CCAUV/08-26

Overview of Acoustical Metrology Research at the NPL

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20 pages inclusive

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.

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.

3 Programme structure

The programme is composed of four principal Thematic areas. There are three technical themes dealing with the measurement standards and a fourth addressing cross-theme knowledge transfer. The 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.

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.

Knowledge Transfer

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

4 Sound-in-air

The NPL projects related to sound-in-air have broad perspective, covering general matters of calibration and traceability that seek to maintain and enhance our capabilities and range of services offered, development of novel instrumentation and its application to solve real-life problems and next-generation metrology based on optical techniques. Some key activities and developments of particular interest to CCAUV are featured below.

The NPL laser pistonphone is a modern implementation of the calculable pistonphone and uses laser interferometry to determine the sound pressure level generated within the device. It was used by NPL as the basis for the measurements for supporting the key comparison CCAUV.A-K2, while all other participants used reciprocity calibration. Measurements with the laser pistonphone therefore provided a valuable means of validating the other measurements in the key comparison by offering a completely independent methodology and alternative set of uncertainty components. A paper has been published in *Metrologia* (Barham 2007) to supplement the data provided for the key comparison, giving details about the device and it measurement uncertainty.

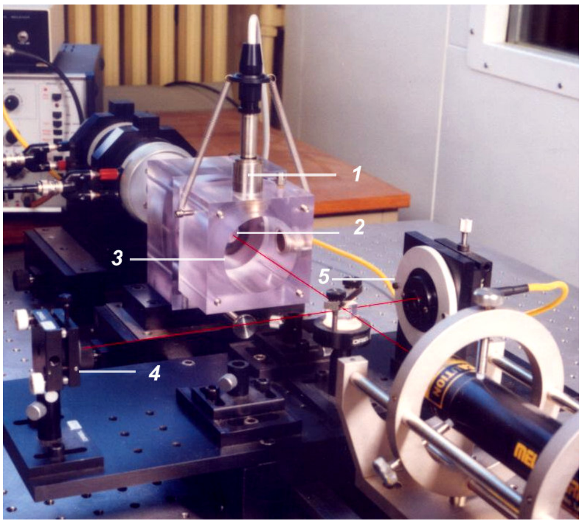


Figure 4.1. The NPL laser pistonphone with end face removed to show the internal configuration, and without the feedback system connected.

Key:

1. microphone under test,
2. piston,
3. cavity,
4. fixed mirror
5. optical detector and fibre.

The NPL facility for primary pressure reciprocity calibration of laboratory standard microphones has been upgraded with new instrumentation and software. While the heart of the system (the microphone, couplers and instrumentation providing the traceability) remains unchanged, new digital lock-in amplifiers and software have significantly reduced run-time and improved repeatability. The transmission line analysis, and calculations of the various complex correction factors, are now performed in the background during the measurement, so results can be viewed as the measurements progress. The new facility became operational in January 2007 after it received it peer-review accreditation to ISO 17025.

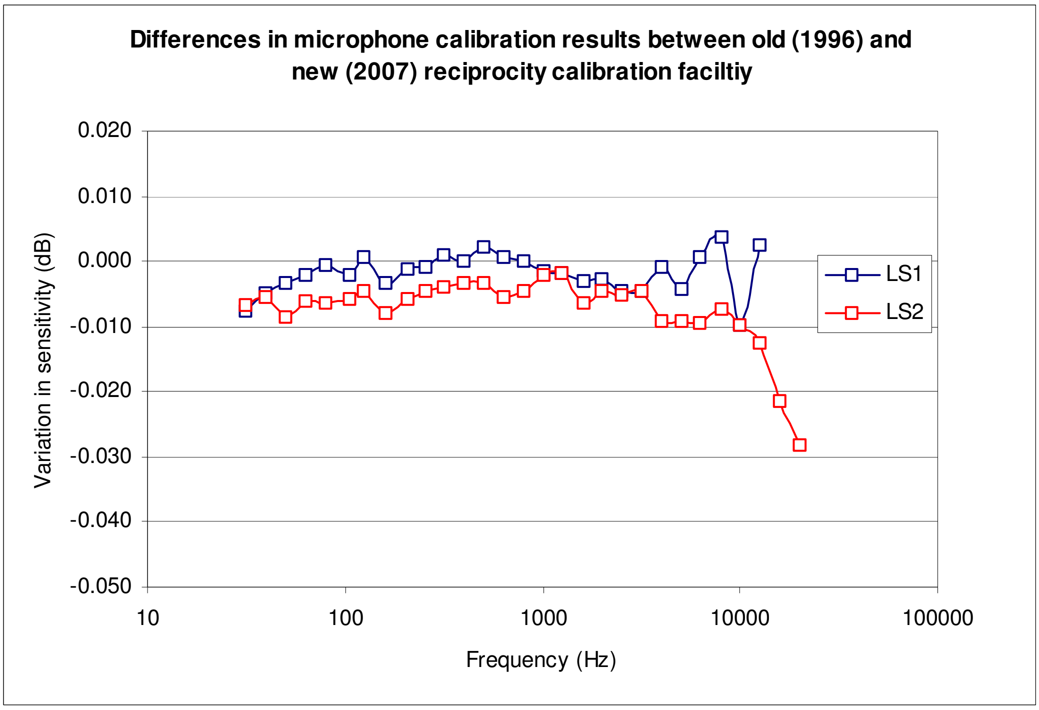
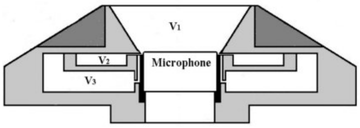


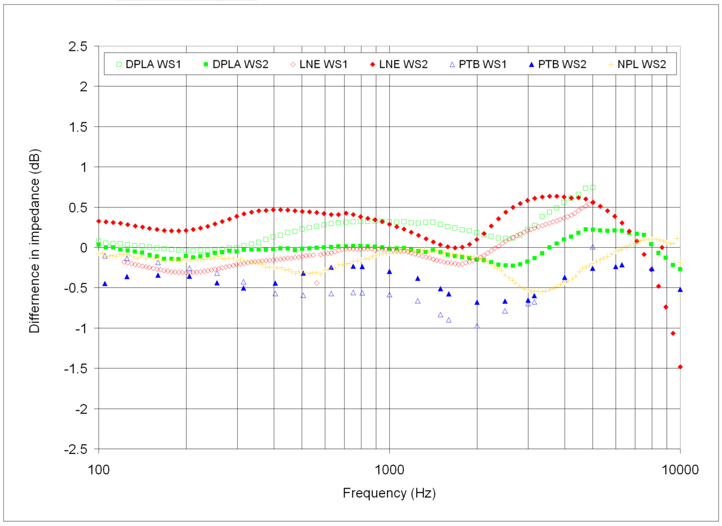
Figure 4.2. Performance of the 2007 implementation of the IEC 61094-2 reciprocity calibration methodology relative to the system used at NPL for CCAUV.A-K1 (2003).

During the same period, NPL made a decision to suspend development of a free-field reciprocity calibration facility. This followed a long period of uncertainty over the commissioning of a new free-field chamber following the re-location of all the acoustical facilities to the new NPL buildings. The main purpose of the facility was to contribute to the establishment of pressure-to-free-field differences for laboratory standard microphone, by participation in CCAUV.A-K4. However after many months of waiting for the laboratory to be completed, and handed over to NPL scientists, it became clear that the new facility would not be fully developed in time to take part in this key comparison, leading NPL to make the regrettable decision to withdraw from the project.

NPL has been leading the revision of IEC 60318-1 which specifies the type of ear simulator used extensively in audiometry, telecoms and audio engineering. Most significantly a new method for determining the acoustical impedance of the device has been added, enabling the device to be tested routinely for conformance with the specifications. The new method has been developed and validated by a EURAMET project, which then went on to establish new normative data for the acoustical transfer impedance. Both these elements have fed directly into the revision of IEC 60318-1 and a final draft version (FDIS) will shortly be circulated by IEC. An NPL report is available on the project (Barham 2008), and a scientific paper has been submitted to *J. Acous. Soc. Am.* It has been possible to make an effective contribution in this field, only because of the international collaboration fostered by EURAMET.

Figure 4.3. The ‘artificial ear’ and a graph showing the level of agreement in measurements of the acoustical transfer impedance from the partners in EURAMET Project 791. The 0 dB line represents the modified lumped parameter specification of the impedance.





A current research priority for NPL is the development and application of MEMS measurement microphones. NPL commissioned the development of the first-generation devices and subjected these to a range of tests and calibrations, including pressure and free-field responses, linearity tests, self-noise and dependence on environmental parameters. Despite the small size of the MEMS microphone diaphragms, one of the limitations of the first-generation devices was the overall form factor of the packaged microphone, which remained sufficiently large to influence the frequency response. Consequently, one of the priorities for the development of second generation devices is to reduce the characteristic dimensions to around 7 mm, which compares with traditional quarter-inch microphones.

The microphone development is also being driven by a small number of selected applications. The most significant of these is environmental noise mapping. NPL has formed a UK consortium to develop a distributed measurement system that can be deployed outdoors, to enable long-term monitoring of environmental noise. The plan is to deploy the system at selected sites for periods of a few months, and prepare noise maps based on real data for direct comparison with those derived from prediction. The system will consist of one hundred measurement nodes. Each will have a MEMS microphone and some electronic hardware to process and store the acoustical parameters to be measured (10 minute L_{eq}, L_N etc.). Periodically this data will be transmitted wirelessly to a central location for further analysis. The system hardware development is due for completion early in 2009. Following testing at NPL, the hardware will then be deployed at the first measurement site where live monitoring is planned to start in the summer of 2009.

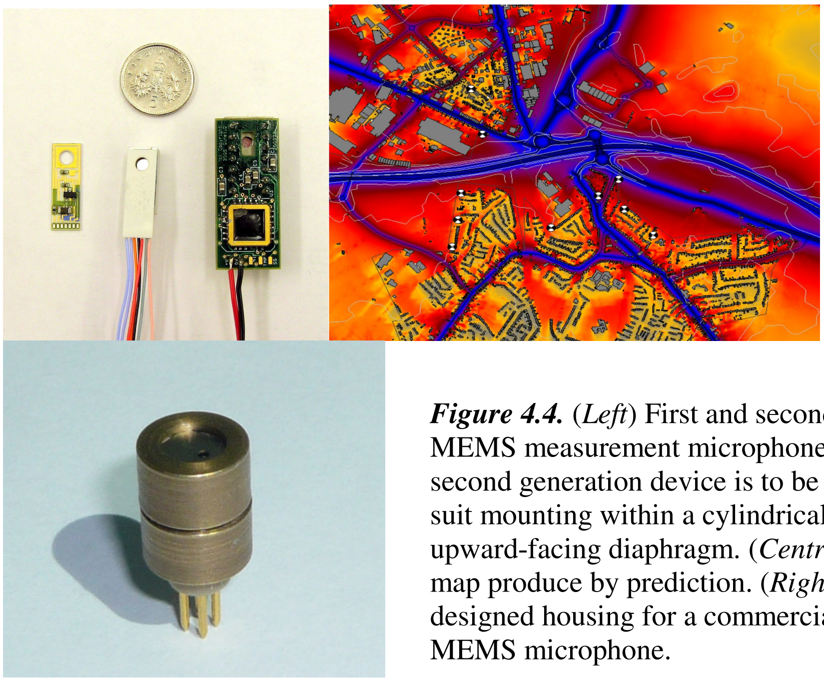


Figure 4.4. (*Left*) First and second generation MEMS measurement microphones. The smaller second generation device is to be re-packaged to suit mounting within a cylindrical housing with upward-facing diaphragm. (*Centre*) Typical noise map produce by prediction. (*Right*) An NPL designed housing for a commercially available MEMS microphone.

NPL has continued research on the use of laser Doppler anemometry (LDA) as a potential method for the future free-field calibration of measurement microphones. This optical technique provides direct measurement, through photon correlation, of the particle velocity component from which pressure can be derived. Progress at NPL has been good, with the LDA method being implemented in a standing wave tube below 1 kHz and comparisons with a microphone being completed. Measurements of the sound pressure in a standing wave tube made using the optical method and with a calibrated microphone agreed to around 0.2 dB. A paper on this work has been accepted for publication in Optics and Laser in Engineering.

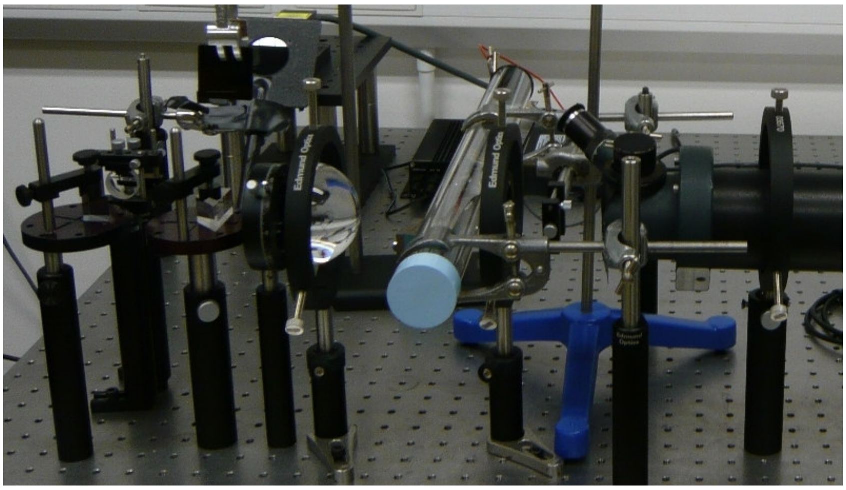


Figure 4.5. The NPL optical LDA system for acoustic particle velocity measurement in a standing wave tube.

The next step is to develop the LDA system for use in a pseudo free-field with a targeted completion date of mid-2009 for initial testing in a full free-field environment. The latter presents significant technical and practical challenges which include; mounting of the optical components *in-situ*, minimizing the amount of seeding needed and dealing with non-acoustic components of the velocity, for example arising from air flow.

5 Underwater Acoustics

The work on underwater acoustical standards at NPL has a number of objectives. A key objective is to maintain primary standards, traceability and international consistency for the UK, and to disseminate 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 at Wraysbury; and to support UK manufacturing industry in sectors such as offshore industry, ocean engineering and science, defence industry and marine renewables industry. NPL has an active research programme in underwater acoustical metrology, and the following are some of the highlights from the last two years.

One of the main themes 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 being designed, constructed and tested. The principle of the method has been demonstrated previously using a pellicle strip to reflect the laser light, the pellicle being so thin that it effectively follows the acoustic particle velocity in the water. For the field mapping, a scanning vibrometer has been used to measure the surface velocity of sonar transducers operating in the range 100 kHz to 500 kHz. The techniques of Fourier acoustics have then been used to predict the acoustic far-field, and the results have been compared to hydrophone scans in the near-field. The technique is complicated by the acousto-optic interaction between the laser beam and the acoustic wave which can give rise to spurious signals, and this is the subject of current study. Another approach to acoustic field mapping is to use the acousto-optic interaction to sense the acoustic wave in a technique we have called acousto-optic tomography. The method uses a laser interferometer to measure the integrated refractive index change across the propagating acoustic wave generated by the transducer. An interferometer, being a displacement or velocity measuring device, interprets this rate of change of optical path length as a displacement or velocity. Obtaining a series of these projections by scanning the laser beam or the transducer, for a number of rotation angles of the transducer, allows a two-dimensional "slice" of the acoustic field to be reconstructed using the same techniques commonly used in medical imaging (X-ray Computed Tomography). Figure 5.1 shows two possible geometric scan arrangements for parallel-beam or fan-beam scanning, both tomographic reconstruction algorithm being the inverse Radon transform. Figure 5.2 shows the measurement results for a 95 by 95 mm, 480 kHz 1-3 composite, 4-element sonar array transducer and are compared to conventional planar hydrophone scans obtained using a 1.5 mm probe hydrophone. The optical method has the potential to enable rapid measurement of the acoustic field without perturbing the field. The work on this method has benefited from the secondment to NPL of Prof. Wang Yuebing of the Hangzhou Applied Acoustic Research Institute (HAARI), China.

Further progress has been made with the development of test methods for panel materials at simulated ocean conditions to determine the reflection loss and transmission loss. The technique adopted uses a parametric array as a directional source to insonify panels of limited size in the Acoustic Pressure Vessel. The work has been a highly successful UK collaborative project involving the NPL, University of Southampton, QinetiQ and DSTL, and a major paper describing the method has recently been published in the Journal of the Acoustical Society of America.

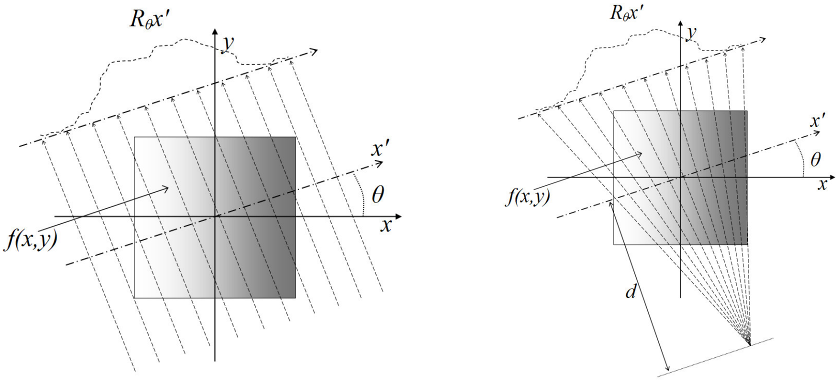


Figure 5.1. Scan configuration for parallel beam (left) and fan beam (right) acousto-optic tomography through a distribution *f(x,y)* at an angle *θ*, producing the Radon transform $R_\theta(x')$.

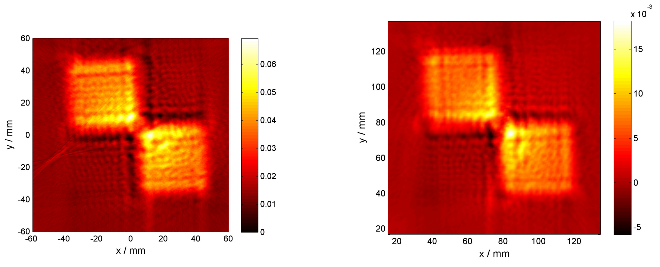


Figure 5.2. Results of reconstructed acoustic pressure magnitude for parallel beam (left) and fan-beam (middle) geometries. An equivalent hydrophone scans is also shown (right).

Recent work on panels testing has concentrated on the use of a directional array sensor to provide a directional receiver and give better rejection of diffracted signals, the aim being to provide more accurate measurements at low kilohertz frequencies. Figure 5.3 shows the measured reflection loss and transmission loss for a high performance test panel.

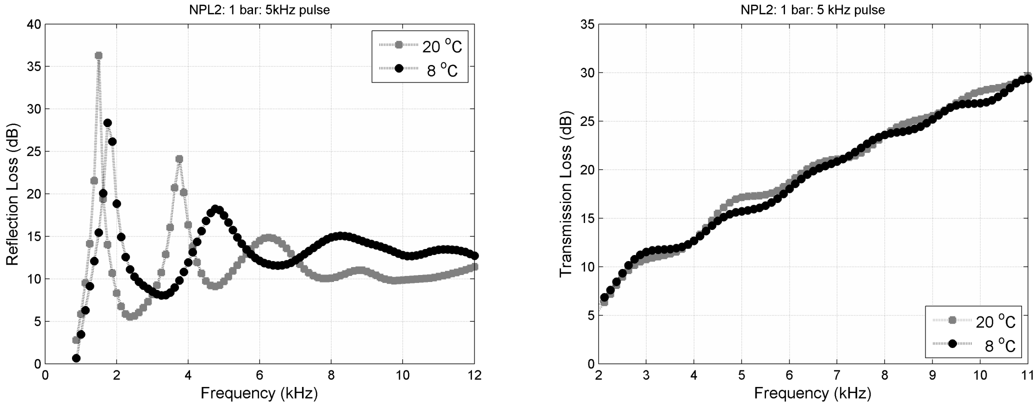


Figure 5.3. The measured reflection loss (left) and transmission loss (right) for a test panel with high performance at low kilohertz frequencies, at temperatures of 8 ºC and 20 ºC.

A method has been established for absolute phase calibration of hydrophones in the frequency range 10 kHz to 400 kHz. The method adopted was the three-transducer spherical-wave reciprocity method using the co-linear configuration of Luker and van Buren which enables many of the errors due to inaccurate positioning to be eliminated (see Figure 5.4). In the NPL implementation, a laser alignment system was used to improve positioning, but even so the alignment could only be done to within ±0.3 mm (positioning hydrophones on the end of 1.5 m poles in a tank of water is not a trivial exercise). Positioning errors increase uncertainties at high frequencies (a 1 mm position error leads to a 50º phase error at 400 kHz), increasing Type A (random) uncertainties. An unexpected error was obtained for some devices due to the fact that the active element was not central in the hydrophone boot. A comparison was made with an optical method used by Prof. Wang Yuebing of the HAARI, China. An NPL report was published and a joint paper is in preparation.

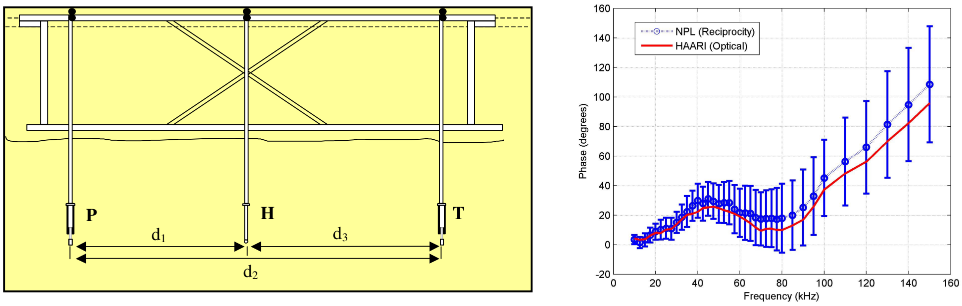


Figure 5.4. Co-linear configuration used for hydrophone phase response measurement (right) and results obtained for a B&K8104 hydrophone using both reciprocity and an optical method.

In another collaborative project with the National Oceanographic Centre and University of Southampton (ISVR) an absolute calibration method for hydrophones buried in sediment has been developed. Hydrophones are commonly buried in marine sediment in acoustic experiments designed to measure sediment properties, including gas content which is important for studies of sediment stability and sediment-derived methane (relevant to climate change). However, the in-water sensitivity values do not apply when hydrophones are buried in sediment. For the calibration method, the same co-linear reciprocity arrangement was adopted as for the phase calibration (see Figure 5.4). This enables a calibration to be made without knowledge of sediment properties (eg absorption) since the equation terms containing sediment properties cancel. Measurements were made in sediment-filled tanks at NPL and at ISVR, and the results show hydrophone sensitivity reduction at frequencies close to resonance, demonstrating that an error will be made if in-water sensitivity used. The hydrophone electrical impedance also shows appropriate changes. Figure 5.5 shows examples of the results obtained. A joint journal paper has been submitted to Journal of the Acoustical Society of America.

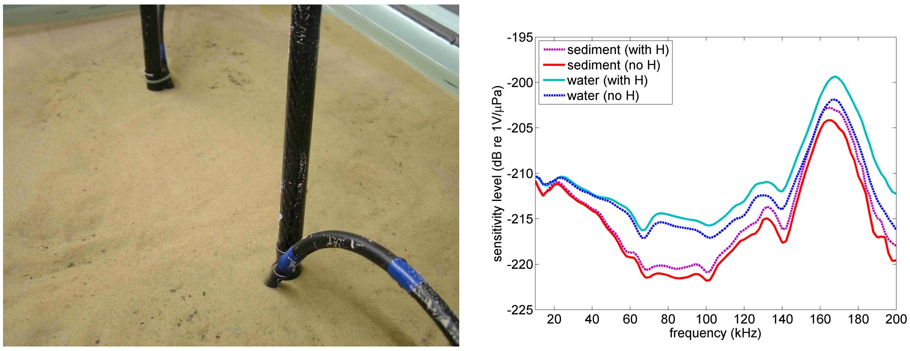


Figure 5.5. Photograph of the hydrophones immersed in sandy sediment (right) and calibration results obtained for a hydrophone in both water and sediment (left). The calibrations were undertaken with and without the central hydrophone shadowing the outer devices (“no H” and “with H”).

There are increasing international legal requirements for Environmental Impact Assessments which cover the effect of man-made noise on marine life. In the UK there are the

Conservation (Natural Habitats &c.) Regulations 1994 (i.e. the Habitats Regulations, HR) and the Offshore Marine Conservation (Natural Habitats, &c.) Regulations 2007 (the Offshore Marine Regulations, OMR) 2007. Such measurements are required in support of off-shore operations for the oil & gas industry and offshore renewable energy (eg marine piling). NPL is developing standardised methods for measuring in-situ impulsive noise such as marine piling, and in addition has been working on methods for measuring continuous noise radiated by vehicles such as ROVs in reverberant tanks. NPL has undertaken commercial work and is fortunate that the commercial data has fed directly into the research work, with commercial data used in publications. Figure 5.6 shows a typical acoustic pulse measured in shallow coastal water 1.8 km away from marine piling during construction for an offshore windfarm. Also shown is a plot of the sound exposure level for each pulse as the hydraulic hammer is gradually increased in energy. NPL has published 5 joint conference papers in last two years on this subject, and a journal paper is in preparation. NPL collaborating with university partners in the UK: Loughborough University, St Andrews University and University of Southampton.

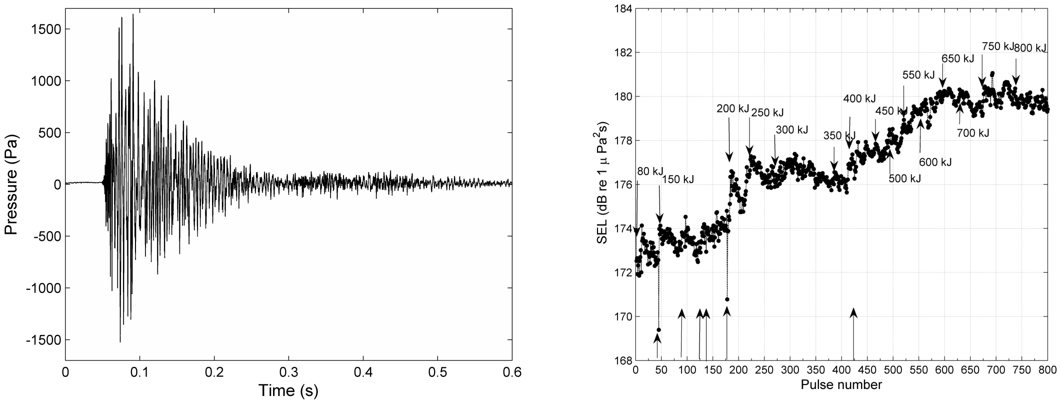


Figure 5.6. Left: Typical acoustic pulse measured in shallow coastal water 1.8 km away from marine piling during construction for an offshore windfarm. Right: Sound exposure level for each pulse as the hydraulic hammer is gradually increased in energy (hammer energy indicated on plot).

The open-water facility at Wraysbury is one of our main dissemination routes for underwater acoustic free-field standards. In last two years, work has been undertaken to model the response of the reference transducers used to derive the coefficients for transducer dependence on temperature and the long-term ageing of the transducers (with measurements validated against measurements in Acoustic Pressure Vessel. This modelling used the historical calibration data for the reference transducers and was done in conjunction with NPL Mathematics and Scientific Computing Group, and results were published in *Meas. Sci. Technol.* **18** (2007). This method of accounting for temperature dependence on a much more rigorous basis has now been implemented for calibrations, and it has resulted in improved uncertainties.

A new equation for the speed of sound in sea water has been developed with Dr Claude Leroy. The equation provides sound speed as a function of temperature, depth, salinity, latitude, and works for all oceans, and has fewer anomalies and better agreement with empirical data. This is achieved by fitting over only the range of values of temperature, depth, salinity which occur in real oceans (rather than over all parameter space). A paper describing the equation has been accepted by the Journal of the Acoustical Society of America and will appear in late 2008. The new equation will be made available interactively via the NPL web-site guides in the next few months

NPL has had a major presence at several international conferences in the last few years including the UAM conference and IEEE Oceans in 2007, and the Acoustics08 conference in Paris in 2008. NPL has organised a total of three scientific sessions at UAM and Acoustics08, and presented a total of 5 invited papers. The last two years has also seen the publication of IEC60565:2006 (in December 2006), a standard which benefited from a major contribution by NPL.

6 Medical and Industrial Ultrasound

The work within the Ultrasound Metrology area at NPL is mainly associated with its extensive medical applications, where the key driver relates to the safe and effective application of clinical techniques. More recently, activity has started involving the development of measurement methods for Industrial applications of ultrasound which typically involve the deployment of High Power Ultrasound in materials processing, cleaning, sonochemistry and waste water treatment. Here, the driver is the optimum application of the technology, leading to better targeted and controlled processes and energy savings. Four specific projects that are currently the subject of metrological research will now be described: three from the Medical Ultrasound area and one from Industrial Ultrasound.

Ultrasound output power generated by medical ultrasonic equipment represents a key parameter related to safety. With accurate ultrasound power values being required to ensure such equipment complies with a series of national and international standards, the standardised method of power measurement has become based on measuring the radiation force exerted by the ultrasonic beam on a specially designed target. A detailed understanding has been developed of factors influencing power measurement uncertainty, and a recent Key Comparison between National Measurement Institutes worldwide has shown that these specialised laboratories are now capable of measuring ultrasound power with an expanded uncertainty (coverage factor, k=2) as low as ±3% to ±4%. Additionally, at physiotherapy power output levels, considerable progress has been made in establishing standard power measurement set-ups for levels up to 20 W.

Despite the relatively widespread acceptance and implementation of the radiation force technique, issues exist which restrict its deployment at the clinical or user level. Primarily related to the high cost of the commercially available measurement instrumentation and the degree of skill and experience the equipment demands of the user, these issues partly arise from the need to isolate the effects of fairly small radiation forces, 0.67 mN per unit watt from the effects of variable and much larger forces caused by unavoidable confounding phenomena. This can be particularly problematic for measurements at diagnostic level power levels, where there is the need to measure powers of a few mW.

There is therefore a requirement for a considerably simpler means of providing traceable ultrasound power measurements, ideally using an alternative measurement principle to radiation force. NPL have developed a new measurement concept: a thermally based, solid-state technique, whose novelty lies in its employment of the *pyroelectric effect*. Early results investigating the potential of the technique as a secondary standard method for measuring ultrasonic power have been encouraging and have been summarised in two recent publications [Zeqiri et al. 2007; Zeqiri and Barrie 2008]. A brief description of the concepts is presented here and the interested reader is referred to these two publications.

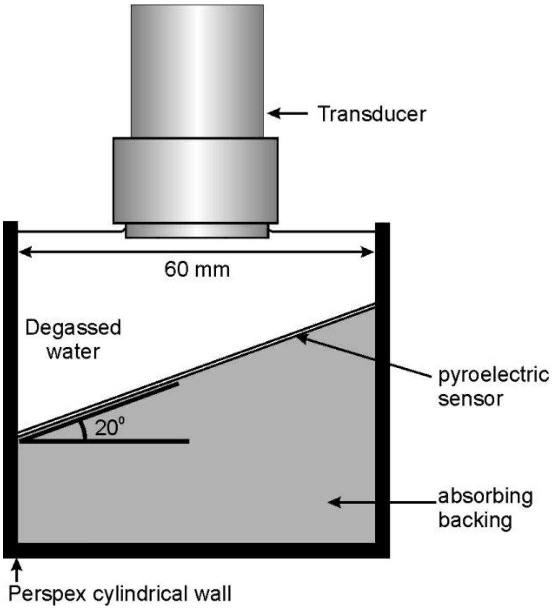


Figure 6.1: Applied ultrasound is transmitted through a thin *pvdf* membrane layer, where the majority of the acoustic power is absorbed within a short distance of the membrane-backing interface, leading to a rapid increase in temperature. For times immediately following transducer switch ON, the *local rate of temperature rise* at a point at the membrane-backing interface will be proportional to the acoustic intensity. By ensuring that the sensor is significantly larger in lateral spatial extent than the acoustic beam, its response immediately after switch ON, and following switch OFF, will be proportional to the local time-averaged intensity integrated over the acoustic beam, or the *total applied acoustic power*.

The sensor utilises the pyroelectric effect induced in a thin membrane of the piezoelectric polymer, polyvinylidene fluoride (*pvdf*). Piezoelectrically active materials are also pyroelectrically active, and whilst the former property has been exploited extremely successfully within ultrasonic metrology through the development of miniature hydrophones, surprisingly little use has been made of the pyroelectric effect. A pyroelectric material will respond to a temperature rise by developing a charge across its two surfaces. What is interesting about the pyroelectric effect, is that the response of a pyroelectric sensor can be configured to be proportional to either the *temperature rise* or the *rate at which the temperature increases*. Figure 6.1 shows a schematic of the sensor structure. The transducer is positioned over a water-filled well whose base comprises the stretched membrane of the pyroelectric sensor. The sensor itself is a layer of *pvdf* backed by a material that is extremely absorbing to ultrasound at the particular frequencies of interest.

Figure 6.2, shows a series of pyroelectric waveforms obtained from repeatedly switching the transducer ON and OFF, showing the good repeatability. The peak signal excursions at switch ON and OFF of the transducer, are related to the applied acoustic power.

Research continues to derive a better understanding of the limitations and potential of the technique. This has involved a number of aspects, ranging from the development of improved backing materials and modified electrode configurations along with the design and fabrication of associated instrumentation. One of the strengths of the method is its sensitivity, which suggests power measurement capability down as low as a few mW's..

Measurement of the acoustic output power is especially important for High Intensity Focused Ultrasound (HIFU) systems which is being used to treat certain cancers and other conditions by the non-invasive thermal ablation of the affected tissue. In planar unfocused fields, the use of a radiation force balance has been considered the most accurate method of measuring ultrasound power. However, radiation force is not strictly dependent on the ultrasound power but, rather, on the wave momentum resolved in one direction. Consequently, measurements based on radiation force become progressively less accurate as the ultrasound wave deviates further from a true plane-wave. HIFU transducers can be very strongly focused with F-numbers less than one: under these conditions, the uncertainty associated with use of the radiation force method becomes very significant.

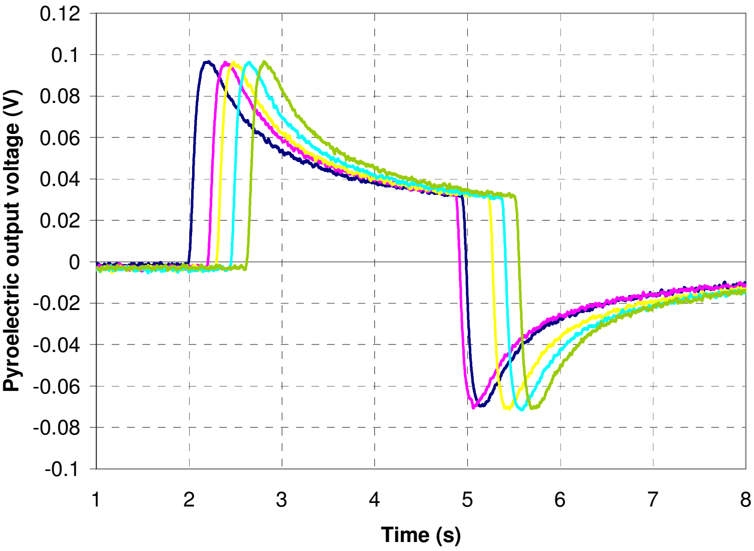


Figure 6.2. Comparison of the pyroelectric waveforms generated using a 3 MHz large diameter reference physiotherapy transducer, operating at a nominal acoustic power of 1 W. The transducer been switched ON and OFF five times over a 220 second period, to investigate the effects of warming of the sensor, particularly the backing material. In between transducer firings, the sensor has been to allowed to cool so that the pyro-electric voltage returns to zero. Over the time-frame of the batch of 5 measurements, the temperature increase of the water within the enclosure was minimal (<0.1 °C).

At NPL, a new method of determining power, appropriate for powers up to 500 W is being investigated. Instead of radiation force, the new method relies on determining the change in buoyancy caused by thermal expansion of castor oil inside a target suspended in a water bath. The change in volume is proportional to the incident energy and is independent of focusing or the angle of incidence of the ultrasound. The principles and theory behind the new method have been investigated, and the characteristics and construction of appropriate targets examined. Figure 6.3 provides a photograph of the set-up, identifying the key components. Development of the methodology is ongoing, but validation tests have been undertaken against conventional radiation force power measurements for a range of acoustic fields. Uncertainties of the method have been estimated and are approximately ±3.4% in the current implementation, with the potential to be reduced these further. The new technique has several important advantages over the radiation force method and offers the potential to be an alternative Primary Standard method. Figure 6.4 shows representative results for the validation exercise, illustrating the linearity of the method alongside traditional raditation force methods for a 1.08 MHz HIFU transducer generating power levels between 4 W and 140 W for 10 seconds.

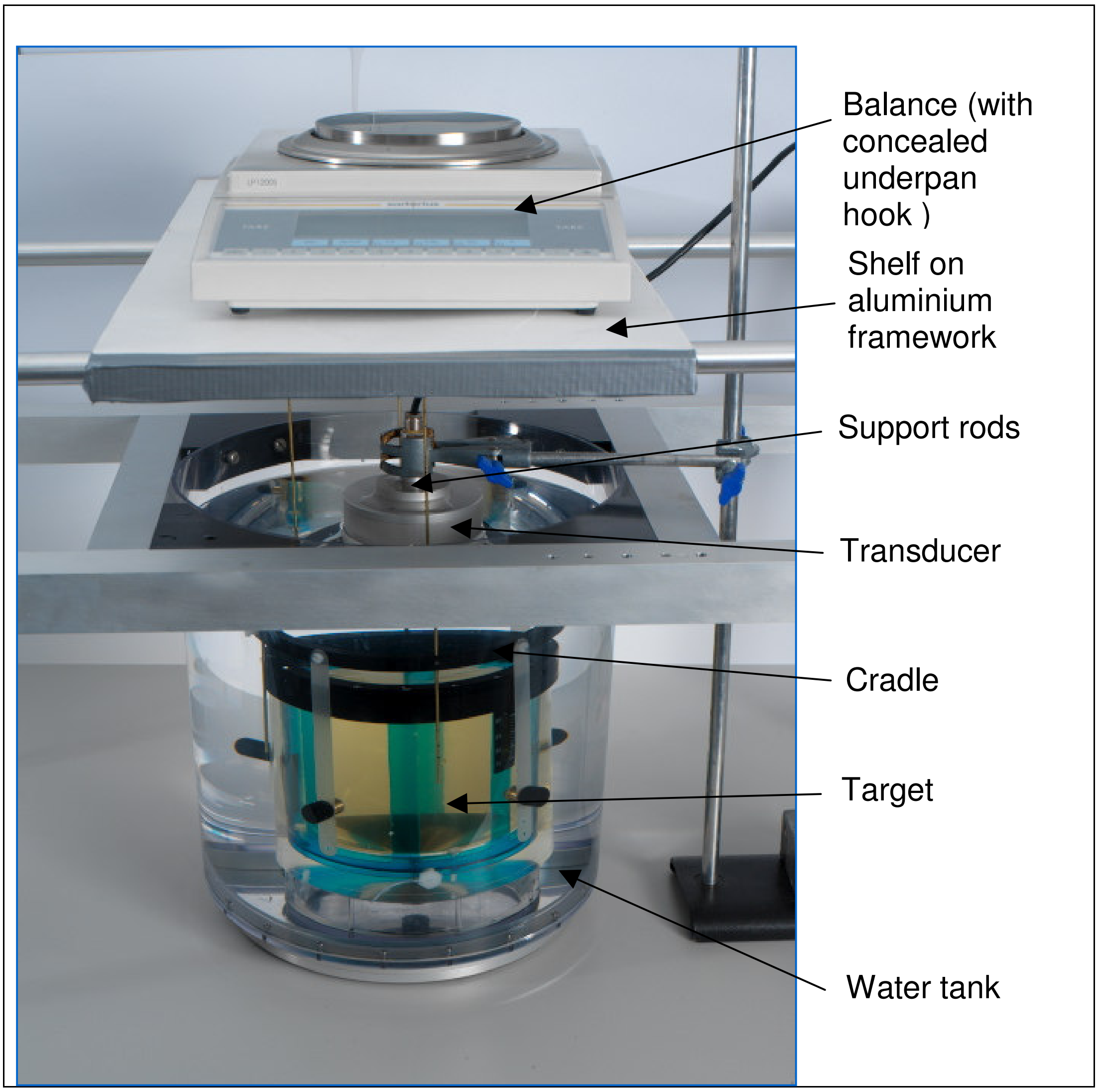


Figure 6.3. Photograph of the target and balance assembly.

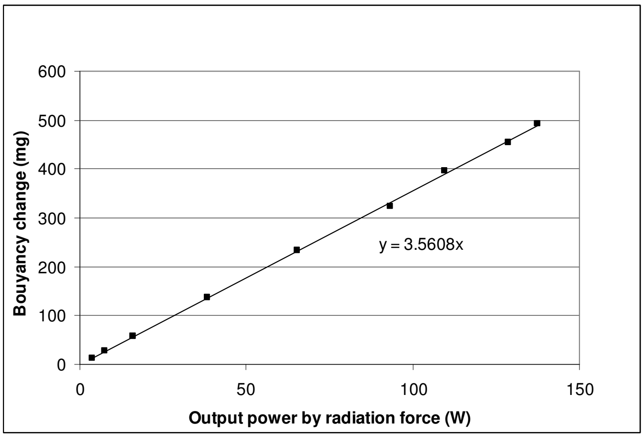


Figure 6.4. Linearity of buoyancy method is presented as a function of transducer output power for exposures of 10 seconds duration. Output power is simply calculated as the radiation force multiplied by the speed of sound, ignoring effects due to focusing, which will be approximately constant at all output levels.

Recently, NPL has embarked on a new research project to develop reference measurement methods for key acoustical properties of tissue-mimicking materials (TMMs). These materials are commonly gelatine-based solids or agar gels, and are employed within Test Objects to evaluate the imaging performance of medical diagnostic scanners. They are also used with the Thermal Test Objects developed at NPL for assessing ultrasound induced temperature rise generated by medical ultrasound equipment. Key Acoustic properties of the TMM relate to:-

- Attenuation or absorption;
- Speed of sound;
- Nonlinearity parameter (commonly termed B/A);
- Backscatter.

For a number of years, NPL has been able to provide reference measurements of the first two of these parameters to industry and hospitals, so current activity relates to developing measurement techniques for B/A and Ultrasound Backscatter. In support of this, a literature review of suitable measurement methods has been completed and early experimental work has concentrated on measurement of the Nonlinearity parameter using what is known as the Finite Amplitude Insertion Substitution (FAIS) technique.

The FAIS method involves monitoring the second harmonic component of a finite amplitude acoustic wave passing through a test sample of known thickness, and comparing this with the harmonic signal content generated through an equivalent path of water, a standard material for which the value of B/A is well established. Derivation of the value of B/A for the TMM requires additional measurements of the attenuation coefficient and speed of sound to be made. Diffraction of the applied acoustic field provides a significant Type B source of measurement uncertainty that must be corrected for. This commonly makes assumptions of the applied acoustic field. At NPL, the effect of diffraction will be reduced, or potentially eliminated altogether, through use of a piezo-electric hydrophone whose aperture (diameter) is significantly large to intercept the whole of the acoustic beam. Measurements have involved applying a 75 mm active element hydrophone that will resolve the plane-wave component in the acoustic field.

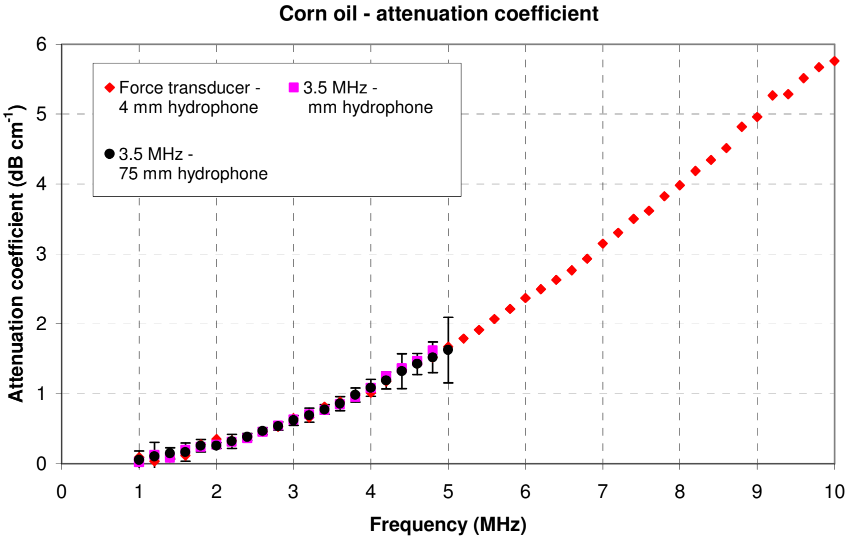


Figure 6.5. Measurements of the attenuation coefficient of corn oil, completed over the frequency range 1 to 10 MHz, using various measurements systems, at a temperature of 20 ± 0.5 C.

Progress to date has involved development of the measurement methodology aided by the fabrication of reference cells of two thicknesses employing 1 mm thick Perspex windows. Additionally, test fluids have been identified that have been used as reference standards for B/A within the literature: corn oil and ethylene glycol. Figure 6.5 shows measurements of the attenuation coefficient of one of the two reference fluids being investigated for determination of the nonlinearity parameter. It is anticipated that the work carried out at NPL will feed into a technical standard which specifies measurement techniques for tissue-like materials through IEC TC87 (WG8: Field characterisation).

Another significant area of metrology relates to the development of characterisation techniques for high power industrial applications. High power ultrasound and its associated phenomenon, acoustic cavitation, finds utility in many areas, from healthcare treatments through sonochemistry, wastewater processing and the degassing of molten metals. Despite this widespread application, there remains an absence of standardised measurement techniques applicable to such fields. Inertial cavitation, the agent responsible for many of the processes associated wih high power ultrasound, cannot be measured directly, but its occurrence and subsequent ‘intensity’ or ‘violence’ may be recorded through many observable secondary effects, such as microstreaming, free radical production, surface erosion, sonoluminescence and acoustic emissions.

To determine the spatial variation of inertial cavitation and to ascertain the threshold acoustic pressure beyond which inertial cavitation is repeatably observed in a multi-bubble system ideally requires simultaneous measurement of a suitable observable, along with a monitoring of the acoustic pressure driving the process. Such investigations have been undertaken at NPL using an acoustic emission approach, based on a bespoke sensor, signal detection system and cavitation reference vessel under development at NPL, UK. The establishment of a reference vessel is considered of strong importance to develop consensus on suitable measurement parameters for characterising inertial and non-inertial forms of cavitation, and to provide a single facility in which different sensors may be compared. Details of the research being undertaken are summarised in the paper by Hodnett and Zeqiri 2008, but key findings are presented in the following figures.

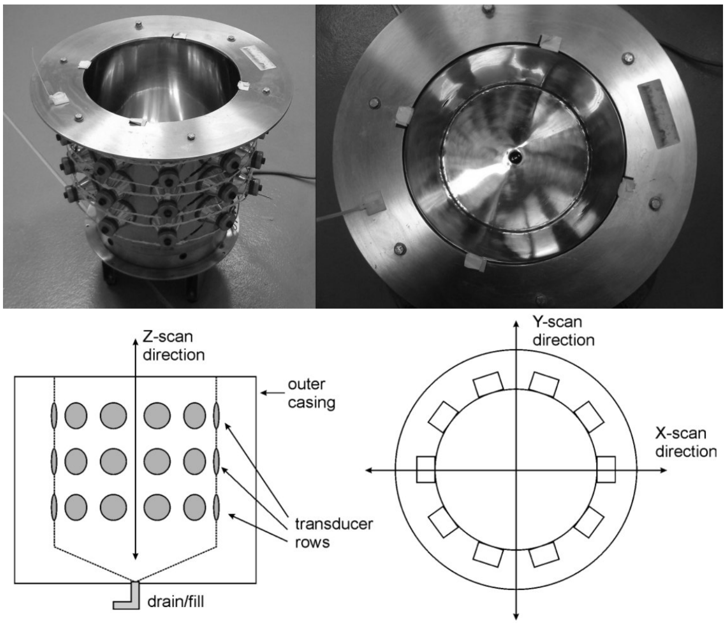


Figure 6.6. The acoustic cavitation vessel at NPL has been developed to provide a reference facility against which a range of cavitation detection techniques may be tested. The 25 kHz vessel has been the subject of extensive characterisation and study at NPL, and is based on a model P1800-25 Ultrasonic Processing Cell, produced by Sonic Systems (Somerset, UK). The figure provides a photograph and a schematic of the reference vessel structure: 30 nominally identical 25 kHz PZT transducers, each 50 mm in diameter, are epoxy-bonded to the vessel wall and radiating horizontally into the central volume.

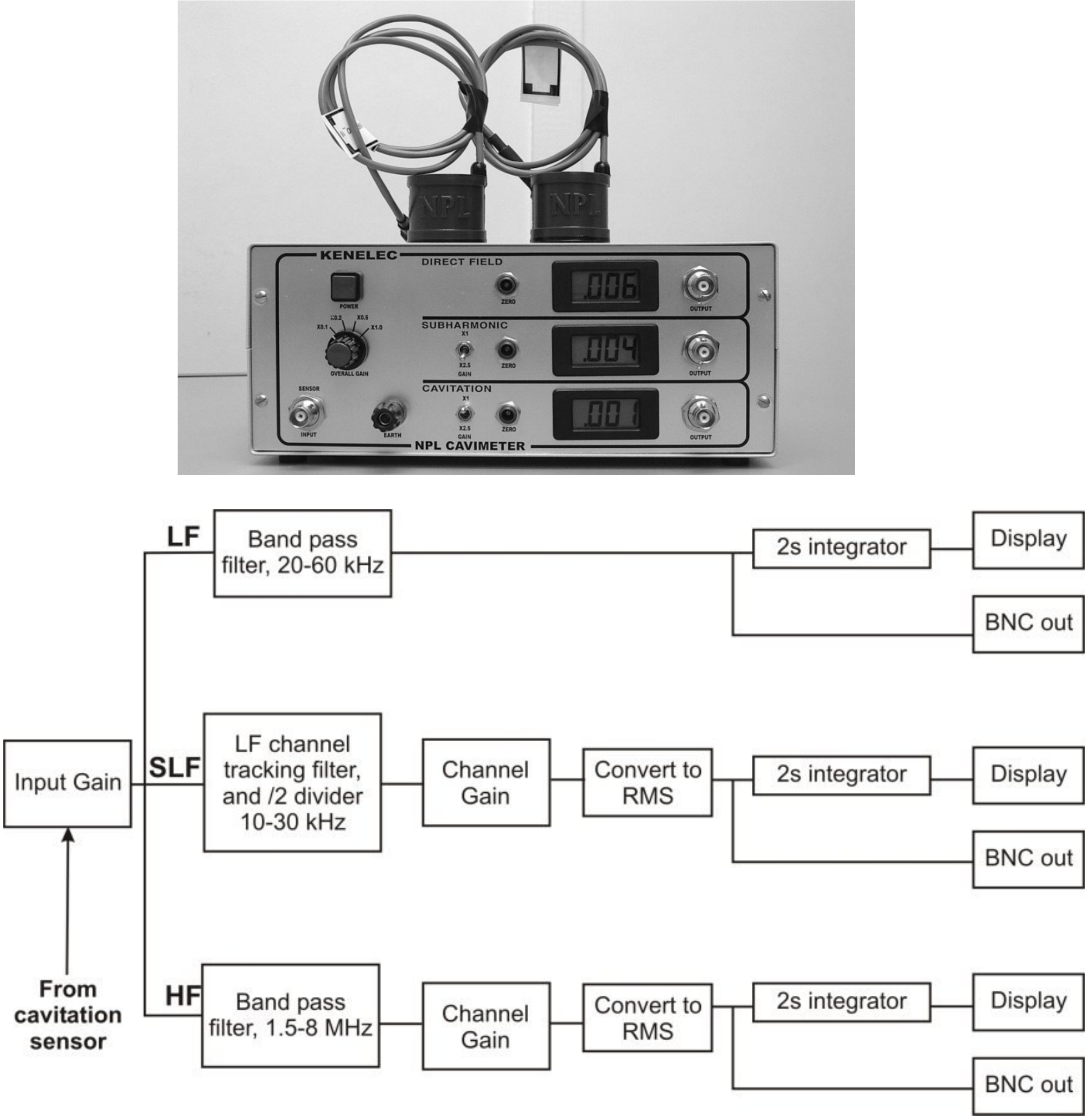


Figure 6.7. In order to characterise the cavitation field generated with the reference vessel, NPL has developed a cavitation sensor which detects acoustic emissions from oscillating and collapsing bubbles (Zeqiri et. al. 2003 a and 2003b). To compliment the specification and design of the cavitation sensor, a signal processing unit known as the NPL Cavimeter has been developed. Its functional specification is based on earlier prototypes and the unit processes the electrical output signals generated by the NPL Cavitation Sensor (NPLCS) simultaneously through three discrete channels, which examine specific characteristics of the received broad bandwidth signal. These are: ***Low frequency (LF) channel*** – designed to filter and display the received signal level in the range 20-60 kHz. ***Subharmonic-low frequency (SLF)*** channel – designed to take the frequency of the peak signal measured by the LF channel and detects the level of the signal at half this frequency (subharmonic). ***High frequency (HF) channel*** – designed to examine the broadband acoustic emissions above 1.5 MHz that arise from inertial cavitation. It has been shown previously that these signals originate from bubble events occurring within the body of the cylindrical sensor. A schematic of the architecture of the signal analysis is shown.

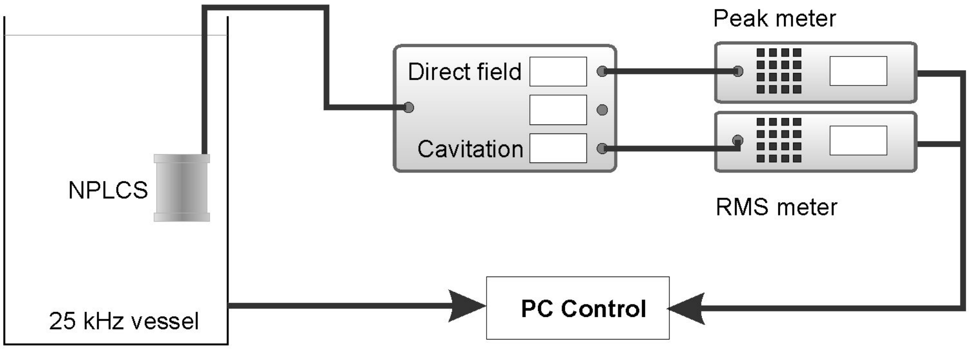


Figure 6.8. Schematic depiction of the experimental arrangement used for simultaneous measurement of the direct field alongside acoustic emissions from inertial cavitation.

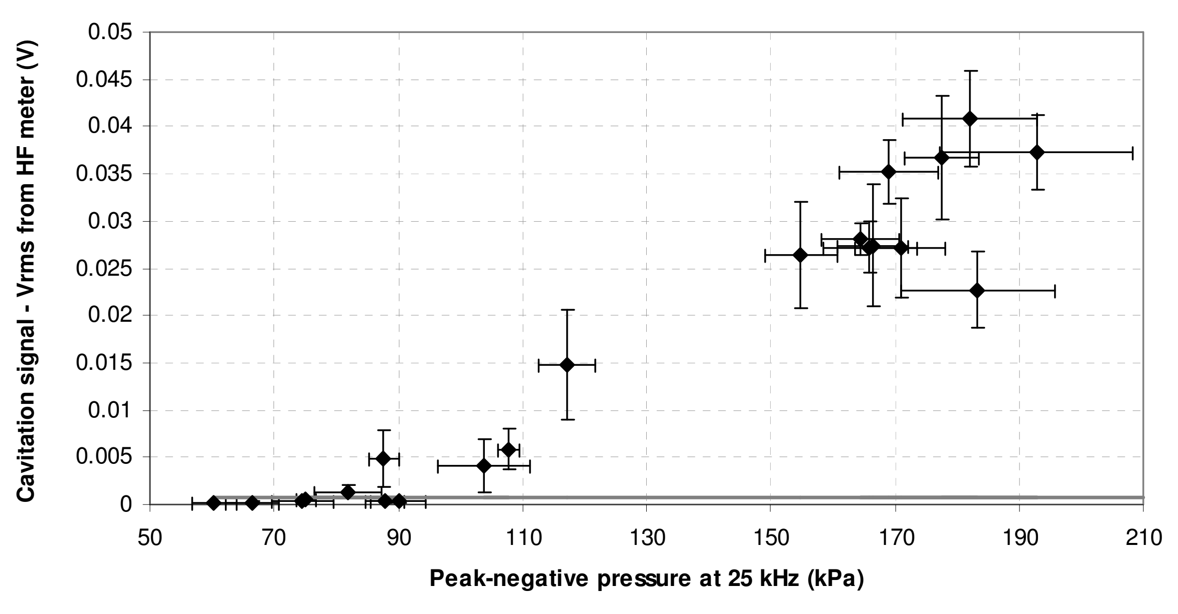


Figure 6.9. Correspondence plot of inertial cavitation signal (y-axis) and its variation with the peak-negative acoustic pressure (x-axis) measured ***simultaneously*** using the NPL Cavitation Sensor and Cavimeter, with the sensor aligned at a specific position with the reference vessel. Measurements have been used to derive a value for the threshold pressure for inertial cavitation (101 kPa ± 14 kPa), which constitutes the tension the liquid, in this case water, has to be put under to generate inertial (violent) cavitation. Uncertainty bars are presented as one standard deviation in the mean of four independent measurements made of both the cavitation signal and peak-negative acoustic pressure.

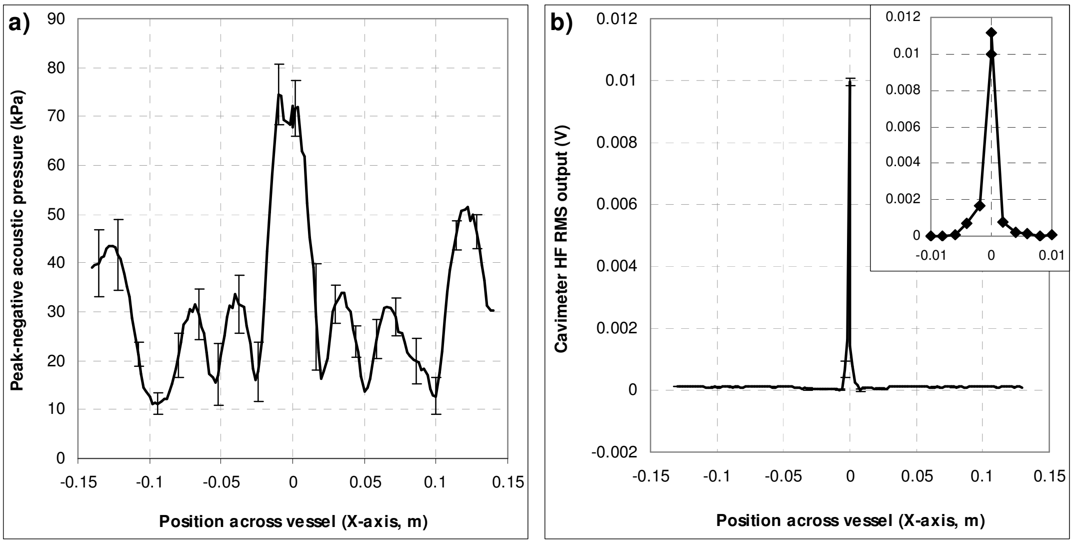


Figure 6.10. Average variation of peak-negative acoustic pressure with X-axis position across the reference cavitation vessel, determined using a Reson TC4038 hydrophone (left), and the corresponding inertial cavitation activity (right) determined using NPL Cavitation Sensor, at a power setting of 20 W. For clarity, error bars (expressed as one standard deviation in the mean of four independent measurements) are shown only for every seventh data point. The inset graph for the inertial cavitation activity plot shows an expansion of the data acquired close to the axis (-10 mm to +10 mm) to demonstrate the sharpness of the spatial variation, and illustrates that only over the central ‘focus’ of the vessel are the acoustic pressures high enough to generate inertial acoustic cavitation.

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