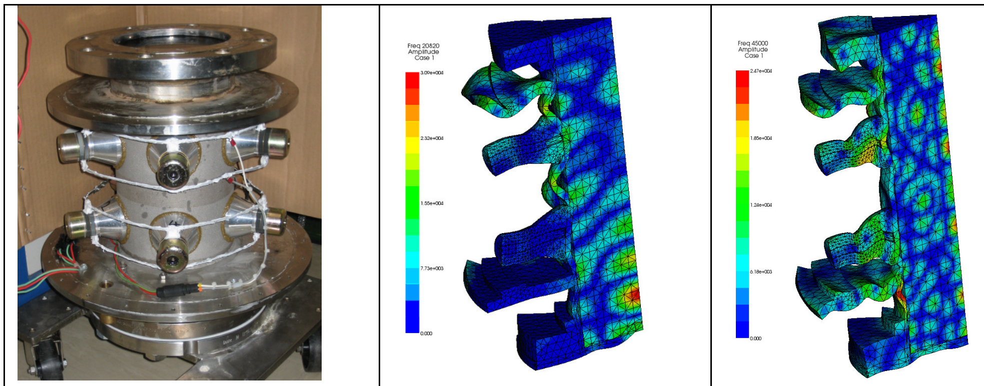


Figure 6.7: Change in the field distribution as a result of varying temperature in RV-25.

Efforts to provide stability to the RV-25 and understanding its operation produced a series of simple, but useful tools for the design of cavitation vessels, for both metrological and industrial use. Fan-based temperature control allowed the uncertainty to be reduced to ±1 dB (over 30 minutes) for powers of up to 400W. More importantly, this permitted measurements of the acoustic power transmitted into the field using calorimetric methods. The modal analysis allowed a predictive analysis of the effects of changing the volume of the vessel and the geometry of the transducers, to produce more isolated “modes”. The fan-based temperature control also enabled the Q-factor of the vessel to be estimated from a pair of hydrophone scans.

NPL subsequently commissioned Sonic Systems (Somerset, UK) to customise an existing vessel so that it could work over two different frequency windows, both 1 kHz wide and centred respectively around 18 kHz and 57 kHz. This vessel (RV-18/57) was fully characterised (three modes within each frequency window), and a more advanced FEM model that included the dynamics of the side-walls was produced. This latter feature allowed the comparison of the model with the actual displacement of the wall, as measured with a laser vibrometer, with excellent results.



a) b) c)

Figure 6.8: a) the acoustic reactor - RV-18/57; b) structural deformation and field amplitude at low frequency and c) structural deformation and field amplitude at high frequency.

As a next step in the development process, a vessel working at 20, 30, 40, 60 and 120 kHz is currently under construction and expected to be delivered by the end of October 2010.

6.2.1 Pump cavitation research

Extending the capability developed in recent years for characterising acoustic cavitation (the driving phenomenon in ultrasonic cleaning, sonochemistry and ultrasonic surgery applications), NPL has developed devices and methods for remotely detecting *hydrodynamic* cavitation occurring in pumps, valves and flow systems. The technique uses broadband transducers coupled externally to casings and pipework, and has been successfully trialled on small and medium scale pump loops at NPL and with external collaborators. Currently, cavitation in pumps is detected via its secondary effects such as bearing vibration, which may only be detected once damage as actually occurred: the new method provides a near real-time indication, and is currently undergoing refinement for full industrial testing.

6.2.2 NPL CaviMeter

NPL has developed award-winning techniques for characterising acoustic cavitation via broadband detection of the sounds emitted by oscillating and collapsing bubbles, developing correlations between these and other cavitation detection techniques such as metal film erosion and chemical oxidation. The cavitation sensor developed at NPL, and the accompanying detection and analysis electronics (now known as the CaviMeter^{TM}) are being developed into a commercial product by an external industrial design company. The resulting prototype systems are being trialled in real-world industrial applications, and discussions are underway with potential licensing partners.

Figure 6.9: CaviMeter^{TM} prototype during industrial trialling.

7 Publications

7.1 Sound-in Air

Comparisons of different measurement instruments for the study of complex industrial noise fields.
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Koukoulas, T, Theobald, P, Schlicke, T*, Barham, R G
Opt. Lasers Eng., 2008, 46, (11), 791-796

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Bravo, A*, Barham, R G, Ruiz, M*, Lopez, J M*, De Arcas, G*, Recuero, M*
Metrologia, 2008, 45, (4), 448-458

Utilization of carbon nanofibers for airborne ultrasonic acoustic field detection using heterodyne interferometry.
Koukoulas, T, Theobald, P D, Zeqiri, B, Bu, I Y*, Milne, W I*
Opt. Lett., 2008, 33, (9), 947-949

7.2 Underwater Acoustics

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Robb G.B.N., Robinson S.P., Theobald P.D., Hayman G., Humphrey V.F., Leighton T.G. and Lian Sheng Wang, Dix J.K. and Best A.I.. “Absolute calibration of hydrophones immersed in sandy sediment”, *J. Acoust. Soc .Am.* vol 125, (5), p2918-2927, 2009.

Robinson S P, Lepper P A, Ablitt J, Hayman G, Beamiss G A, Theobald P D and Dible S. “A methodology for the measurement of radiated noise from marine piling”. *Proceedings of the 3rd International Conference & Exhibition on "Underwater Acoustic Measurements: Technologies & Results",* Napflion, Greece, June 2009, ISBN; 978-960-98883-4-9.

Robinson, S. P. “Towards guidelines for the measurement of underwater radiated noise from marine piling”, Proceedings of the one-day conference “Assessing and managing the potential impact of marine piling noise within the evolving regulatory framework”, organised by Crown Estate and the UK Marine Science Coordination Committee, February 24th 2010. Invited paper.

Robinson S. P, Theobald P. D, Lepper P.A., Hayman G., Humphrey V. F., Wang L. S., Mumford S.. “Measurement of underwater noise arising from marine aggregate operations”. *Proceedings of the Second International Conference on the Effects of Noise on Aquatic Life*, Cork, August 2010.

Theobald P, Paul Lepper, Stephen Robinson, Dick Hazelwood. “Cumulative noise exposure assessment for marine using Sound Exposure Level as a metric”. *Proceedings of the 3rd International Conference & Exhibition on "Underwater Acoustic Measurements: Technologies & Results",* Napflion, Greece, June 2009, ISBN; 978-960-98883-4-9.

Theobald, P D, Lepper, P A, Robinson S P Gordon J. “Effectiveness of exclusion zones and soft-starts as mitigation strategies for minimizing acoustic impact from

underwater noise sources" Proceedings of the 10th European Conference on Underwater Acoustics, Istanbul, July 5-9, 2010, p87-88.

Theobald P D, S. P. Robinson, Triatafillos Koukoulas, and G. Hayman. "Measurement and imaging of high-frequency sonar fields using acousto-optic tomography". *J. Acoust. Soc. Am.* vol **125** (4), p2555, 2009.

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