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REPORT

The Provision of Standards for Underwater Acoustics at Simulated Ocean Conditions by Use of the NPL Acoustic Pressure Vessel

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THE PROVISION OF STANDARDS FOR UNDERWATER ACOUSTICS AT SIMULATED OCEAN CONDITIONS BY USE OF THE NPL ACOUSTIC PRESSURE VESSEL

by

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ABSTRACT

In this report, a description is given of the work to provide standards for underwater acoustics at simulated ocean conditions in the UK. This has been achieved by the establishment of the NPL Acoustic Pressure Vessel (APV) which enables acoustic measurements to be made at hydrostatic pressures of up to just under 7 MPa (equivalent to about 700 m of water depth) and at water temperatures ranging from 2 °C to 35 °C. A description is given of work required for the commissioning of the APV. A full technical specification of the facility is also provided.

Also described are some of the measurements undertaken in the APV. These include absolute calibrations of hydrophones and projectors, and measurements of transducer impedance and directional response. Using the APV, each of these parameters may be determined as a function of water temperature and hydrostatic pressure. The results of the initial testing of some commercially available transducers are presented, demonstrating the significant variation that may be encountered in transducer response with environmental conditions.

Finally, a discussion is presented of some of the current limitations of the facility, and the proposed future work to improve its capability is described.

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CONTENTS

1. INTRODUCTION

This report gives a description of the establishment of standards for underwater acoustics at simulated ocean conditions in the UK. The acoustic work described was undertaken at the National Physical Laboratory (NPL) using the NPL acoustic pressure vessel facility (APV).

A historical account of the process required to establish the APV facility at NPL is given along with a description of the measurement techniques employed when using the vessel. The procedure used by NPL is described in brief with results being shown as a comparison against relative temperature and pressure changes, results are also shown for a comparison of calibrations conducted in both the APV and the NPL large open tank facility.

1.1 BACKGROUND

1.1.1 Requirement for underwater calibration

Underwater acoustics involves the generation, propagation and detection of sound in water. The main application areas in marine acoustics are the off-shore industry, defence and oceanographic science. UK industry is highly active in these areas, with the UK leading Europe in the production of underwater acoustical systems.

The defence-related applications of underwater acoustics include the classic applications related to anti-submarine warfare, but specific applications include active and passive sonar, mine-hunting, weapons guidance and counter measures [1,2]. In the post cold-war environment, interest has begun to move away from deep cold-water applications and toward applications in coastal waters, often in tropical climates. This provides its own challenges, one of which is ensuring the acoustic performance over a range of different water temperatures.

In the off-shore industry, not only are acoustic techniques used to detect the presence of hydrocarbon fuels beneath the ocean floor, but acoustic systems are commonly used in the extraction process, for example acoustic positioning systems are used to position vehicles underwater. In this industry, there is a clear trend toward working in deeper water as the shallower coastal waters become more heavily harvested. This is setting new challenges as the acoustic systems are required to work at greater depth and over greater ranges [3].

In oceanographic science, acoustic methods are used for sea-bed mapping, bio-mass evaluation, ocean acoustic tomography, and the study of marine life [4]. The oceans are perhaps the most under explored areas on the planet, with still comparatively little known about the deep ocean.

All acoustic systems use acoustic transducers to generate and detect sound. When products are sold, performance specifications quoted to the customer will often include absolute sensitivity (source level in the water is often of prime importance in determining range or detection limits), and the directivity (important for beam forming). Accurate measurement of these performance parameters is important for ensuring unambiguous specification and acceptance testing. Determining the acoustic performance requires acoustic measurements to be made [5], and for the measurements to be meaningful, they must be traceable to common standards of measurement [6,7]. In the UK these are provided by NPL which is the only

National Metrology Institute in Europe to be actively involved in underwater acoustics, placing the UK in a pivotal position in this field [8,9].

NPL currently provides a range of both calibration and testing services for the underwater acoustics community under the NMS Acoustic Metrology Programme. With the drive towards improved technical performance and the need for overall quality systems increasing, these measurements play an increasingly important role for the underwater industries such as oceanography, defence, fisheries and the off-shore oil and gas industries. Traceable calibrations and measurements are currently provided down to 1 kHz using the various NPL open tank facilities, the largest of which is a circular wooden tank 5.5 metres in diameter and 5 metres deep equipped with a precision positioning system which allows for accurate positioning of transducers and hydrophones. All calibration and testing carried out in the open tank facilities are limited to ambient static pressures and temperatures which differ from those encountered in applications in the ocean.

1.1.2 Demand for simulated ocean conditions

As underwater acoustic applications are required to operate at ever increasing depths, there is an increased demand to carry out acoustic measurements under full ocean conditions. This requirement has led to the introduction of small laboratory pressure vessels, which allow testing of acoustic devices at elevated hydrostatic pressure without the need for expensive sea trials. One of the limitations with this is that the relatively small size of the pressure vessels used restrict the range of measurements that are able to be made and can prevent acoustic measurements from taking place. Acoustically "transparent" pressure pots are also used in large laboratory test tanks and open water facilities to provide the capability for acoustic measurements to be made, but the transparency to the acoustic field is an approximation which is valid only at low frequencies [5]. One way to overcome the limitation of only being able to carry out measurements at low frequencies whilst at elevated hydrostatic pressure is to undertake calibrations in a larger closed pressure vessel, which has the ability to closely control both temperature and pressure. In addition, a test chamber of this type should provide an environment for working, which is large enough to enable free-field conditions to be realised down to a few kilohertz with the ability to provide adequate positional control for the transducers and hydrophones under test.

1.1.3 The need for the Acoustic Pressure Vessel

Having assessed the future need for standards at simulated ocean conditions [10-12], NPL commissioned the acoustic pressure vessel (APV) and it is now in operation at National Physical Laboratory (NPL). It provides a unique facility, as until recently, no commercially available acoustic test facility of this type existed in the UK. Following the establishment and commissioning, the vessel forms an essential part of the UK's National Measurement System for underwater acoustics. The facility will enable the development and dissemination of measurement standards, which in turn will provide industry with traceable calibrations and tests for underwater acoustical devices under simulated ocean conditions. Final testing of acoustic systems can often only be carried out at sea during a full sea-trial utilising specifically designed research vessels. Trials can be exceedingly expensive but are often necessary for final product testing and do allow for operation at the full working depth and at full power without the risk of cavitation. However, the APV is particularly effective for the acoustic testing and calibration of devices at the early to mid-stages of a project where the great expense and inconvenience of sea trials can be eliminated along with having the ability to control the experimental conditions, this is an important consideration for the most accurate measurement on individual transducers and hydrophones.

The APV is some fifty years old and has until recently been operated by the Underwater Reference Detachment (USRD) of the Naval Research Laboratory in the USA [13]. The relocation of USRD to the Naval Undersea Warfare Center in Newport Rhode Island led to the UK securing the test chamber through a collaboration between the Defence Evaluation Research Agency (DERA) and NPL. DERA/MOD purchased the vessel through a standing arrangement between DERA and USRD and it is provided on permanent loan to DTI and operated on-site at NPL. The acquisition of the APV was the only realistic opportunity for the UK to acquire such a facility as designing and building a vessel to an equivalent specification would have been outside of any budgetary constraints.

NPL started the process that would lead to the APV being operated in Teddington back in 1996 when USRD made it known to NPL that they were going to relocate to Newport, Rhode Island in 1998 [14]. It was made clear that both of the acoustic pressure test facilities operated in Orlando would not be required following the relocation and that it would be possible for the UK to secure the ownership of the test chamber if desired. The costs of removing the vessel from the building, which previously housed the test chamber, along with the costs associated with shipping the vessel to the UK and the establishment of the facility at NPL were borne by DTI as the basis of establishing a UK national facility. The facility is unique within the private sector in Europe and the first of its type to be made available for commercial use.

The project was undertaken in two phases: Phase one involved the de-commissioning of the vessel in the USA and transferring it to the NPL site; Phase two involved establishing the accommodation/services and commissioning the vessel at NPL. This process was concluded in July 2000 when the facility received the certificate for practical completion and was officially opened on 31 October 200 by Mr Alan Woolley, Director Eurofighter at MoD Defence Procurement Agency.

1.1.4 Establishment of the facility at NPL – Phase one

NPL staff examined the facility whilst still in operation at USRD to examine all aspects of the system, this enabled the serviceability of the vessel and associated systems to be assessed and specifications drawn up. The conclusion was that, whilst the system was operated perfectly in the USA, parts of the system would need to be replaced, in particular those associated with the heating and cooling circuits. A system design and operation review was also undertaken as part of the process to decide on how to operate and accommodate the facility at NPL. It was decided that the main elements of the existing equipment would be transferred from the USA with the most useful items being the primary pressurisation system consisting of six bladder accumulators and the antivibrational mounts, these items were put back into service as part of the final NPL system. During a further visit by NPL staff, the vessel was subjected to a three-day non-destructive test (NDT) examination. This inspection was carried out by a company that was approved by the insurers for the NPL site and consisted of inspecting all the critical weld areas on the vessel along with a pressure test to 1500 psi (1.5 times the operating pressure of the test chamber), the purpose of the examination was to prove that the vessel functioned correctly without any flaws being present that might effect the integrity of the vessel.

The vessel started the journey to NPL in May 1998 when it was fully decommissioned and removed from it's original location, this was achieved by removing a section of the building wall and extracting the vessel on a temporary rail system erected for the task. Figure 1.1 shows the vessel being prepared for lifting onto the low loader following the removal from the building that housed the vessel during operation at USRD.

Figure 1.1: Vessel being prepared for lifting.

The vessel was transported by road from Orlando to Jacksonville where it was loaded onto the Falstaff for the journey from USA to Southampton, England. The vessel is pictured in Figure 1.2 being hauled onto the Falstaff in readiness for the voyage to the UK, the trip took approximately three weeks and commenced in June 1998.

Figure 1.2: Vessel being hauled onto the Falstaff.

Once on British shores the vessel was transported by road to a business park in Southampton where it remained for two months. During that time the vessel was once again NDT inspected to confirm that no damage had occurred during the transportation period. Following the successful examination, new upgraded vessel supports were attached in place of the original ones and all exterior surfaces were refurbished with a special epoxy paint, which protects the vessel surfaces from the effects of condensation. Skilled craftsmen can be seen in Figure 1.3 removing the original vessel supports in preparation for the improved ones that took their place.

Figure 1.3: Outriggers being replaced.

The fully refurbished vessel was transported to a heated warehouse in Portsmouth where it was stored in secure conditions until further funding became available from DTI to progress to phase two of the project.

1.1.5 Establishment of the facility at NPL – Phase two

Before the vessel could undertake the final leg of the three thousand mile journey to NPL, partial completion of the engineering work was required. The building that now houses the acoustic pressure vessel facility was originally the plant room that contained the equipment to supply the site with compressed air, this had to be de-commissioned and re-installed in another location. In addition, the existing concrete floor had to be re-laid with the insertion of piles and pile caps of suitable strength to take the weight of the vessel and the roof that was later to be extended in height had to be removed to allow for the vessel to be lifted into it's final position by crane. Figure 1.4 shows the vessel being positioned inside the building where the facility is currently being operated.

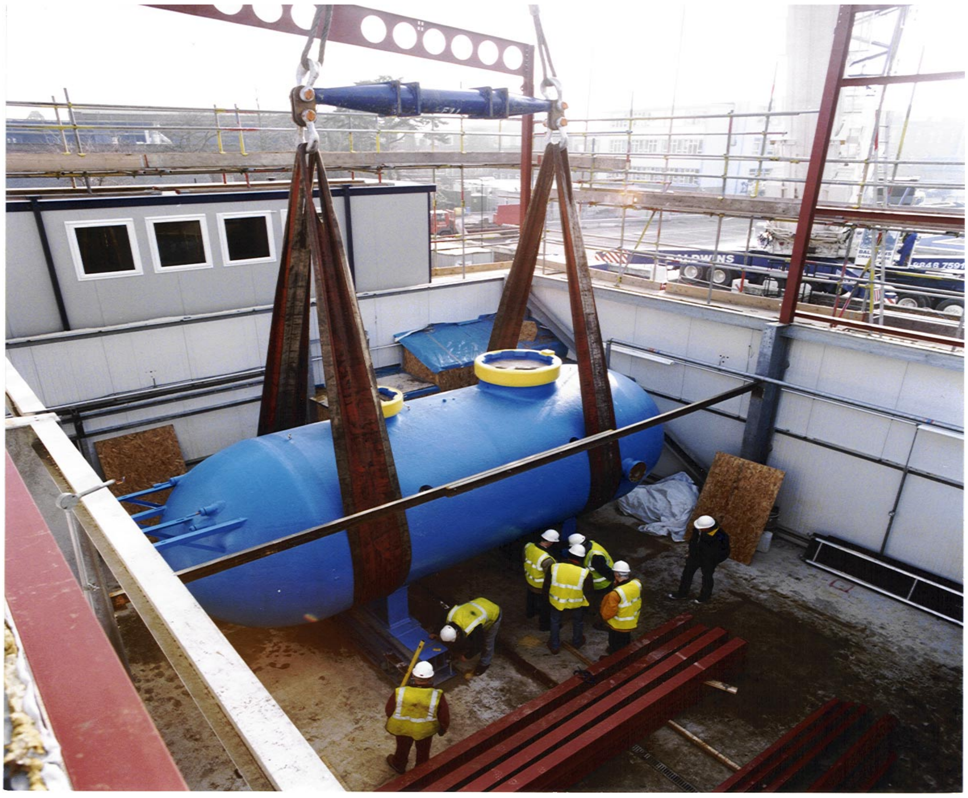

Figure 1.4: Vessel being positioned in new building on the NPL site.

The transportation of the vessel from storage in Portsmouth along with the preparation and site work associated with this particular lift took over two days. A police escort was required for the vessel when moving it to NPL and one of only two 1000 tonne cranes in the country was required for the lift. It arrived on several low loaders and took an entire day to assemble the crane.

With the vessel in position, all remaining installation work took place including the laying of the pipe runs to the vessel from the various supporting systems, the installation of the mezzanine floor level along with the removable sections of flooring. In addition, the new roof was finished and the office and control room areas were erected. During the commissioning stage, all pipe work was subject to pressure testing and was witnessed by the insurance company approved inspectors along with a final pressure testing of the vessel and all related safeties on the system.

A view of the finished facility taken from the ground floor level can be seen in Figure 1.5 the test chamber can be seen in the background encapsulated in the thermal insulating layer, which helps to maintain a constant water temperature within the vessel for prolonged periods of time. The Head tank, plate heat exchanger and pipe runs are also pictured along with the spare large lid and some of the acoustic absorbers which line the internal walls of the vessel.

Figure 1.5: Plant room area.

2. THE ACOUSTIC PRESSURE VESSEL

2.1. TECHNICAL DESCRIPTION OF THE APV AND FACILITY

The pressure vessel shown schematically in Figure 2.1 consists of a 7.6 m long by 2.5 m diameter tank and is manufactured from several sections of Firebox steel. The main cylindrical body of the vessel was constructed from two, four inch think plates that were both forged and rolled to give the correct thickness and shape. The two finished plates were welded together to achieve the specified vessel length. The domed end sections were made from several sections of steel, each section having a decreased thickness so that each domed end section is reduced to two inches thick. After fabrication, the completed domed end portions were welded to the cylindrical body to form the completed vessel shell. The vessel weighs 69,000 kg, this increases by approximately 32,000 kg when the 26,000 litres of water required to fill the chamber has been added.

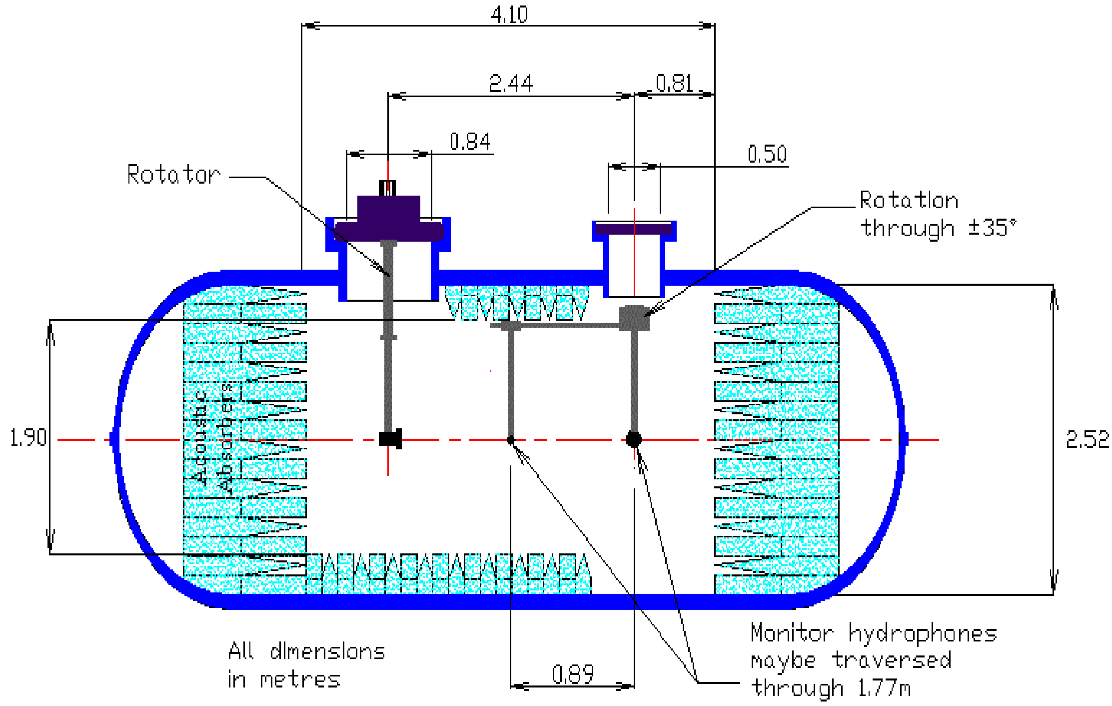

Figure 2.1: Vessel schematic.

Also highlighted in Figure 2.1 is the lining of acoustic absorbers that cover strategic sections of the interior vessel walls. The absorbers are manufactured from a damp mixture of pine dust and cement and form a material known as Insulkrete. The acoustic properties of the Insulkrete wedges are described in detail in reference [15] and appear to be quite suitable for this type of application, as their acoustic performance does not vary significantly over the operational specification of the test chamber. This would not be true for many of the modern acoustic panels that are manufactured from viscoelastic type materials since these tend to be tuned for particular environmental conditions and do not appear to be effective over the entire operational range of the vessel.

Figure 2.2: Vessel interior.

Figure 2.2 shows a photograph of the Insulkrete wedge installation within the APV. The view is looking in the direction of one of the hemispherical ends, the length of the wedges that line the interior of the vessel vary from approximately one to three feet in length.

There are two circular ports situated on top of the test chamber allow access for devices, materials or any items under test. The ports have access diameters of 0.50 m and 0.85 m respectively; the large lid is capable of supporting devices weighing up to 350 kg and has a rotator shaft positioned through it's centre. This allows for any items attached to the mounting flange situated at the bottom of the shaft to be rotated through a full 360° while the vessel is at full pressure. With the large lid weighing approximately 1 tonne, any mounting processes involving the large lid are carried out with the lid removed from the vessel port and seated securely on the lid rack system adjacent to the port. The small port does not have the ability to mount devices directly to it but allows access to position pre-mounted devices to the internal slideway system. The slideway system has the capability to hold two lighter devices via mounting cradles, one of which has the ability to be rotated under control through approximately ± 30°. This is primarily used to line devices up acoustically prior to measurements taking place, as it is not possible to carry out this rotation while the test chamber is at pressure. The second cradle attached to the slideway is at a fixed separation distance from the main cradle and does not have the ability to be rotated. The entire slideway system has the capability to be traversed along the length of the test chamber enabling positioning of devices to separation distances in the range 1 m to 2.5 m.

All mounting of devices to the mounting poles takes place outside of the vessel with the adjustments for the different device heights calculated and applied to the final mounted device lengths, this ensure that the devices are all on the same centre line when in their respective measurement positions within the tank. The lids are lowered into position by use of the overhead crane that allows for fine continuous control of speed. Once in position, the pneumatic actuators that act as the lid closure mechanisms close the port covers. The device cables are fed out from the vessel through the cable feed-through assemblies situated on top of each lid and then interfaced with the scientific instrumentation situated in the control room. Following this action, the cable feed-through assemblies are tightened to a specific torque setting to prevent any cable extrusion from taking place while the vessel is under applied hydrostatic pressure. In addition to the standard method of feeding device cables through the stuffing box assemblies, it is possible to utilise any one of six, two-piece plate assemblies that are situated around the main diameter of the vessel wall. The plate assemblies, which are a new addition to the test chamber since arriving in the UK, each cover an eight-inch hole through the vessel wall. It is believed that the original intention was to utilise the six holes for viewing the inside of the vessel during testing. It is believed that this was never implemented and the holes were covered with blank plates. The inner plate of the new two piece plate assemblies are designed to be easily removable giving the ability to modify the plates to suit particular requirements that may fall outside of the limitations of the standard feed-through assemblies positioned on the two lids. For example, it is now possible to mount bulkhead connectors that match customer devices to the plate and with modification, it will also allow devices having large cable diameters to be fed through into the vessel.

Figure 2.3 Mezzanine floor level.

A view in the direction of the control room can be seen from Figure 2.3. Both ports can be seen along with the lid closure mechanisms, lid rotator motor and gearbox, cable feed-through assemblies and all necessary lid attachments required to operate the vessel. The pre-soak tank and control room windows are also visible in the background.

To avoid air bubbles on either the acoustic wedges or other surfaces, the water in the vessel is maintained air-free by being evacuated prior to and during the filling processes. Once filled, the water temperature can be controlled over the range 2 °C to 35 °C using the water circulation system. Two boilers, each designed for a maximum duty of 200 kW and a chiller designed for a duty of 240 kW provides the power required to meet this operational temperature range. Any temperature changes must occur prior to any pressurisation cycles taking place as temperature change may only occur while at atmospheric pressure. Pressurisation is generally achieved by using two high-pressure pumps. In addition to the pumps, five dry-air accumulators are used when either *quiet* conditions or a rapid rate of change is required, they can be seen along with the high-pressure pumps in Figure 2.4. The rate of pressurisation/de-pressurisation is controlled via a bi-directional flow control valve situated in the high-pressure pipework between the pumps and the test chamber and is continually monitored and adjusted by the facility's control system.

Figure 2.4: High pressure plant equipment.

Before any pressurisation can occur the vessel must be purged to eliminate any air pockets that may be present in the vessel, particularly around the lid areas. This is carried out by using the high-pressure pumps to force water into the bottom of the vessel and force any remaining air out through the lids and vents on the top of the tank and. Water sensors in the vent lines indicate when water is present. For safety reasons, it is only possible to proceed with pressurisation cycles when this state has been reached. A full operational specification is set out in Appendix 1 of this report. The ability to provide acoustic and mechanical isolation from plant equipment and ground borne noise is further enhanced by the vessel being seated on air mounts; this provides the ability via an air compressor to raise the vessel before measurements take place so that there is no coupling between the test chamber and any other surfaces such as the ground or first floor area. From the plot shown in Figure 2.5, it can be seen that it is possible to achieve environmental conditions lower than sea state zero within the tank

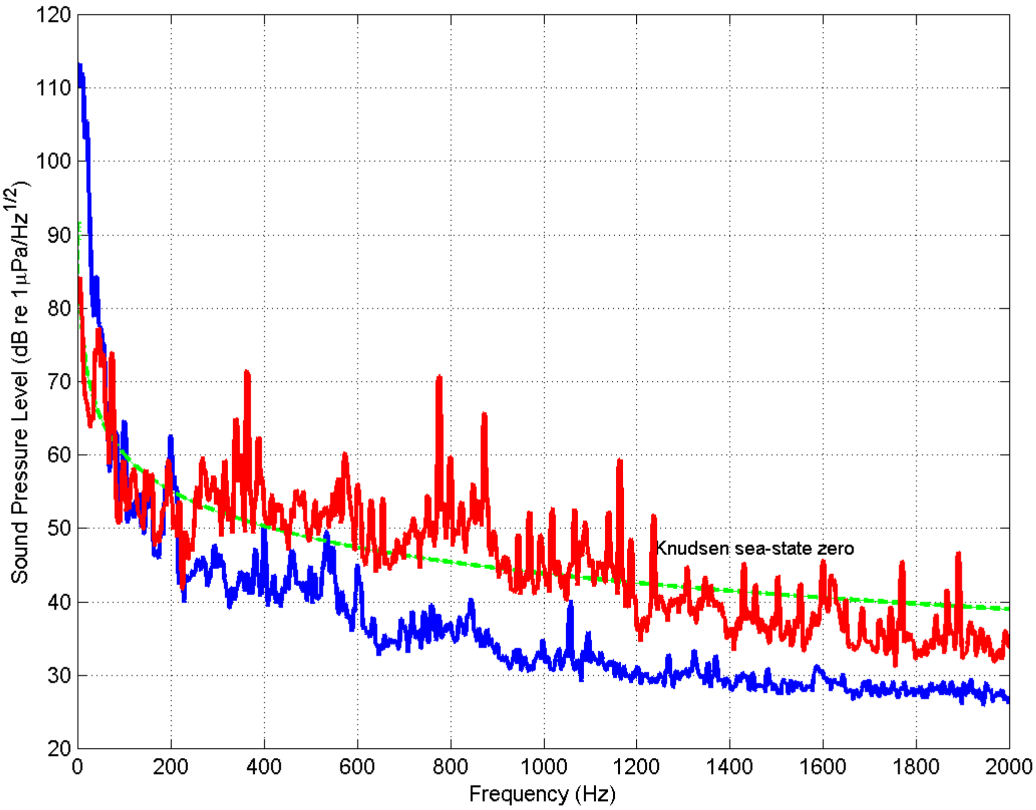

Figure 2.5: Ambient noise in the APV measured using a low noise hydrophone. The red curve was measured without the anti-vibration mounts active, and the blue curve was measured with the anti-vibration mounts powered up.

A versatile operator control and monitoring system incorporating all non-acoustic tasks is run through a PC-based control system and is shown in Figure 2.6. This interfaces with a programmable logic controller (PLC) that in turn operates the individual plant items. The control system provides a live status of every pieces of plant equipment, displaying vital information such as tank water levels, flow rates, pressures, temperatures along with valve and pump conditions.

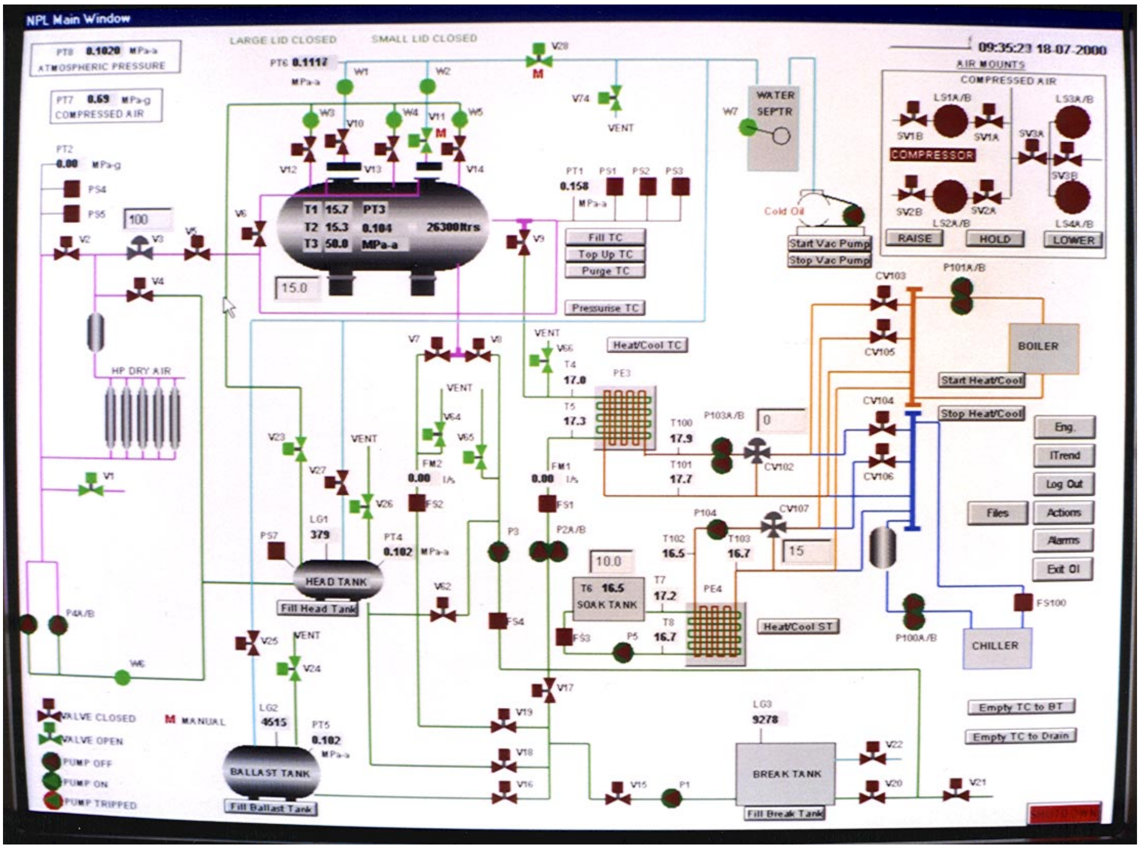

Figure 2.6: Display of facility control system.

Additional features of the system enable the operator to have a wide and versatile control of all operations with a built in protection to prevent the operator from making unintentional changes or putting the system into an unsafe condition, this is aided by the presence of a pass word system that will only allow entry to the system at certain levels depending on the users system knowledge. There are three levels of entry, each allowing only specific tasks to be carried out, the highest-level allowing the individual operation of each piece of plant equipment to take place within the safety constraints of the system along with access to diagnostic screens. It is possible to access pre-programmed sequences that cover standard operations from the main display window, these include such tasks as pressurising the test chamber, pressure profiling and altering the test chamber temperature, these tasks can be carried out by operators who have minimal knowledge of the facility. The system also saves all the information gathered from the plant equipment for a seven-day period, this is a useful function as it enables plots to be presented and saved showing variations of pressure and temperature against time. Included within the scope of the control system is the control of the pre-soak tank. It is a small (1 m by 2 m) open tank situated on the mezzanine floor level and the water temperature within the tank can be controlled independently from the main test chamber over the range 2 °C to 35 °C. This enables devices to be pre-conditioned at temperatures that may vary from that of the vessel prior to measurements taking place.

3. MEASUREMENT METHODOLOGY

3.1 METHODOLOGY FOR TRACEABILITY

In order to make the most effective and efficient use of the APV, some thought is required as to the methodology to be used to disseminate standards. For some of the parameters that are required to characterise an electroacoustic transducer, for example directional response, only relative measurements are made with the results normalised to some reference direction, typically the maximum response angle. However, where the absolute sensitivity of a hydrophone or projector is needed, a number of options are available.

Calibrations of underwater acoustic transducers at simulated ocean conditions could be undertaken using an absolute method such as the method of three-transducer spherical-wave reciprocity [16]. This method has the advantage that it can be implemented with high accuracy and does not require a reference transducer that has already been calibrated. In some cases, such an approach is appropriate and the results of initial free-field reciprocity calibrations in the APV are presented in Section 5. However, this method is time consuming to perform, requiring at least three separate measurement arrangements. In the APV, this presents particular logistical difficulties since a lid must be removed before a transducer can be replaced. Although some accuracy is sacrificed, an alternative approach is to rely on relative calibration methods such as a comparison or substitution method. This allows the calibration to be performed much more rapidly, enabling a more efficient use of time in the APV.

One disadvantage of relative calibration methods is that reference transducers are required that have been calibrated over the full range of environmental conditions (temperatures and pressures) that are to be encountered in calibrations of unknown devices. This requires a great deal of initial work to characterise the reference transducers before calibrations may be attempted for customers. In addition, it is not very satisfactory if the reference transducers used vary greatly in performance with temperature and hydrostatic pressure since large corrections will then have to be applied to the reference sensitivities and this may introduce large uncertainties into the calibration process. So the ideal reference transducers would have relatively stable responses with temperature and pressure.

Unfortunately, relatively little reliable information is available on the performance of commercially available hydrophones and projectors as a function of temperature and depth. Since it would be prohibitively time consuming to make a systematic assessment of every available candidate transducer before deciding on the most appropriate devices to use, a decision was made to adopt three transducers from USRD as reference devices in the APV.

Of the three transducers, two are projectors (the F27 and F30) and one is a hydrophone (H52). They have been designed to be stable with temperature and depth and their performance has been evaluated by calibration in the Acoustic Pressure Tank Facility (APTF) at USRD. The approach taken in using the transducers at NPL is as follows:

- NPL undertakes absolute calibrations of the three reference transducers using the primary standard method of free-field reciprocity in the NPL Open Tank Facility

(OTF) to provide the reference sensitivity of the transducers at ambient pressure and 18 °C;
- NPL makes use of the data supplied by USRD for the variation of response of the transducers with temperature and pressure.

By this approach, the reference sensitivities for the three transducers are traceable to primary standards in the UK, but the coefficients used to correct the reference sensitivities for the variation in response are derived from the USRD data. It is intended that in due course NPL will fully characterise the three transducers and derive new values for the coefficients to compare with the USRD data.

3.2 THE USRD TRANSDUCERS

The calibrations of the USRD transducers at NPL in the Open Tank Facility (OTF) are shown in the following figures. Figure 3.1 and 3.2 show the transmitting voltage response of the F27 and F30 in the range 1-40 kHz and 10-150 kHz respectively. Figure 3.3 shows the receive sensitivity of the H52 hydrophone in the frequency range 1 kHz to 200 kHz. These calibration data are used as the reference data for the three transducers when they are used in relative calibrations. When calibrations are undertaken using the reference transducers at temperatures and pressures other than those that pertain to the reference calibrations in the OTF, corrections are made to reference sensitivities to account for the slight dependence on environmental conditions.

The performance specification of the USRD transducers is given in the USRD transducer catalogue [17]. Salient features are described in Appendix 2 along with the values for coefficient of pressure and temperature variation derived by NPL form the USRD data.

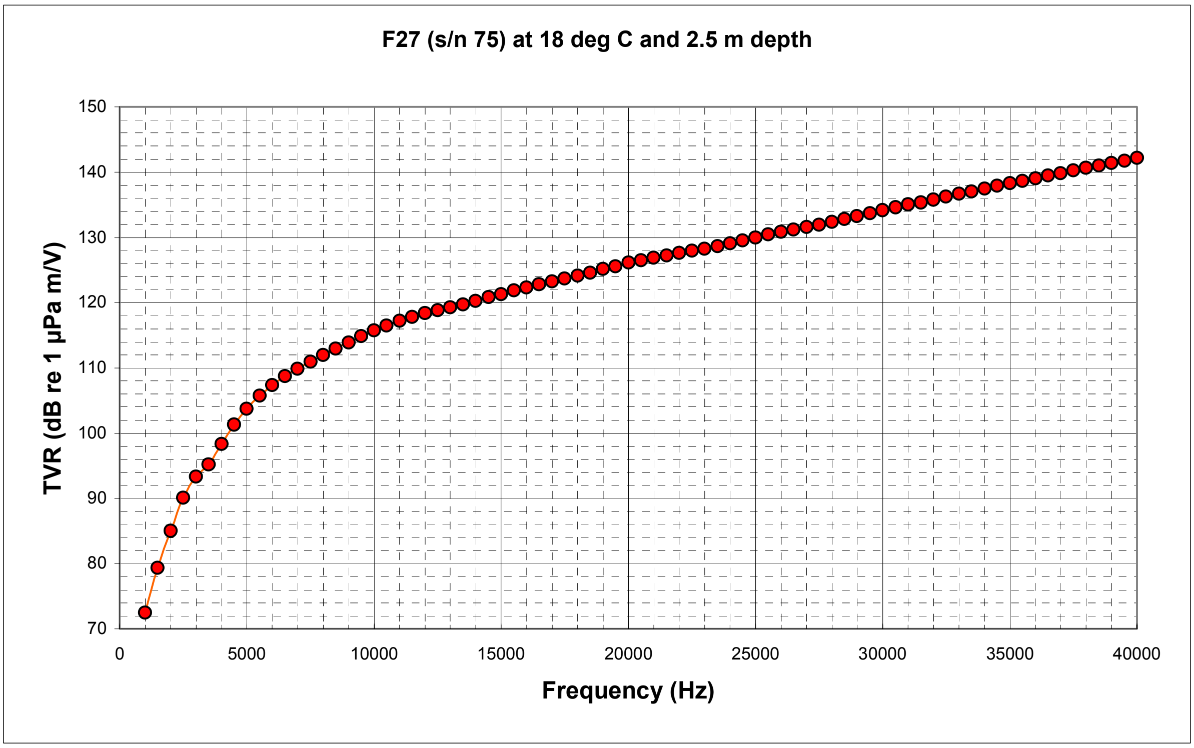

Figure 3.1: The transmitting voltage response (TVR) of the F27 calibrated in the NPL OTF.

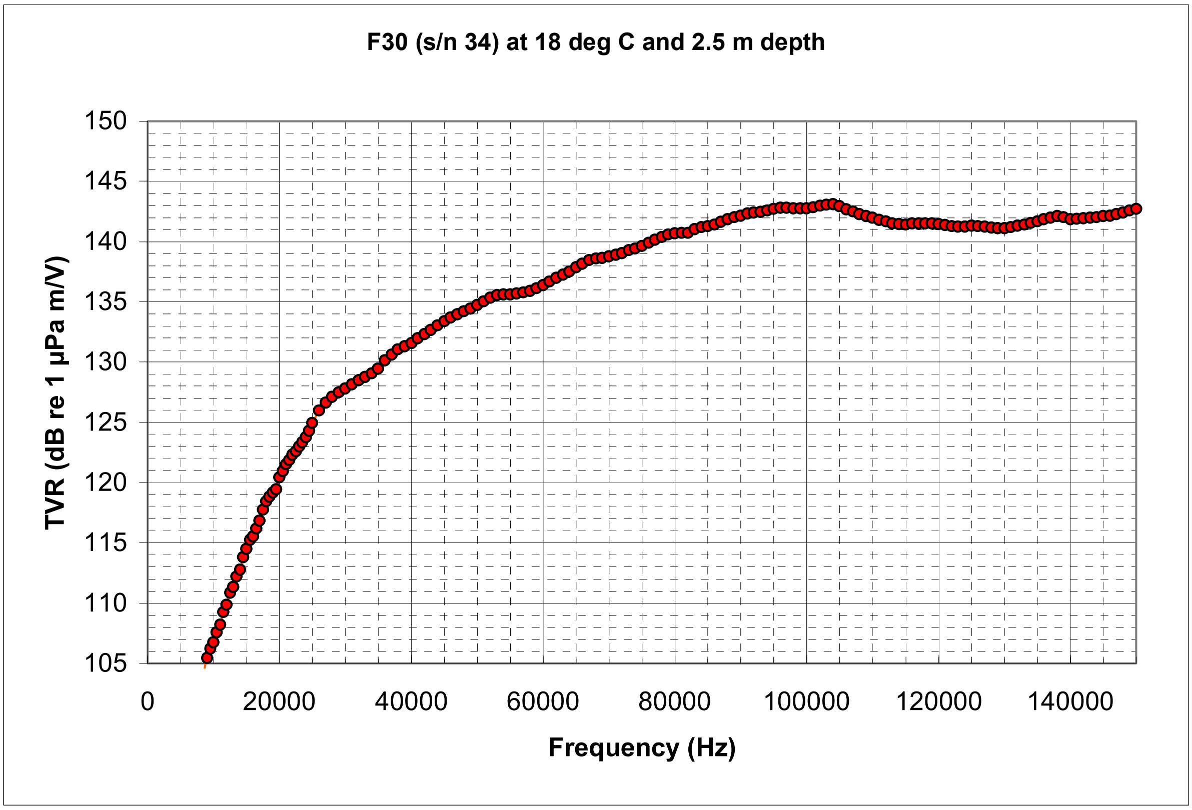

Figure 3.2: The transmitting voltage response (TVR) of the F30 calibrated in the NPL OTF.

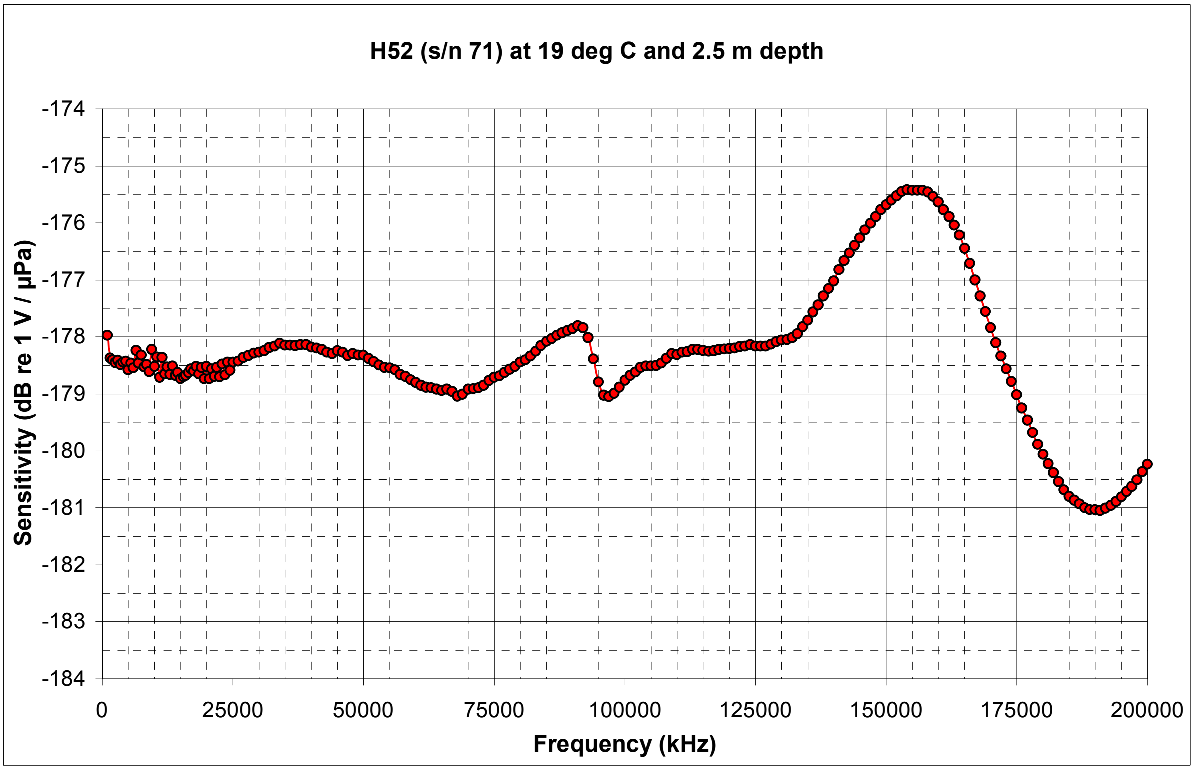

Figure 3.3: The receive sensitivity of the H52 calibrated in the NPL OTF.

4. MEASUREMENTS OF ELECTRICAL IMPEDANCE AND DIRECTIONAL RESPONSE

4.1 ELECTRICAL IMPEDANCE

4.1.1 Introduction

The electrical impedance or admittance is an important parameter describing the behaviour of underwater electroacoustic transducers [5, 18]. The variation of the electrical impedance of a device with pressure and temperature may be a useful indicator as to its performance as a projector or hydrophone when subjected to those same changes in pressure and temperature. However, this has had limited investigation. The electrical impedance of a device at ambient pressure and temperature can be measured in the NPL open tank facilities using a Hewlett Packard HP4192A impedance analyser under the control of in-house software. While the measurement of electrical impedance in the pressure vessel requires the same basic procedures, there are differences in the mounting arrangements and the measuring instrument used, necessitating modifications and additions to the existing software.

4.1.2 Instrumentation and software

The impedance analyser used in the pressure vessel facility is the Hewlett Packard HP4294A. This is an improvement over the older HP4192A in terms of measurement speed and capability. Having a display, as opposed to a simple numerical readout, enables a full admittance/impedance loop to be measured and displayed directly on the analyser. The analyser is controlled by in-house measurement software that currently performs stepped frequency measurements of conductance and susceptance over a pre-defined range of frequencies. The measured data is transferred to the PC and displayed in any one of a number of user defined formats, for example in the form of an admittance loop. A zeroing routine enables correction for the effects of any extension cable used during the measurements.

4.1.3 Mounting considerations

For an electrical impedance measurement, the device may be mounted on the large port or either of the two small port cradles. Since both impedance analysers use continuous wave sinusoidal signals, consideration has to be given to positioning of the device within the vessel since, especially for low frequency omni-directional devices operated close to resonance, the measurement may be affected by reflections from the pressure vessel walls. Adjustable mounting poles are used enabling the device to be positioned at the optimum depth to avoid reflections from the top and bottom of the vessel. For directional devices, some improvement may be achieved by rotating the device to different position to avoid a direct reflection.

4.1.4 Results

The electrical impedance of various transducers has been measured over a range of pressure and temperature, and the results plotted in the form of an admittance loop (susceptance versus conductance).

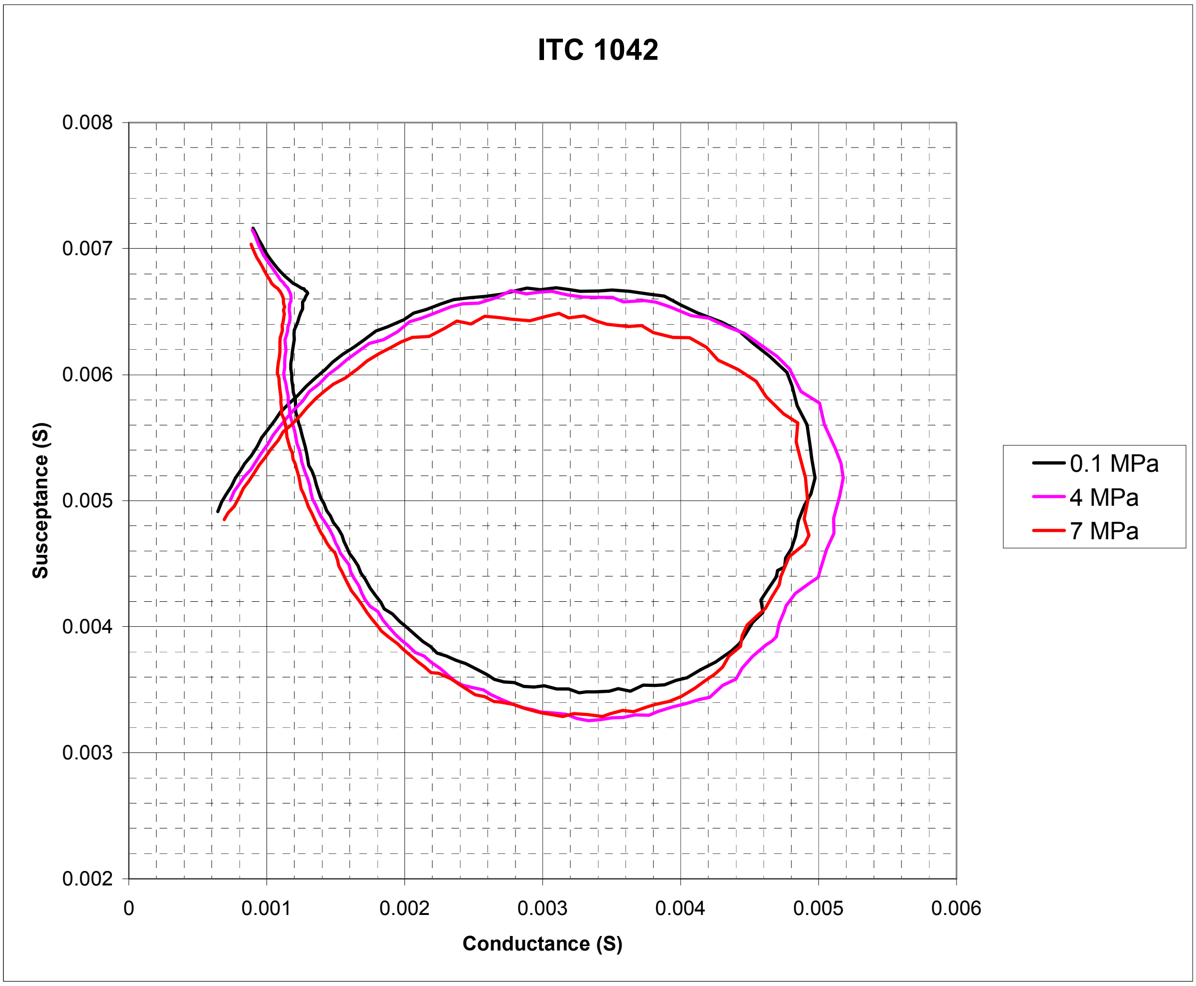

Figure 4.1: Admittance plot of ITC 1042 hydrophone, 50 kHz – 140 kHz.

Figure 4.1 shows an admittance plot of an ITC 1042 spherical hydrophone measured over the frequency range 50 kHz to 140 kHz, a range which includes the hydrophone's main radial resonance. The measurement has been repeated at 0.1 MPa (no applied pressurisation), 4 MPa and 7 MPa (maximum pressure), and the results indicate that the electrical characteristics show relatively little change when the hydrophone is subjected to changes in pressure.

Note that the hydrostatic pressures reported are absolute pressures, so ambient pressure (no extra applied pressure) corresponds to 0.1 MPa and not zero pascals. This is the case with all the reported hydrostatic pressures in this report.

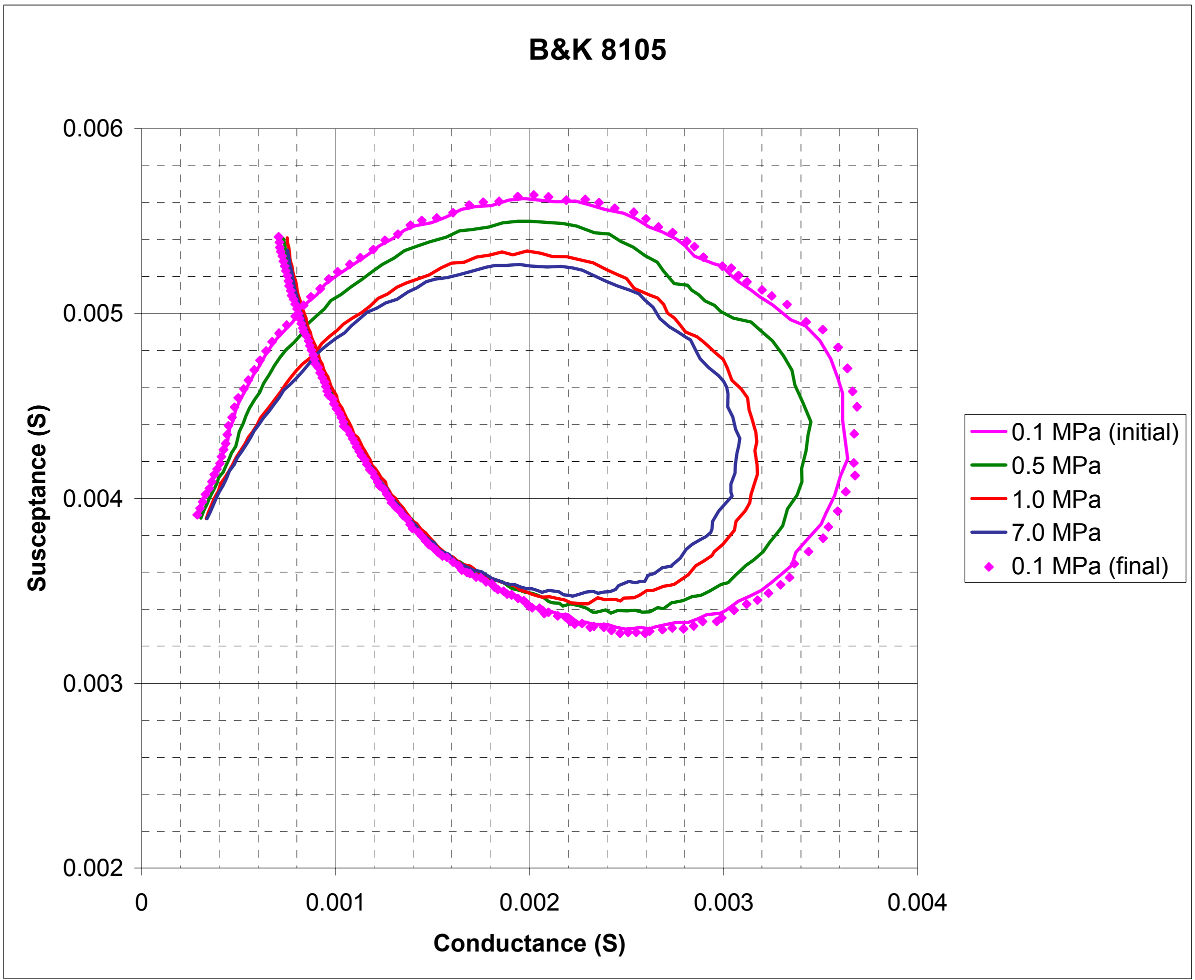

Figure 4.2: Admittance plot of B&K 8105 hydrophone, 75 kHz – 175 kHz.

Figure 4.2 shows an admittance plot of a B&K 8105 hydrophone measured over the frequency range 75 kHz to 175 kHz (again this covers the radial resonance). The measurement has been repeated at 0.1 MPa, 0.5 MPa, 1 MPa and 7 MPa. Although this is also a spherical hydrophone similar in construction to the ITC 1042, the way in which its electrical characteristics change with pressure is noticeably different; there is a relatively large change as the pressure increases up to 1 MPa, but then the hydrophone seems to remain fairly stable as the pressure increases all the way up to 7 MPa.

One possible explanation for this behaviour may be that there is some compliant material (e.g. air) in the hydrophone moulding, which is effectively fully compressed by the time the pressure reaches 1 MPa. At pressures greater than this, relatively little further compression takes place resulting in only a small change in the size of the admittance loop. To check that these changes were not the result of permanent damage to the hydrophone caused by the pressurisation, the measurement was repeated after the vessel had been depressurised. This is displayed as a dotted line and can be seen to be very close to the initial pre-pressurisation measurement. Similar results have been obtained with two different examples of the B&K8105 hydrophone.

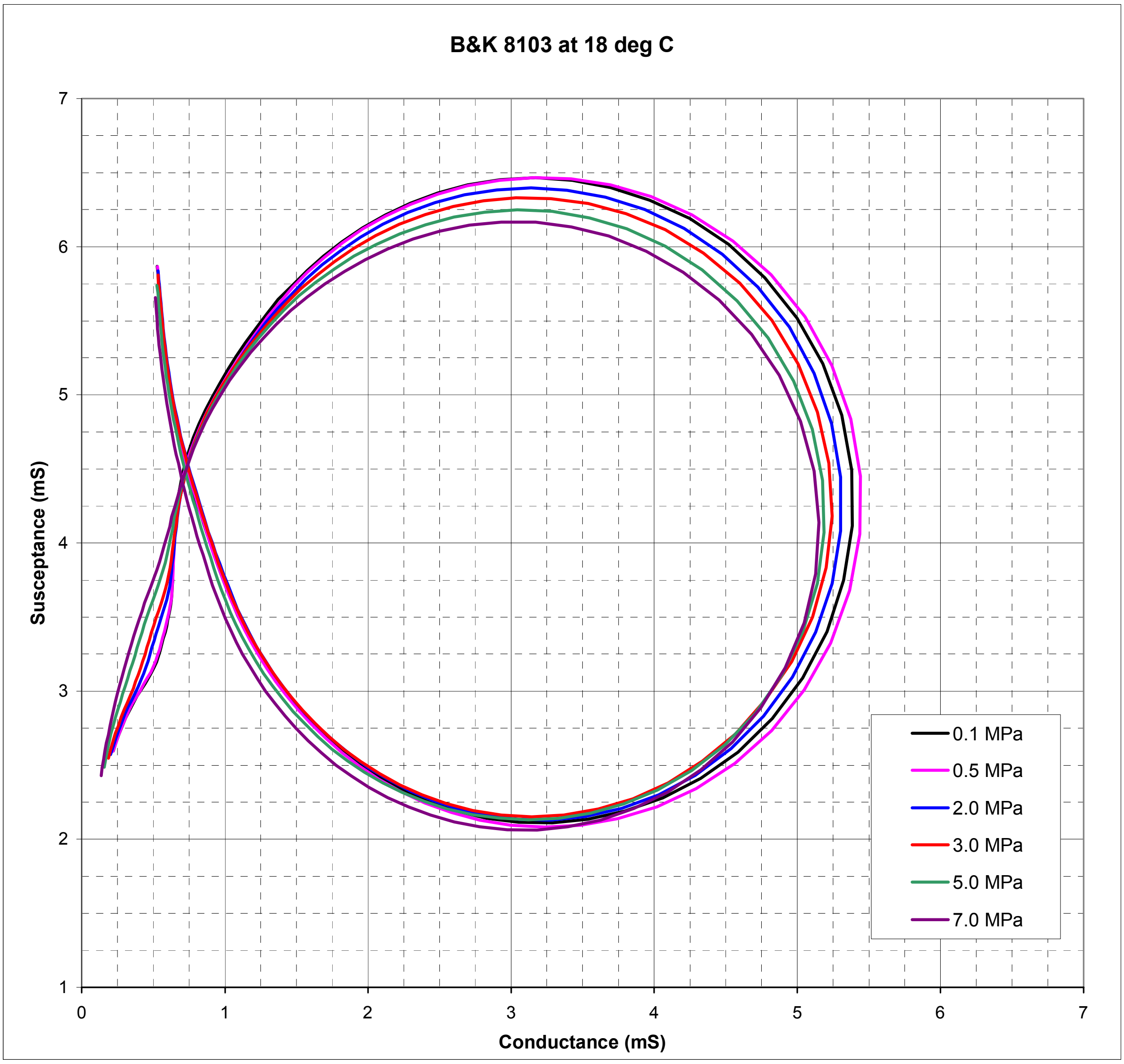

Figure 4.3: Admittance plot of B&K 8103 hydrophone, 100 kHz to 370 kHz.

The conductance and susceptance of a B&K 8103 hydrophone was measured over the frequency range 100 kHz to 370 kHz and at various pressures from 0.1 MPa to 7 MPa. Two resonances occur within this frequency range for this cylindrical hydrophone: a radial resonance at approximately 125 kHz and a length mode resonance at approximately 250 kHz.

The effect of pressure on the admittance loop is shown in figure 4.3, and it can be seen that there is a gradual reduction in the size of the length mode loop and a flattening of the radial resonance as the pressure increases. Like the ITC 1042, the change is relatively small and proportional to the increase in pressure.

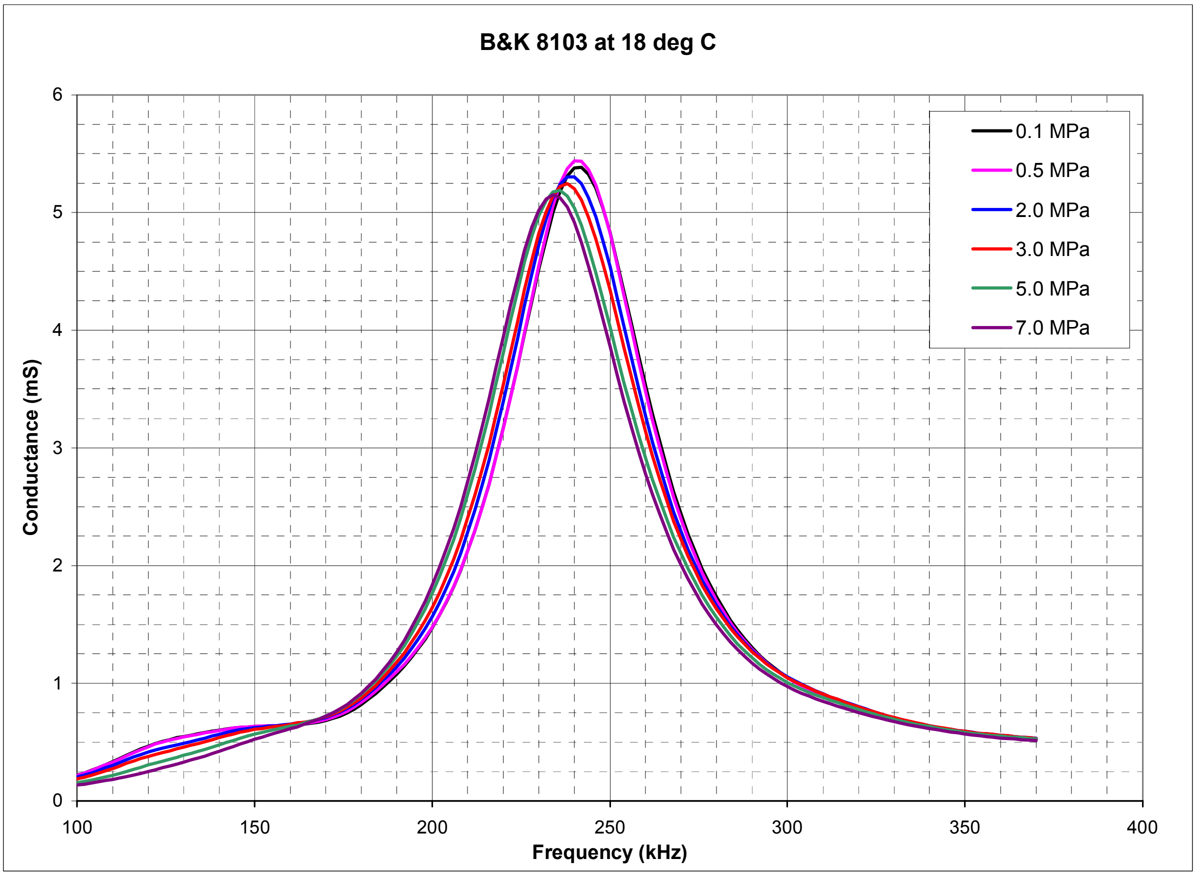

Figure 4.4: Variation of frequency of resonance with pressure.

Figure 4.4 shows the same measurement data as Figure 4.3 plotted in the form of a conductance versus frequency graph. From this we can see that not only is the value of the conductance reduced as the pressure increases, but also that the frequency of resonance decreases with increasing pressure. There appears to be an increase in damping of the resonance as the hydrophone is subjected to greater pressure.

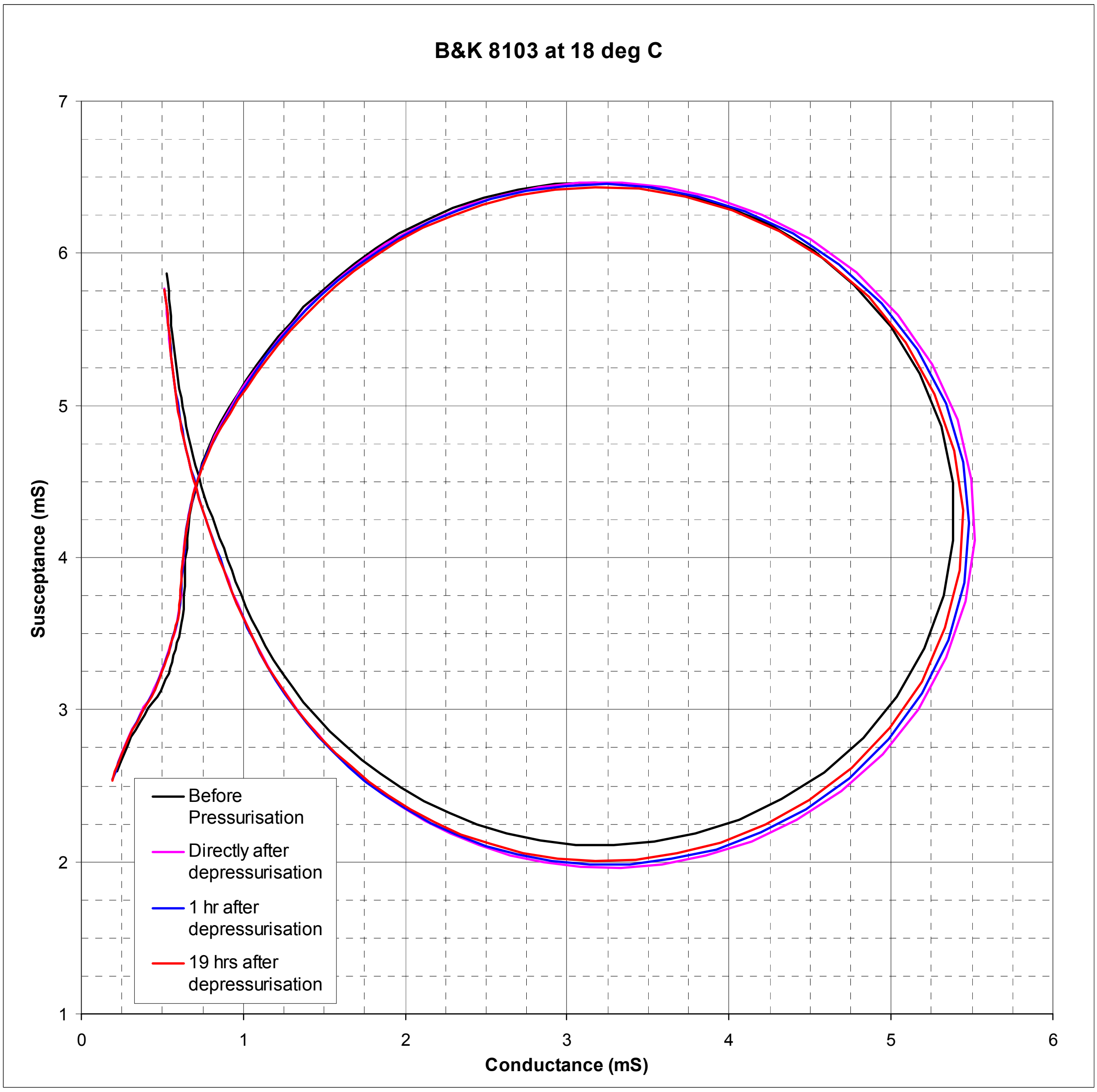

Figure 4.5: Admittance plot of B&K 8103 hydrophone, 100 kHz to 370 kHz, after pressurisation.

After the completion of the admittance measurements of the B&K 8103 hydrophone at pressure, the vessel was depressurised and the measurements repeated immediately. The conductance and susceptance were then measured again after intervals of one hour and nineteen hours. The results are shown in figure 4.5, and from this it can be seen that there is a small hysteresis effect in that, even after nineteen hours, the admittance loop still has not quite returned to its original size.

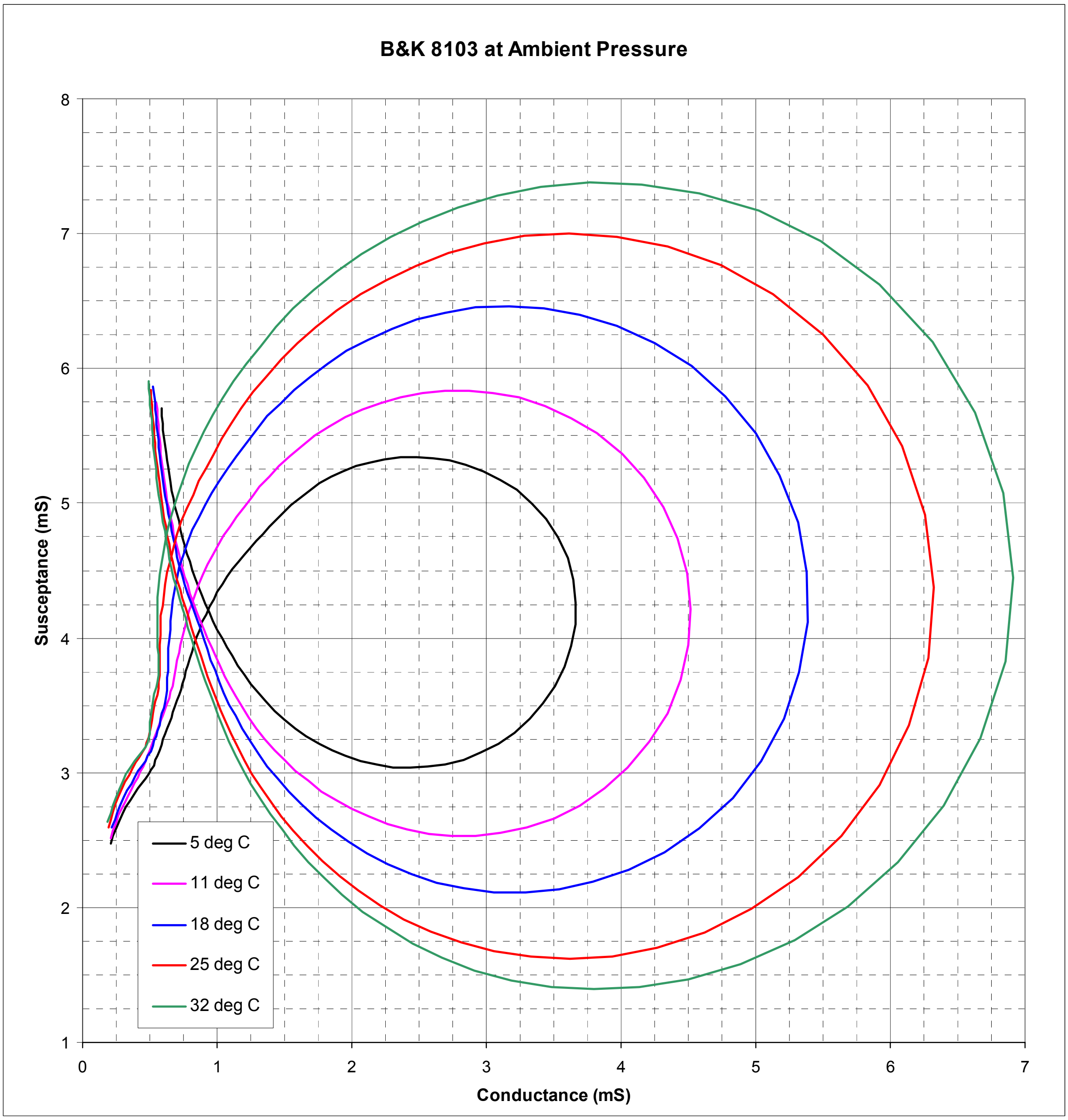

Figure 4.6: Admittance variation with temperature of B&K 8103 hydrophone, 100 kHz to 370 kHz.

With the pressure vessel depressurised, the conductance and susceptance of the B&K 8103 hydrophone was measured, over the same frequency range, while varying the temperature of the water in the vessel. Measurements were made at five temperatures: 5 °C, 11 °C, 18 °C, 25 °C and 32 °C. The results are shown in figure 4.6, and from this it can be seen that variations in temperature have a dramatic effect on the length mode resonance of the hydrophone, with the conductance at resonance almost doubling as the temperature increases from 5 °C to 32 °C.

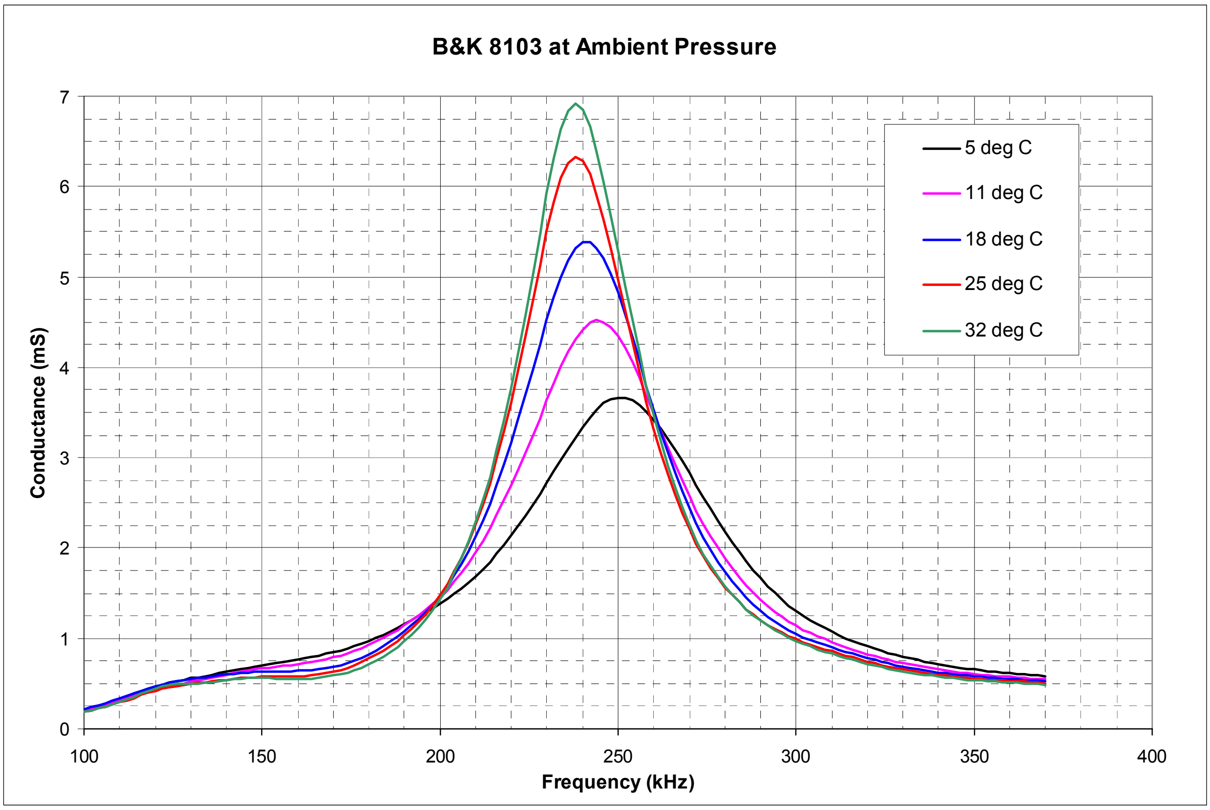

Figure 4.7: Variation of frequency of resonance with temperature.

Figure 4.7 shows the variation with temperature data for the B&K 8103 hydrophone plotted in the form of a conductance versus frequency graph. From this we can see that, once again, not only is there a change in the value of the conductance at resonance, but also a shift in the frequency of resonance. As the temperature increases, the frequency of resonance decreases, with the most noticeable change occurring at lower temperatures.

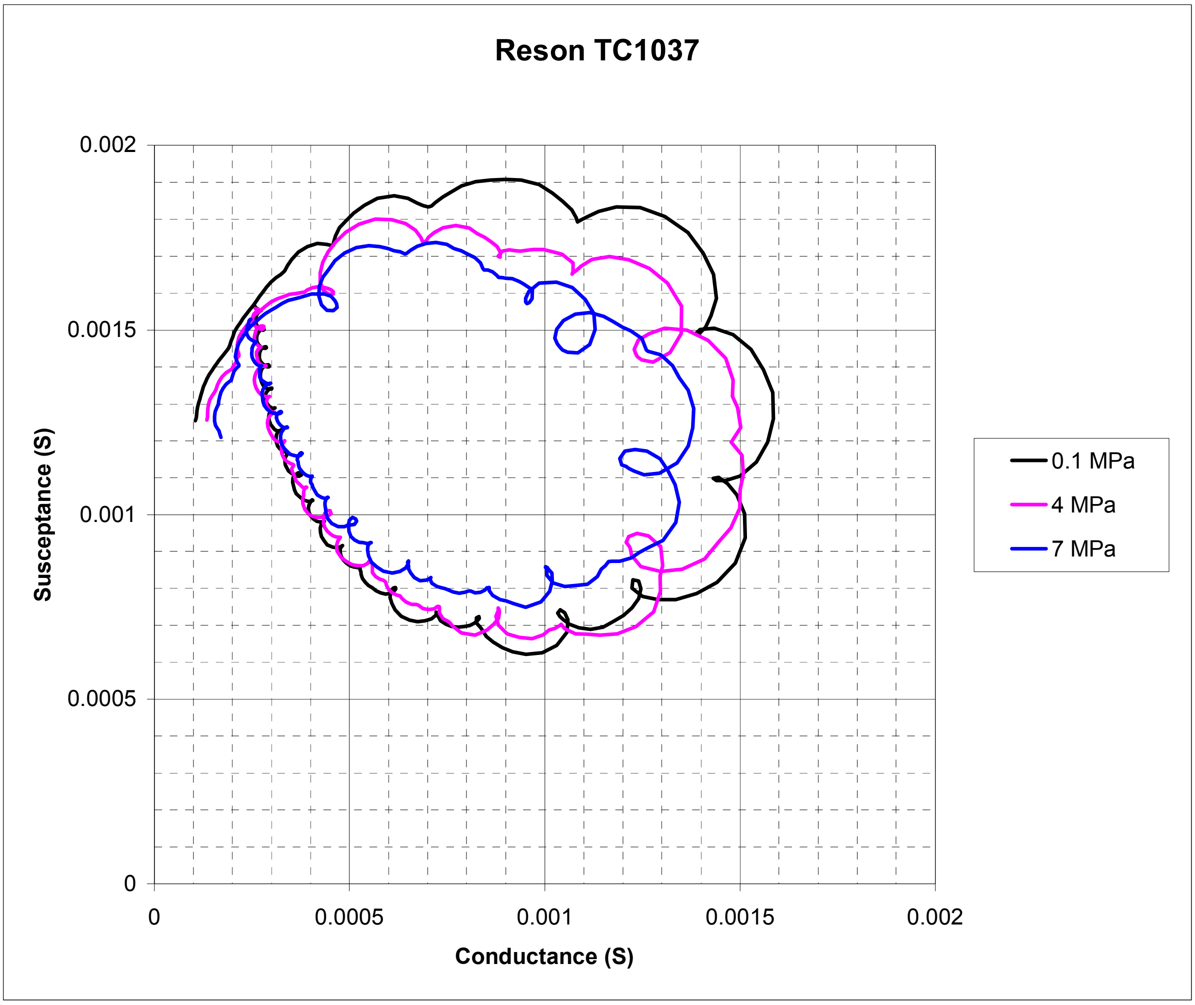

Figure 4.8: Admittance plot of Reson TC1037 transducer 5 kHz – 12 kHz showing the effect of reflections from the pressure vessel walls.

The effect of reflections from the pressure vessel walls is clearly illustrated in figure 4.8. The device is a Reson TC1037 transducer measured over the frequency range 5 kHz to 12 kHz at ambient pressure, 4 MPa and 7 MPa. Although this device has some degree of directionality at these frequencies, the beamwidth is still large enough to allow reflections to interfere with the measurement, and these appear as subsidiary loops around the main loop. Despite this interference, the effect of the pressure change on the admittance loop is clear to see, and this is different again to the previous devices. While, like the B&K 8105, the effect is significant, the changes in the admittance loop are in general more proportional to the changes in pressure.

4.1.5 Discussion and uncertainties

Interference from reflections is clearly encountered when measuring the electrical impedance of low frequency devices, such as the Reson TC1037 transducer shown above. This demonstrates that the use of continuous wave signals for the measurement of electrical impedance in the APV may lead to errors due to the reflections affecting the radiation impedance of the transducer, particularly at frequencies close to resonance. The typical uncertainty in determining the electrical impedance in a perfect free field would be of the order of 1% or better. Although this may still apply for high frequency devices in the APV, the accuracy will be degraded for low frequency projectors where the anechoic wedges cannot be relied upon to eliminate reflections. The measurement of electrical impedance is also possible using gated tone bursts, the measurement at each frequency being completed before the arrival of any reflections from the pressure vessel walls. This could potentially be accomplished by using a two-channel signal analyser to measure voltage and current and the phase difference between them. Another potential benefit of this method would be the ability to measure electrical impedance at higher drive levels, an important requirement when characterising projectors.

4.1.6 Conclusions

Many different types of transducers are used at various depths and latitudes in the ocean, and relatively little is known of the way in which their electrical characteristics change when placed in these environments. The results obtained so far, from the limited measurements in the pressure vessel, indicate that significant variations in impedance are observed for some devices. There is a general need to characterise the variation of the electrical impedance of transducers when subjected to changes in pressure and temperature

4.2 DIRECTIONAL RESPONSE

4.2.1 Introduction

While the performance of many sonar systems used in the ocean depends on the directional properties of their transducers and arrays [1, 5], the characterisation of these properties is rarely done under the same conditions of pressure and temperature as those encountered in actual use. Significant changes in the directional response of devices due to pressure and/or temperature could lead to variations in the performance of systems dependent on location in the sea. The capability to characterise the directional response of a device in the acoustic pressure vessel, over the full range of pressure and temperature, has now been established.

4.2.2 Method

The large lid of the pressure vessel has a motor capable of rotating the device mounted to it through 360°. A reference hydrophone mounted on one of the small port cradles can be used to monitor the signal transmitted by the device while it is rotated through the angular range of interest. (Alternatively, if the device to be measured is a hydrophone, a projector can be mounted on the small port cradle and the signal received by the hydrophone on the large lid can be monitored.) To be able to characterise many types of device while maintaining speed and accuracy of measurement, it is useful to be able to perform two types of rotational scans:

- Continuous, where the device is rotated at a constant rate while the signal level is measured, and corresponding angular position read, at regular intervals. This is the faster of the two types of scans and would be used for the majority of measurements.

- Discrete, where the device is rotated through the required angular range stopping after each pre-defined angular step to take the measurement. Because the device is stationary while the measurement is made, the signal analyser can be re-ranged and the measured signal averaged, giving greater accuracy when the signal level is low or noisy.

Both of these types of scans can be performed, at ambient pressure and temperature, in the NPL open tank facilities

4.2.3 Instrumentation and software

The instrumentation used is basically the same as that used in the NPL open tank facilities. A continuous wave signal at the frequency of interest is produced by a Hewlett Packard HP 33120A function generator and fed into a Vinculum gating unit to produce a tone burst. The length and repetition rate are adjusted according to the frequency, the Q of the projector and the echo-free time and reverberation level in the vessel. A selection of power amplifiers is available to drive the projector with this signal, the choice of which to use generally depending on the measurement frequency. The signal received by the hydrophone is amplified by a Stanford Research SR560 preamplifier and then filtered by a Krohn-Hite 3944 band pass filter (if required). A Hewlett Packard HP 89410A vector signal analyser, triggered by the Vinculum gating unit, is available to measure the level of the steady-state portion of the tone burst.

The instrumentation and pressure vessel motors are controlled by a PC running in-house software. The pressure vessel motor controllers are linked to the PC via the RS232 interface, while the instrumentation is controlled via the IEEE-488 (GPIB) interface. Further procedural features exhibited by the software to enable directional response measurements in the acoustic pressure vessel include:

- Selection of the small port cradle on which the reference transducer is mounted.

- Setting up the RS232 interface to enable the PC to communicate with the pressure vessel motor controllers.

- Updating the motor controllers after power down. The motor positions are stored by the displays but not by the motor controllers, so the displayed positions are converted to encoder counts and sent to the motor controllers.

- Homing the small port carriage by moving it to a known position (at the near mechanical limit), and setting the displayed distance from the large port according to the selected cradle.

- Moving the small port carriage to set the distance between the transducers in the pressure vessel to the required separation.

- Moving the lid rotator motor at a pre-defined constant rate while monitoring the angular position.

- Moving the lid rotator motor to a given angular position.

4.2.4 Results

An air-backed piston transducer was mounted to the large lid of the pressure vessel, and its directional response at 200 kHz measured using a B&K 8105 reference hydrophone. The discrete scanning method was used, with measurements taken at one degree intervals. Figure 4.9 shows the variation of the directional response of the transducer with temperature, displaying scans at 12 °C and 25 °C. Although both scans were measured over an angular range of ±180°, only –90° to +90° is displayed since all the features of interest occur within this range, with very little signal being transmitted out of the back of the transducer. It can be seen that the change in temperature causes a shift in the position of the sidelobes, which is possibly related to the change in the speed of sound in water and the corresponding change in the wavelength of the signal. But there is also a noticeable change in level of the outer pair of sidelobes, and a further characteristic of the response is the appearance of a "shoulder" on the lower part of the main lobe as the temperature increases.

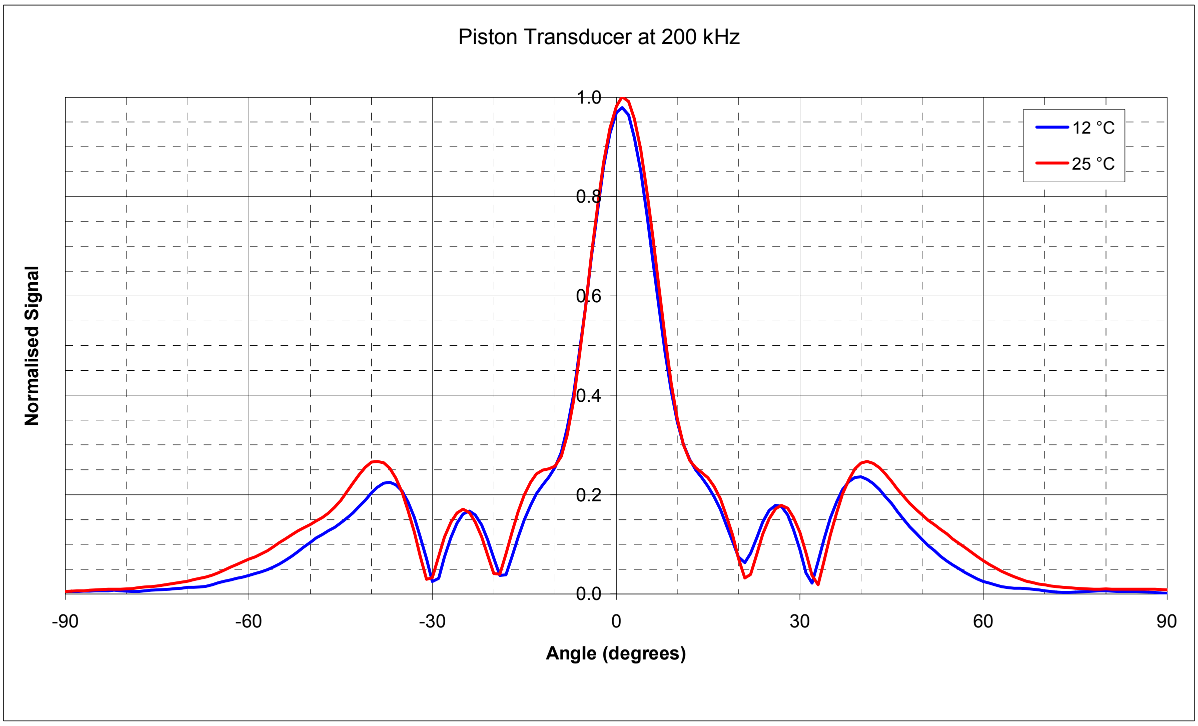

Figure 4.9: Directional response of the piston transducer at 200 kHz.

The directional response of a USRD F27 transducer at 40 kHz was also measured in the vessel, but for this device the pressure was varied, with scans performed at 0.1 MPa, 3 MPa and 7 MPa. The continuous scanning method was used, giving a measurement rate of approximately two measurements per degree while rotating from –180° to +180°.

Two sets of measurements were made: one using a B&K 8105 as the reference hydrophone, and the other using a USRD H52. Figure 4.10 shows the directional response measured using the B&K 8105 hydrophone, and this appears to show a change in output of the F27 transducer as the pressure changes. The output increases noticeably as the pressure changes from ambient to 3 MPa, but then there seems to be relatively little change as the pressure rises to 7 MPa.

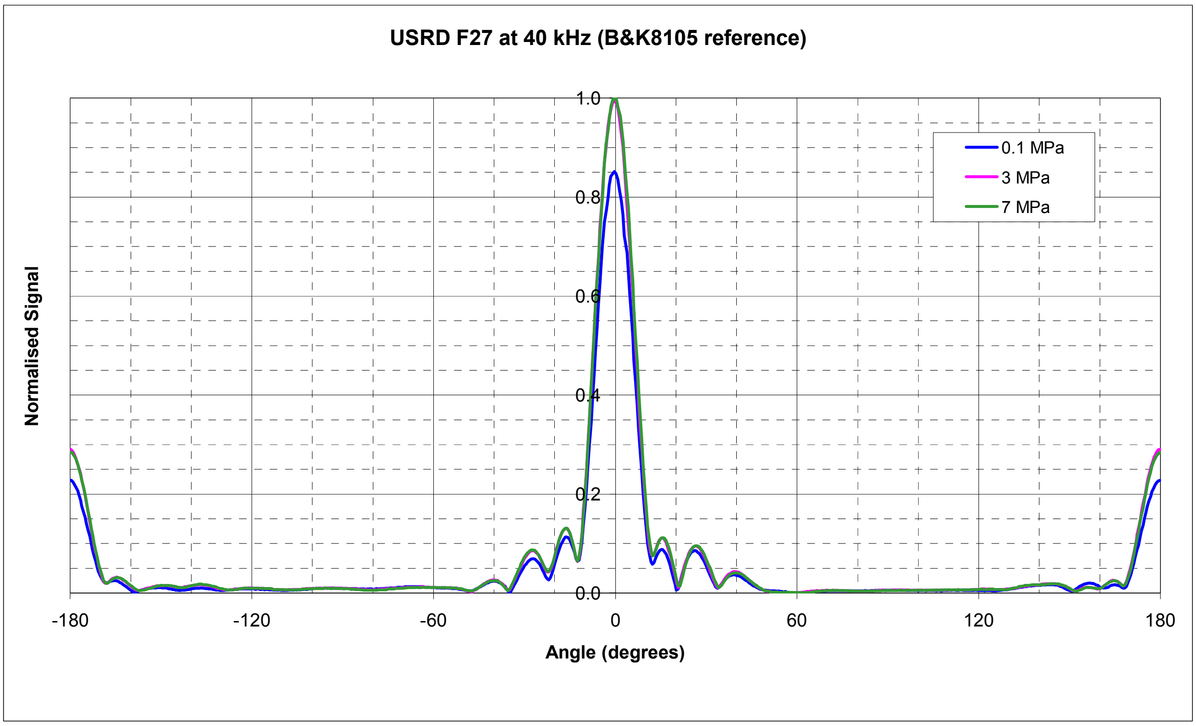

Figure 4.10: Directional response of USRD F27 transducer at 40 kHz measured using a B&K8105 reference hydrophone.

This characteristic, however, is not shown by the measurements made using the USRD H52 reference hydrophone (Figure 4.11), with the output of the F27 transducer remaining relatively constant throughout the full range of pressure changes. From previous measurements, the receive sensitivity of the H52 hydrophone at 40 kHz is known to change relatively little when subjected to changes in pressure (approximately 2% from ambient to 7 MPa), and so we can conclude that the measurements using the H52 hydrophone as a reference indicate the true variation of the output of the F27 transducer in response to changes in pressure.

The apparent variation in the F27 response shown by the measurements using the B&K 8105 hydrophone is due to the change in the receive sensitivity of the B&K 8105 with pressure. It can be seen that this change follows the change due to pressure in the admittance loop of the B&K 8105 shown in the previous section in that there is initially a large change as the pressure increases from ambient, but relatively little change with variations at higher pressures. A change in the sensitivity of the reference hydrophone will be seen as an overall percentage shift in signal level throughout the scan, and where this is significant, a correction has to be applied before the response of the device under test can be assessed.

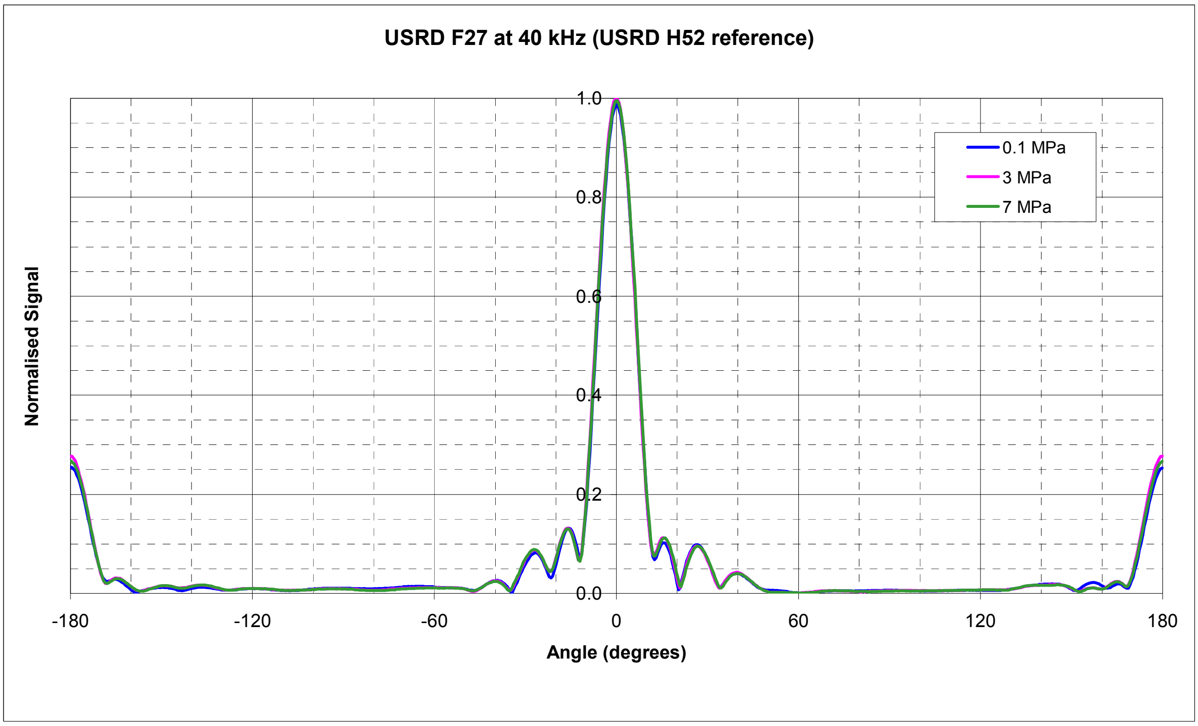

Figure 4.11: Directional response of USRD F27 transducer at 40 kHz measured using a USRD H52 reference hydrophone.

4.2.5 Discussion and conclusion

The directional response measurement capability of the pressure vessel is performing satisfactorily though still in its infancy. Clearly the ability to align transducers is more limited in the APV than in the OTF. This will potentially lead to increased uncertainties in directional response measurements. The first improvement that is required is the ability to vary the height of one or both transducers, preferably under automated control.

More work can be done to characterise different devices, and to compare and understand the variations in their directional properties with pressure and temperature. Currently, only rotational scans can be performed in the vessel. With the present motor control system, the capability to perform line scans along the length of the vessel could also be added. By improvements to the control and positioning systems within the vessel, there is the potential to extend the range of scans that can be performed to include cylindrical and possibly planar scans.

5. ABSOLUTE CALIBRATIONS BY THE RECIPROCITY METHOD

5.1 INTRODUCTION

The calibration of devices at various pressures and temperatures requires knowledge of the pressure and temperature characteristics of the reference transducers used during the calibration. The characterisation of these reference transducers can only be done by performing numerous calibrations, at various pressures and temperatures, using an absolute calibration method such as three transducer spherical-wave reciprocity [16]. This is the absolute calibration method currently used in the NPL open tank facilities [19,20], and the methodology already exists. However, the different mounting and alignment arrangements in the pressure vessel require changes to the measurement procedures and software, which are described below.

5.2 PROCEDURES

The reciprocity method uses three transducers measured in pairs. The NPL large open tank has three carriages, enabling all three devices to be mounted in the tank throughout the calibration. Each pair of transducers is rotated to face each other in turn for each stage of the measurements. The small open tank has only two carriages, and so one of the pair of transducers has to be changed after each measurement stage. The pressure vessel has only two ports, but the carriage beneath the small port has two mounting cradles, and so the potential exists to mount three devices in the vessel at the same time. Although the three devices would be positioned in a line, rather than the equilateral triangle used in the large open tank, consideration was given as to whether the method could be adapted to use this arrangement. With the number of calibrations required, the time saved by not having to lower the pressure in the vessel and remove the lids to re-mount the devices would be considerable. To perform the calibration with the transducers mounted in a linear arrangement requires the ability to rotate the middle transducer through 180° to face each of the end transducers, and also some way of moving the middle transducer out of the way while performing the measurements between the end transducers. At the moment the central cradle has no rotational capability, and there is currently no way of raising or swinging the cradle remotely, so it was eventually conceded that the transducers would have to be mounted in pairs. The measurement procedure is therefore based on that used in the small open tank with the following changes:

- There is no motorised control of the vertical position of the transducers in the pressure vessel, and so the vertical alignment of the transducers has to be achieved by the use of adjustable mounting poles.
- The range of available separation distances between the transducers is determined by which small port mounting cradle is used.
- The small port extension cradle cannot be used for directional devices since it has no azimuth alignment capability.

5.3 INSTRUMENTATION AND SOFTWARE

The instrumentation used is basically the same as that used in the NPL open tank facilities except that the transducer impedances are measured using a HP 4294A Impedance Analyser rather than the HP 4192A Impedance Analyser. A continuous wave signal at each measurement frequency is produced by a Hewlett Packard HP 33120A function generator and fed into a Vinculum gating unit to produce a tone burst. The length and repetition rate are adjusted according to the frequency range of the calibration, the Q of the projector and the echo-free time and reverberation level in the vessel. A selection of power amplifiers is available to drive the projector with this signal; the choice of which to use generally depends on the range of measurement frequencies. The drive current is measured using a Tektronix CT-2 current probe, the output of which is fed into Hewlett Packard HP 8494G and HP 8495G calibrated, programmable, switchable attenuators. These are used to bring the drive current down to a level comparable to the signal received by the hydrophone to avoid problems due to non-linearities in the measuring system. Both the output of the attenuators and the signal received by the hydrophone are routed via a Hewlett Packard HP 8762A programmable switch through a Stanford Research SR560 preamplifier and then a Krohn-Hite 3944 band pass filter to a Hewlett Packard HP 89410A vector signal analyser which is used to measure the level of the steady-state portion of the tone burst.

The instrumentation and pressure vessel motors are controlled by a PC running in-house software. The pressure vessel motor controllers are linked to the PC via the RS232 interface, while the instrumentation is controlled via the IEEE-488 (GPIB) interface. Further tasks which have to be accomplished by the software to enable three transducer spherical-wave reciprocity measurements in the acoustic pressure vessel include the following:

- Selection of the small port cradle on which the transducer is mounted.
- Setting up the RS232 interface to enable the PC to communicate with the pressure vessel motor controllers.
- Updating of the motor controllers after power down. The motor positions are stored by the displays but not by the motor controllers, so the displayed positions are converted to encoder counts and sent to the motor controllers.
- Homing the small port carriage by moving it to a known position (at the near mechanical limit), and setting the displayed distance from the large port according to the selected cradle.
- Moving the small port carriage to set the distance between the transducers in the pressure vessel to the required separation.
- Control of the HP 4294A Impedance Analyser to enable measurement of the transducer impedances.

5.4 RESULTS

The procedure and software was validated by calibrating hydrophones in the pressure vessel, at ambient pressure (0.1 MPa) and temperature, and comparing the results to those obtained from reciprocity calibrations in the open tanks.

Figure 5.1 shows the results obtained from reciprocity calibrations over the frequency range 10 kHz to 120 kHz of a USRD H52 hydrophone in the pressure vessel and the large open tank. Both calibrations were done at ambient pressure and a water temperature of 18 °C. The error bars indicate the typical measurement uncertainty values of ±0.5 dB, and the degree to which the two sets overlap is very encouraging. In fact, the maximum difference between the two calibrations at any one frequency is around 0.3 dB.

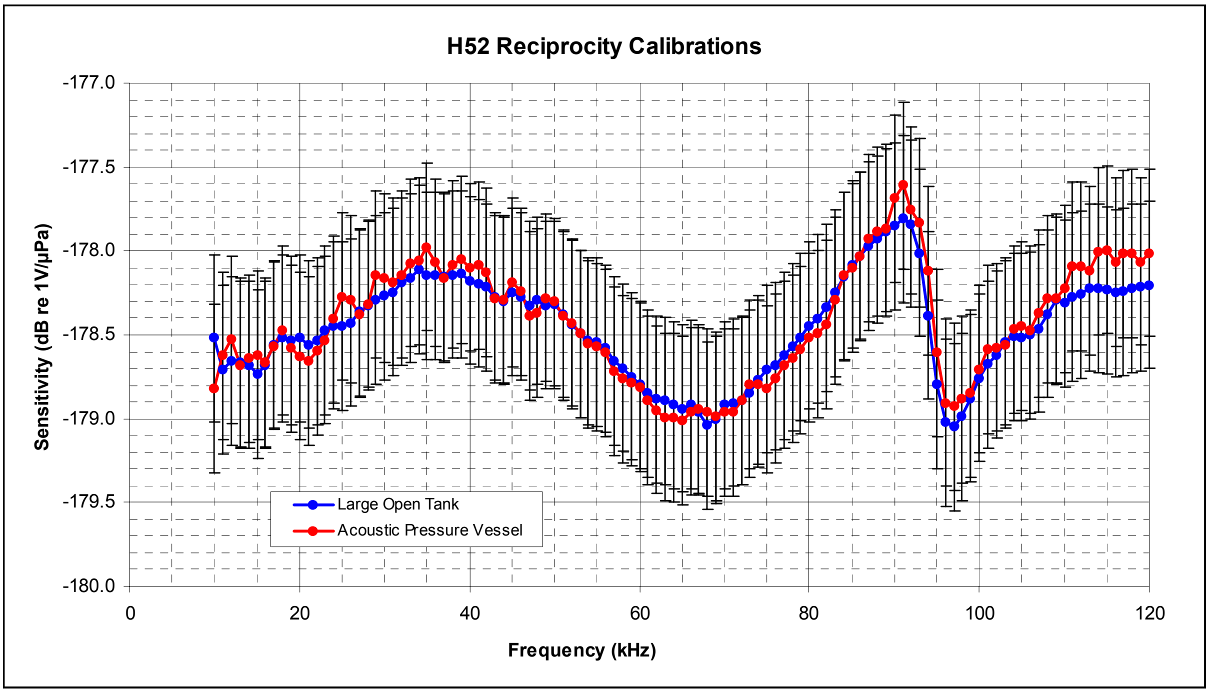

Figure 5.1: Comparison of low frequency reciprocity calibrations at ambient pressure.

For the higher frequency range, one of the NPL reference hydrophones, a Reson TC 4034 transducer, was calibrated in the pressure vessel, again at ambient pressure and temperature. The results were compared with the reference data obtained from reciprocity calibrations in the open tank facilities, and are shown in Figure 5.2. Once again, the error bars indicate the typical measurement uncertainty values of ±0.5 dB. Although the two sets of error bars overlap to some extent at all the frequencies, showing that the two calibrations agree within the measurement uncertainties, the agreement is generally not as good as for the low frequency calibration. This was probably due to the limited control over the positioning of the transducers within the pressure vessel leading to small inaccuracies in the alignment of the transducers, which have a greater effect on the accuracy of the measurements at higher frequencies.

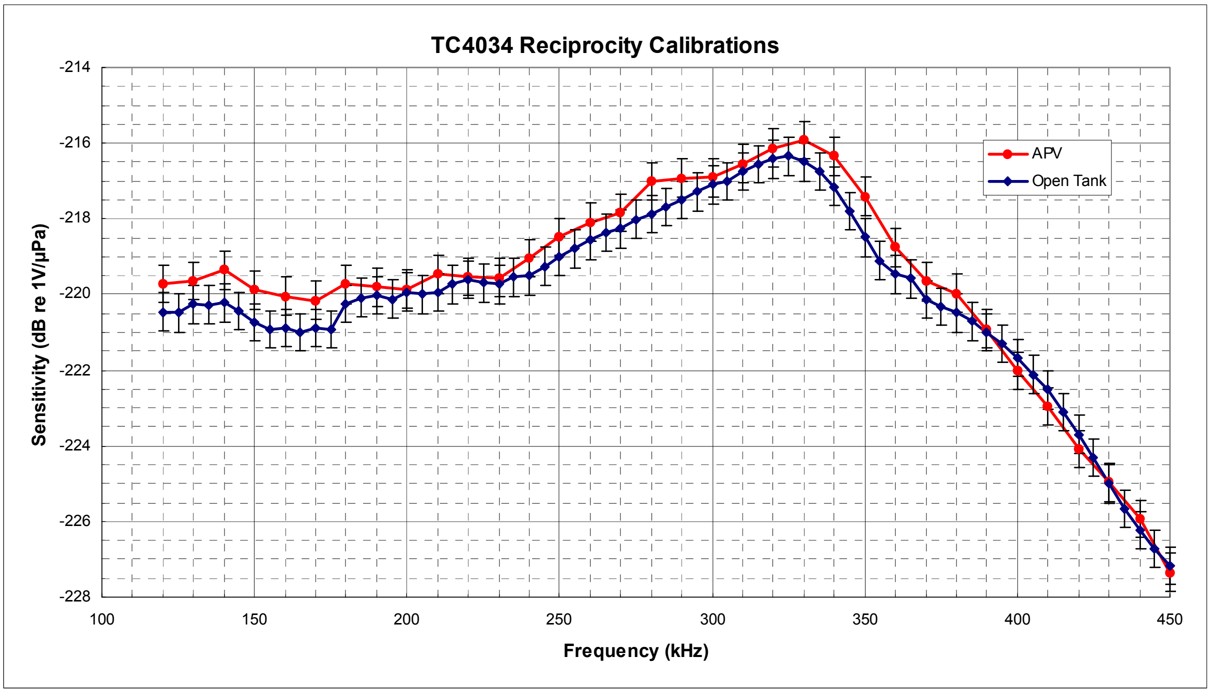

Figure 5.2: Comparison of high frequency reciprocity calibrations at ambient pressure.

5.5 CONCLUSIONS

Preliminary results of reciprocity calibrations in the pressure vessel compare well with those obtained from calibrations in the NPL open tank facilities, for which there is already a published uncertainty budget [19]. This is very encouraging, However, whilst agreement at low frequencies is as good as would be expected from separate calibrations in the open tank facilities, there is room for improvement at the higher frequencies. Since the basic calibration system and methodology is identical to the open tanks implementation, most of the uncertainty budget for the APV should be the same. However, limitations in the current pressure vessel positioning systems, in respect of the degrees of freedom of movement of transducers, can lead to greater inaccuracies in the alignment of the transducers, and to consequently larger uncertainty components. Improvements in the control over the mounting and positioning of transducers in the pressure vessel need to be considered, not only to improve the accuracy of the measurements, but also to enable the three transducers used for a reciprocity calibration to be mounted in the vessel at the same time, and the calibration to be completed without the need to open the vessel.

6. MEASUREMENTS OF TRANSDUCER RESPONSE VARIATION WITH TEMPERATURE AND DEPTH

6.1 INTRODUCTION

As has been previously stated, relatively little information is available from manufacturers regarding the variation in response of transducers with temperature and depth, and relatively little reported in the literature [21]. The results presented in Section 4.1 indicated that some transducers appear to exhibit changes in electrical impedance when the transducer is subjected to either a pressure or temperature variation. However, the sensitivity of a device, either projector or hydrophone cannot be determined directly from this measurement technique and an acoustic calibration is required to obtain the sensitivity of the transducer under test. The primary standard calibration method of three-transducer spherical-wave reciprocity [16, 19] could be used for this purpose. However, to increase the speed of measurements, the calibrations reported here were undertaken with a relative method where the USRD reference transducers were used as acoustic standards. This procedure eliminated the need to swap devices or re-mount during the measurement cycle.

6.2 METHOD

The reference projector used to obtain the absolute sensitivity values for a hydrophone under test was mounted to the large lid's rotator shaft via the standard mounting flange; the hydrophone was mounted to one of the small port cradles with access being gained through the small lid. The devices were allowed to soak at the temperature of interest for a minimum of several hours prior to measurements taking place. Following the initial mounting of devices, the projector was aligned acoustically with the hydrophone at a suitable frequency and the hydrophone was then traversed to the desired separation, this is set and carried out under automatic control through the acoustic software.

With the test chamber at the desired environmental condition, the impedances of both the projector and hydrophone were measured (unless the hydrophone has an integral preamplifier). With this measurement completed, the sensitivity was determined by placing the hydrophone under test in the acoustic field of a calibrated projector, the projector being then driven with a discrete-frequency tone-burst and measurements are made on the steady-state hydrophone signal. The sensitivity of the hydrophone under test was calculated from the quotient of the hydrophone voltage to the acoustic pressure at the frequency of measurement, the acoustic pressure being calculated from the known sensitivity of the calibrated projector, the electrical current driving the projector and the separation distance between projector and hydrophone.

6.3 RESULTS

The USRD F30 projector was used as the reference transducer to undertake the measurements displayed in Figures 6.1 – 6.4. The use of only one projector increases the speed with which measurements can be made, but restricts the frequency range to the operating range of the F30 (about 10-150 kHz). The two devices used for the examples shown below are a Brüel & Kjær 8104 and a Brüel & Kjær 8105. The plots indicate that the individual characteristics of commercially available underwater devices may alter significantly when they are subjected to elevated hydrostatic pressures and a variation in temperature. The results displayed below were generated from one measurement cycle being carried out at the environmental condition of interest with no repeats being conducted.

6.3.1 Variation with pressure

Figures 6.1 and 6.2 shows calibrations of a B&K 8105 hydrophone conducted at atmospheric pressure and three elevated hydrostatic pressures. Significant changes in receive sensitivity are visible, particularly around 64 kHz where the relative difference between atmospheric pressure and 1.0 MPa is up to approximately 2.5 dB. Towards the resonance of the device the receive sensitivity reduces by up to approximately 1.2 dB and the trend is in fact to flatten out the response of the device over it's entire frequency range. It can be seen, consistent with the impedance measurements for this hydrophone shown in Figure 4.2, that the majority of the changes occur at low pressure up to about 1.0 MPa, with substantially less change taking place between the range 3.5 MPa to 7.0 MPa. This can be seen more clearly in figure 6.2 where the three calibrations shown were made at different pressures up to 1.0 MPa. The characteristic of this device is for the initial change in sensitivity of +2.5 dB at 1 MPa to increase marginally when further pressure is applied. As previously indicated, this may be because of some compliant material introduced during the manufacturing process, possibly even the inclusion of air under the rubber boot. These results would suggest that noticeable differences in sensitivity would be produced while using this particular model up to depths of around 100 metres.

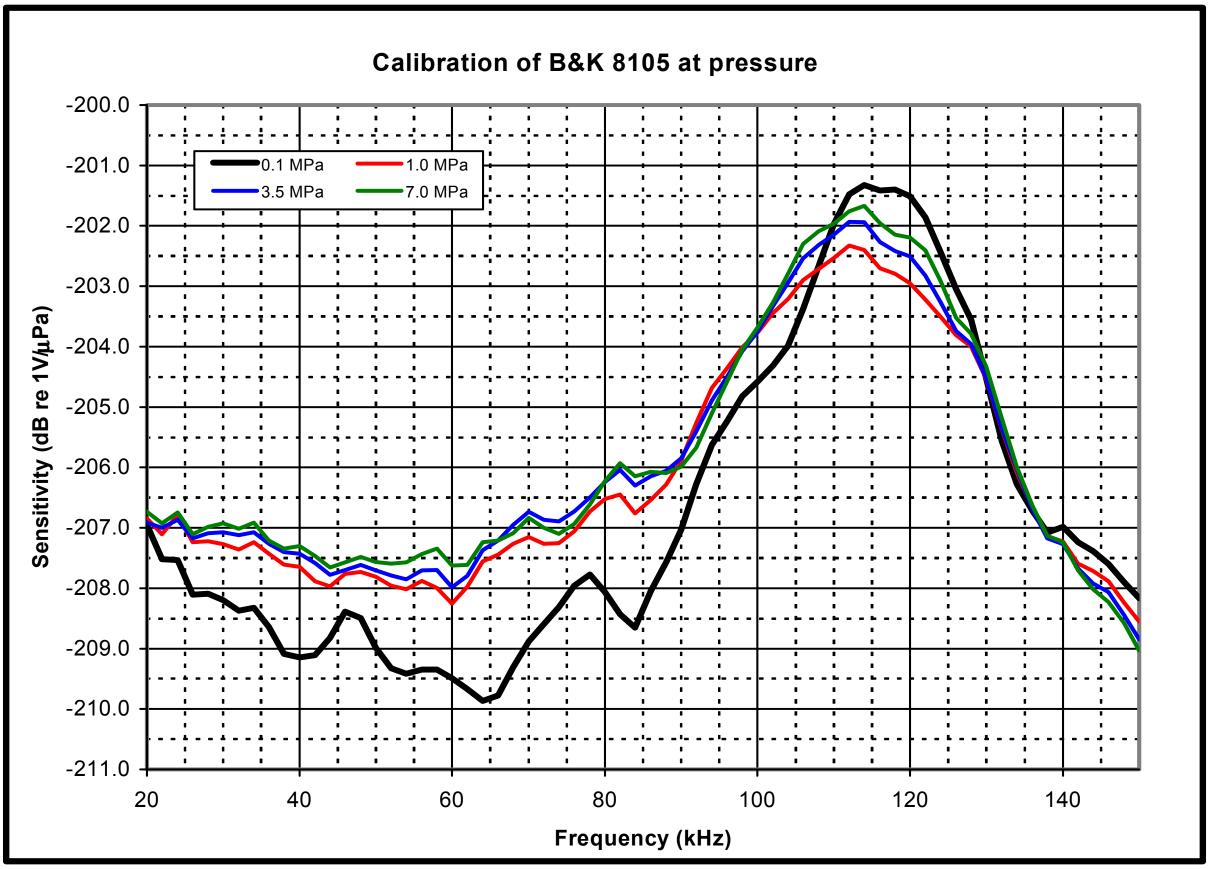

Figure 6.1: Calibration of a B&K 8105 at elevated hydrostatic pressure.

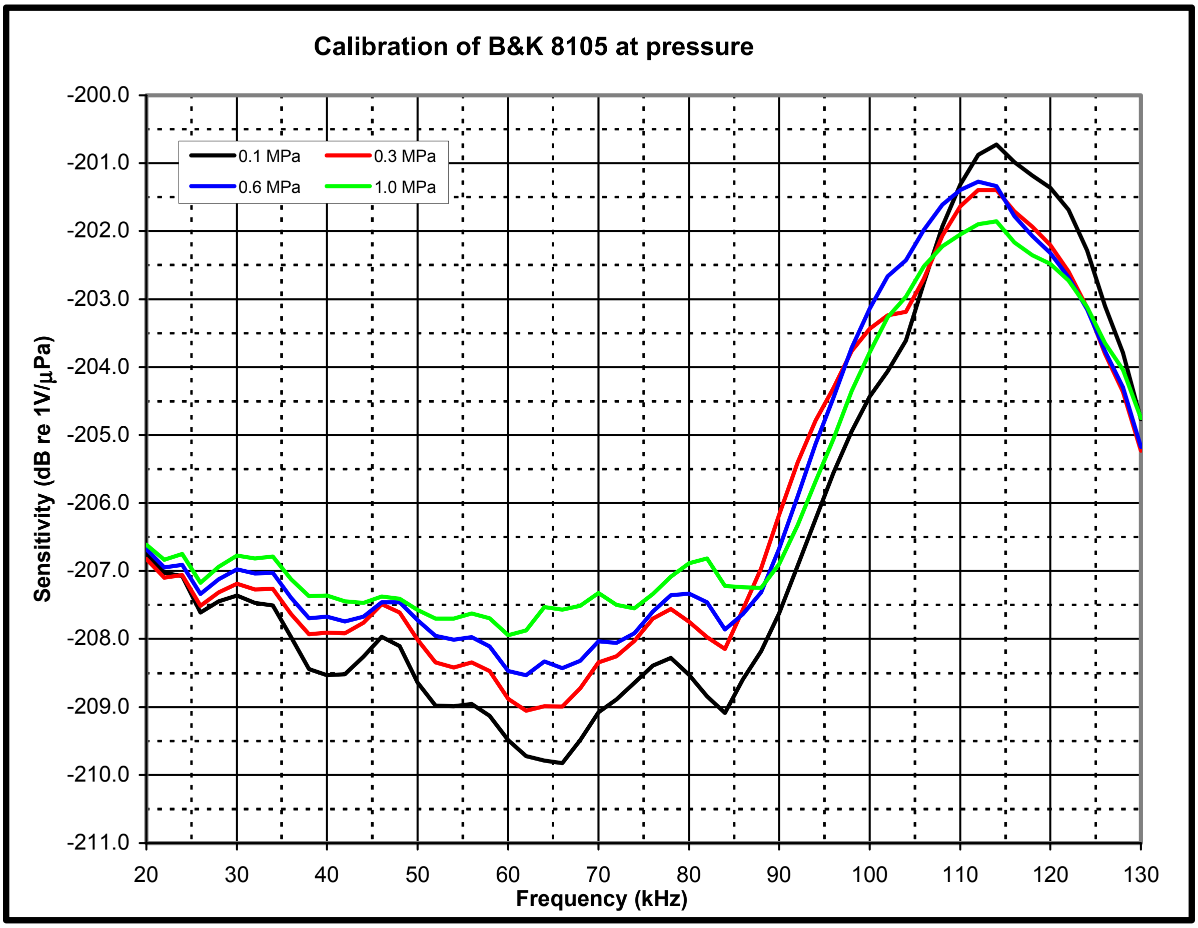

Figure 6.2: Calibration of a B&K 8105 at elevated hydrostatic pressure.

Figure 6.3 shows a calibration of a B&K 8104 conducted at atmospheric pressure and four elevated hydrostatic pressures. Significant changes in receive sensitivity are once again visible, in the case of this device, particularly around 57 kHz where the relative difference between atmospheric pressure and 1.0 MPa is up to approximately 2.0 dB. The trend for the variation of sensitivity with pressure in this case is quite complex, with different behaviour being exhibited at frequencies above the resonance frequency compared with frequencies below resonance. At frequencies higher than the resonance frequency, the majority of the changes occur at low pressure up to about 1.0 MPa with substantially less change per megapascal taking place in the range 2.0 MPa to 7.0 MPa. The characteristic of this device is for the initial change in sensitivity of +2 dB at 1 MPa to gradually reduce with continual pressure increase until the sensitivity measured at 7 MPa is lower than that at atmospheric pressure. At low frequencies, a gradual reduction in sensitivity with applied pressure is observed. Once again, a noticeable difference in sensitivity will be produced while using this particular model up to depths of around 100 metres.

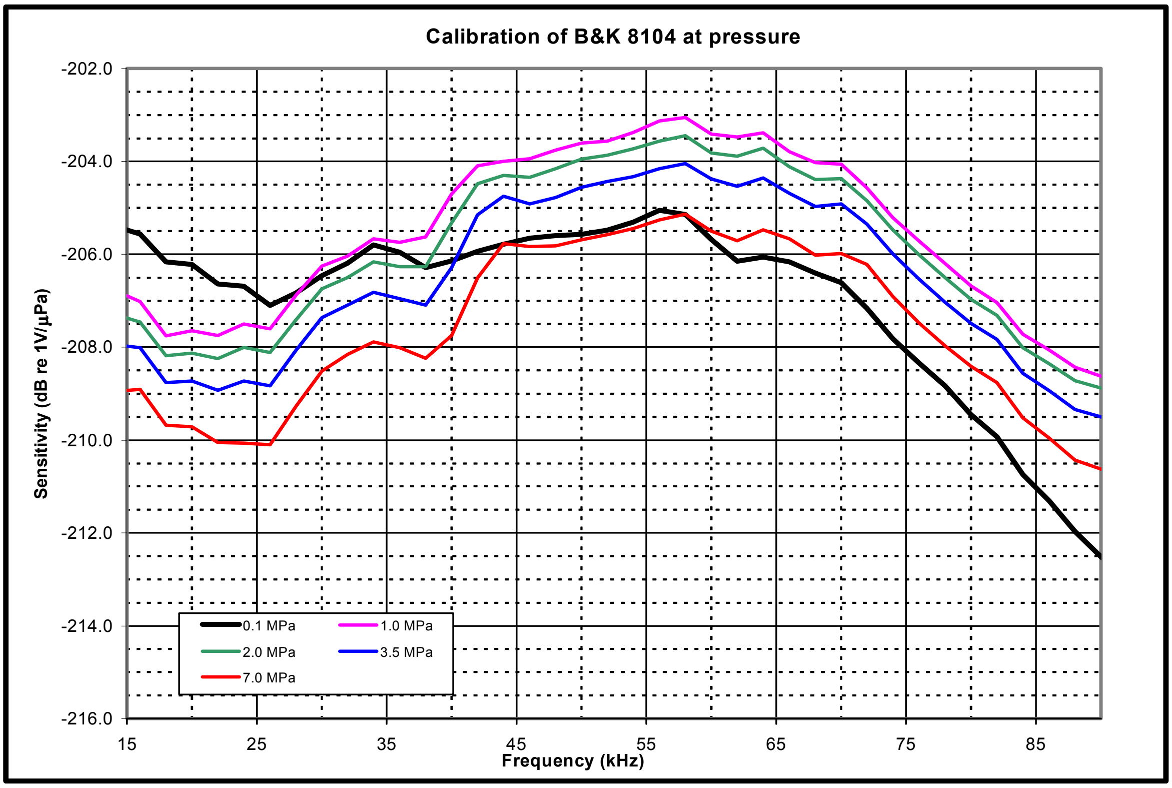

Figure 6.3: Calibration of a B&K 8104 at elevated hydrostatic pressure.

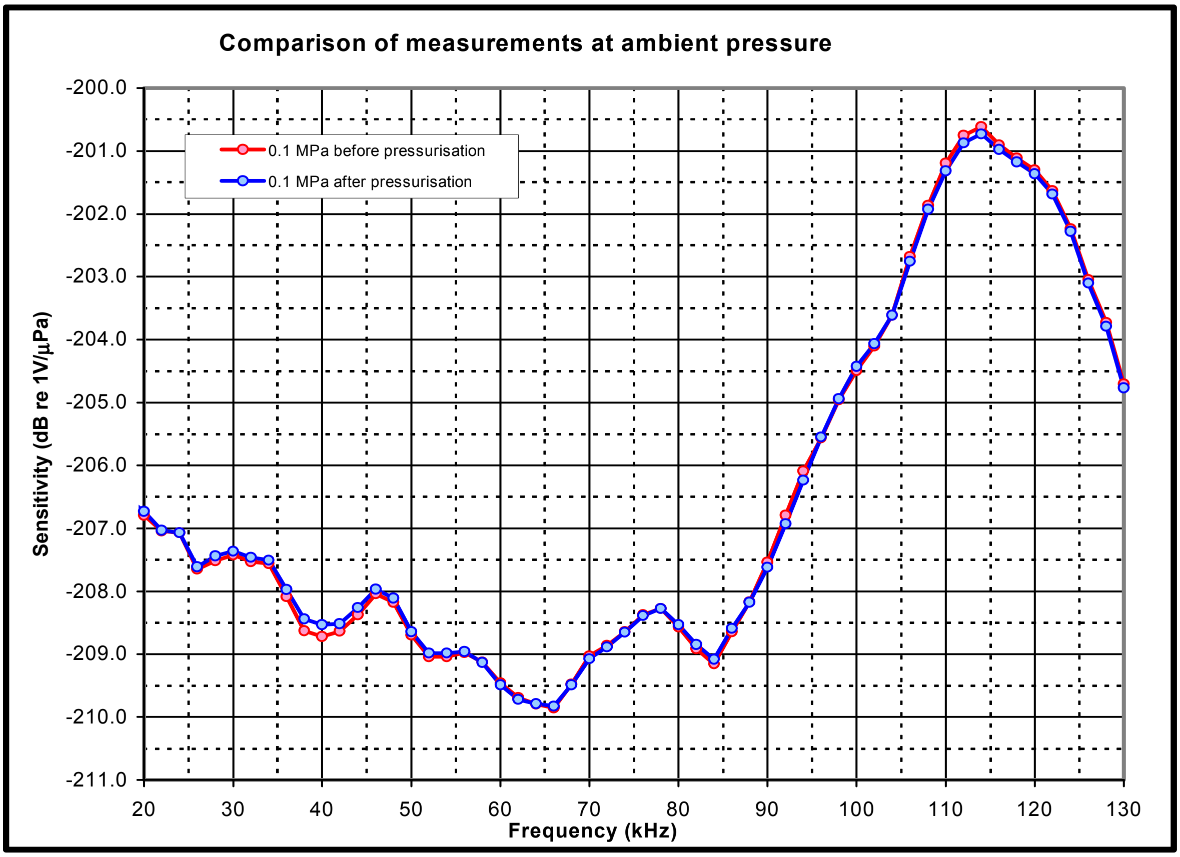

Figure 6.4: Comparison of calibrations of a B&K 8105 before and after a pressurisation cycle.

Figure 6.4 shows the results for two calibrations conducted on a B&K 8105. One has been carried out prior to the device being subjected to a pressurisation cycle up to a maximum of 7 MPa, the other being the results for a calibration that was taken immediately following the depressurisation of the test chamber. The results show good agreement in absolute measured sensitivity and would indicate that there are no sustained effects on the device when it is subjected to elevated pressures.

6.3.2 Variation with temperature

Figure 6.5 shows a calibration of a B&K 8105 conducted at temperatures of 10 °C and 30 °C. Significant changes in receive sensitivity are visible when the water temperature is changed, particularly at low frequencies (at around 30 kHz) and also up around the resonance (about 107 kHz) where the relative difference between the two calibrations is approximately 2.5 dB. The trend for variation is not a systematic shift in a particular direction but one that varies between an increase and decrease in sensitivity across the measured frequency range.

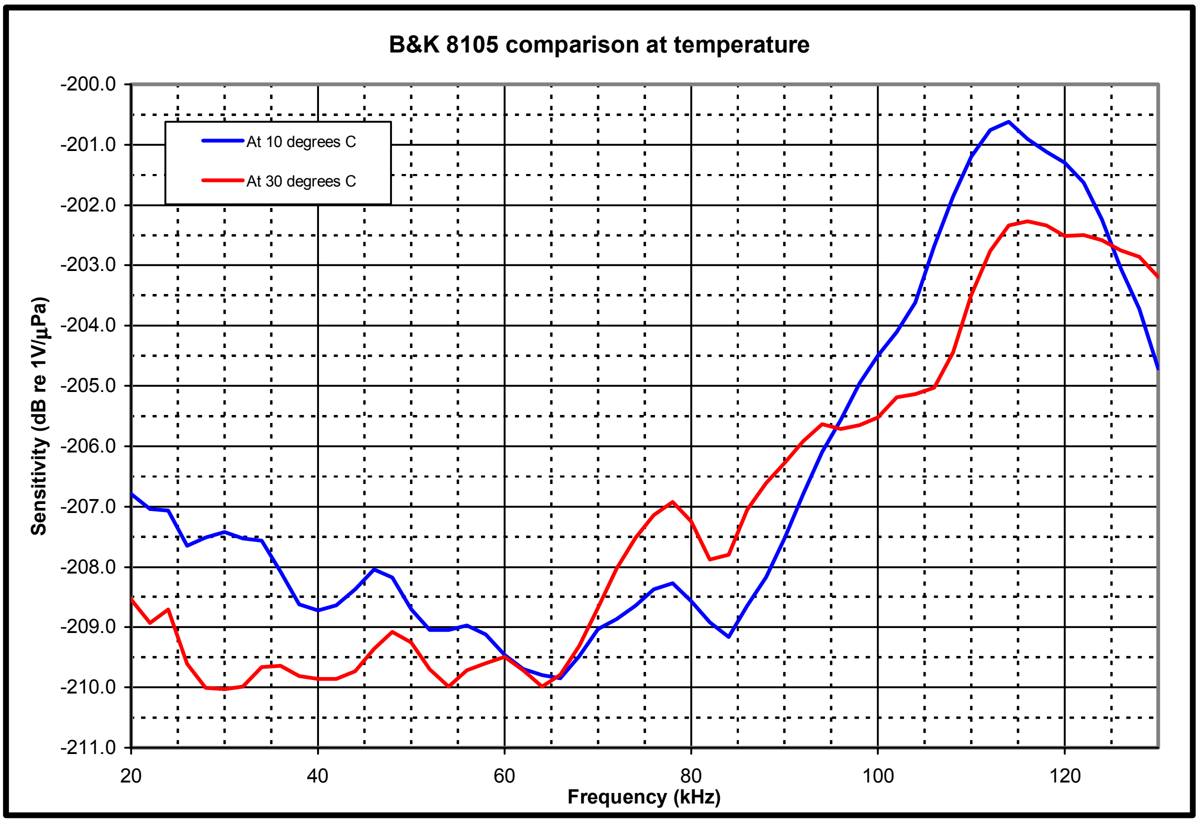

Figure 6.5: Calibration of a B&K 8105 at different temperatures.

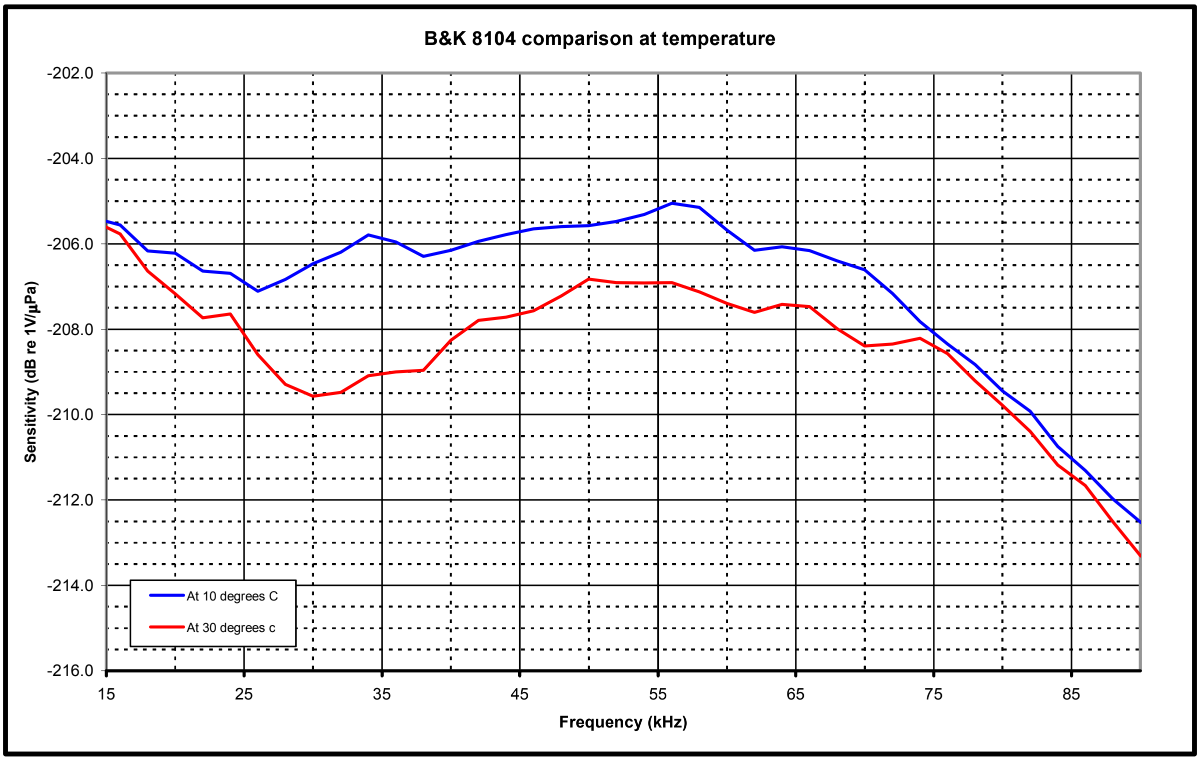

Figure 6.6: Calibration of a B&K 8104 at different temperatures.

Figure 6.6 shows a calibration of a B&K 8104 conducted at temperatures of 10 °C and 30 °C. Significant changes in receive sensitivity are once again visible when the water temperature is changed, in this case low down in the frequency range of the device, between 25 kHz and 70 kHz and then again at frequencies in excess of 100 kHz. The maximum relative difference between the two calibrations is approximately 3.2 dB at 33 kHz. The trend appears to be systematic in that when the temperature is raised, the sensitivity is reduced across the entire frequency range. However, the shift is not consistent and varies in the range 0.0 dB to 3.2 dB across the range.

6.3.3 Discussion and uncertainties

The relative measurement technique used here has proved to be very successful in determining sensitivity values of both projectors and hydrophones. It is significantly quicker in both set-up time and measurement time compared with the free-field reciprocity or a substitution method, there being no requirement for a third device in order to calculate the sensitivity for the device under test. This is an important consideration for the APV facility as the mounting and tank preparation is a more complex and time-consuming matter than in an open tank environment. This renders other techniques such as three-transducer spherical-wave reciprocity and comparison with a reference hydrophone less economical for the vast majority of routine work.

However, such a technique is in general less accurate than a substitution calibration, there being a number of extra potential sources of error being introduced into the method [22, 5]. Clearly, the absolute calibration of the reference transducer and the uncertainty assigned to its temperature and pressure coefficients contribute to the overall uncertainty. Moreover, when using a calibrated projector, it is much more difficult to be sure of eliminating the effects of any non free-field conditions that may exist in the sound field. Also, good alignment between both devices in the measurement process is required to provide accurate results. Misalignment will in general result in a reduction of the measured sensitivity and introduce an error into the results; with this in mind care must be taken during the initial setting-up period to ensure the best alignment possible is obtained. In general, it is preferable to replace the hydrophone under test with a calibrated reference hydrophone at the start and/or end of the measurements, thus providing a means of checking the calibration. This approach has been adopted for customer measurements in the APV. A provisional uncertainty budget has been established for this relative method and the overall expanded uncertainty varies from ±1.0 dB to ±1.5 dB (expressed for a 95% confidence level).

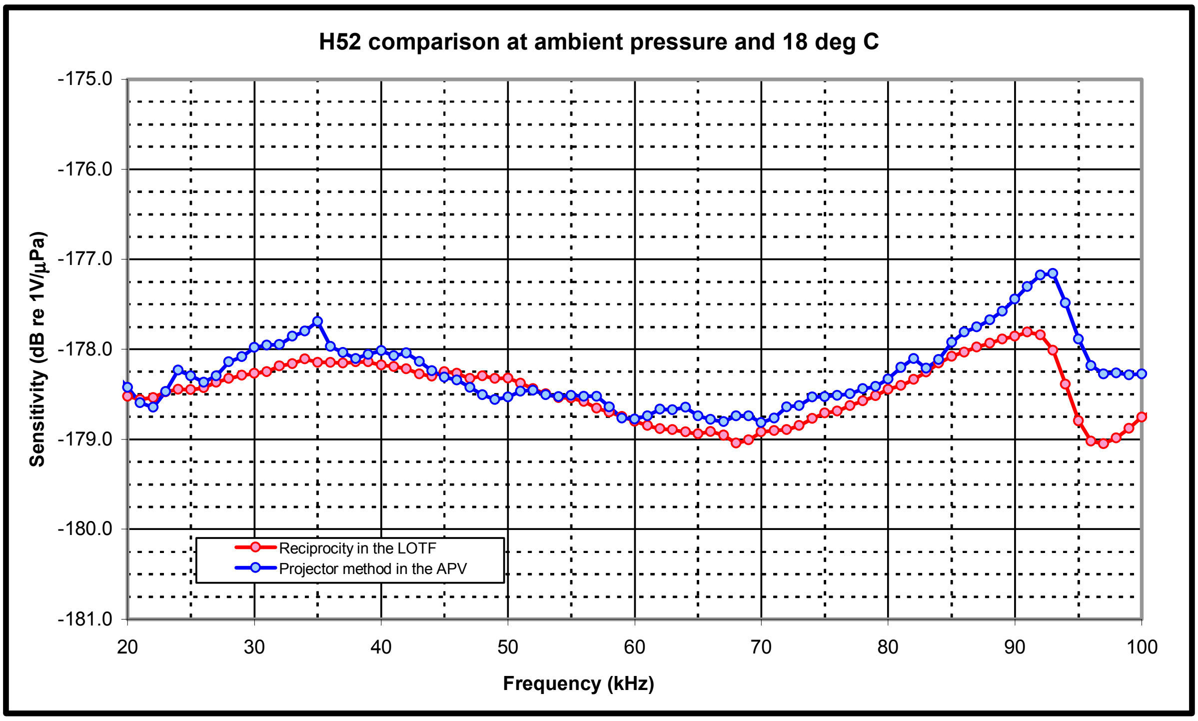

Figure 6.7: Plot of sensitivity agreement between large open tank and APV.

Shown in figure 6.7 is the agreement obtained between measurements carried out in the NPL large open tank facility by three-transducer spherical-wave reciprocity and those conducted in the APV with reference to the calibrated projector using the pre-determined calibration data for the F30 projector. The hydrophone used for the example shown is the USRD H52 receiver. The largest deviation is approximately 0.9 dB at 95 kHz. These results are within the estimated uncertainties and give further confidence that the approach adopted here can provide reasonable accuracy if carefully applied.

6.3.4 Conclusions

The results previously displayed for the two example devices indicate that there is value in conducting further tests of this nature on other types of commercial devices as each model tends to have a characteristic unique to its own design. Some models show little effect when subjected to a change in hydrostatic pressure and elevated temperatures. Others can show significant changes at shallow depths, while others still show a continual change with increased depth. The results suggest that wherever possible, customer calibration work should also be carried out at the temperature and depths at which the device is used in the field; this would give enhanced value and worth to the results supplied.

7. CONCLUSION

7.1 SUMMARY OF CURRENT STATUS

Standards for underwater acoustics at simulated ocean conditions are now provided in the UK by NPL using the Acoustic Pressure Vessel. The APV enables acoustic measurements to be made at hydrostatic pressures of up to just under 7 MPa (equivalent to about 700 m of water depth) and at water temperatures ranging from 2 °C to 35 °C. The report has described some of the work required for the commissioning of the APV, including a comprehensive technical description.

The APV has been used to determine the variation in response of a number of common transducers and hydrophones as a function of temperature and hydrostatic pressure. It is important to realise that just because a variation in response is obtained for a transducer, it does not mean that the transducer is a “bad” transducer. If the device is only to be used in a laboratory tank at modest depths and over a limited range of temperatures, the influence of the variations described here are likely to be negligible. However, if a device is to be used over the wide range of conditions that may exist in the ocean or open-water environment, then it is desirable that the transducer be characterised to determine the variation in its response so that this variation may be accounted for in any measurements taken in the field.

It is clear that even hydrophones of relatively simple design can exhibit variations in response with hydrostatic pressure and temperature. Ostensibly, one might expect that the simpler the design, the less variation there would be in response. So a simple ball hydrophone would be less likely to vary than a more complicated design involving elements consisting of multiple rings, cylinders with rubber end caps, etc. Any design which involves compliant material integrated within the element (in addition to the outer encapsulating material) may well have more potential for exhibiting large changes with pressure or temperature. Clearly any air trapped in the hydrophone will also provide a compliant layer that will quickly be compressed under the action of applied hydrostatic pressure. However, without a sustained systematic study of different types of hydrophone (and possibly some modelling of transducer response), it is not possible to be definitive about the causes of the variation.

One conclusion that is possible from the results of measurements so far is that changes in the electrical impedance are in many cases a good indicator of changes in the absolute sensitivity. This is particularly true around the resonance frequency of the transducer. A measurement of electrical impedance may therefore be used as a rapid check on the potential for variation in sensitivity.

The USRD transducers chosen as reference devices have shown good stability with temperature and hydrostatic pressure. It is intended that other transducers may be selected as reference devices once a stable response has been demonstrated. In particular, transducer are required that may be used as reference transducers at frequencies greater than 200 kHz.

7.2 FUTURE WORK

Although the APV has been shown to work satisfactorily, there are a number of areas where improvements to the engineering are desirable. For example, the internal rigging in the vessel is essentially the same as that which was present at USRD for many years and would benefit from upgrading. The improvements planned include:

- Incorporating adjustment to the height of the transducers, preferably under automatic control, to improve alignment for directional transducers;
- Increasing the flexibility of the transducer mounting in general so that a variety of devices can be accommodated;
- Increasing the flexibility in the use of the extension cradle – for some applications it would be advantageous to be able to move the extension cradle relative to the main cradle, and even to be able to "swing" the transducer mounted there away to the side of the tank;
- Increase the variety of cable sizes that can be accommodated;
- Establish the capability to mount large panels within the APV for testing properties of materials;
- In the longer term, establish the capability to scan a transducer along axes orthogonal to the main tank axis.

In terms of the scientific research and development, a number of further developments are planned, some of which are dependent upon the improvements described above:

- Improve the implementation of the free-field reciprocity method to reduce uncertainties and increase speed;
- Improve the speed and flexibility of relative calibrations in the APV and assess accuracies;
- Increase the flexibility of impedance measurement to enable measurements to be taken using tone-burst signals;
- Fully characterise the performance of the current reference transducers with temperature and pressure at NPL;
- Characterise the acoustic properties of the APV more fully in terms of reverberation time, echo free time, echo reduction of anechoic lining, background noise levels, etc;
- Investigate techniques to extend the lower frequency range of measurements;
- Undertake comparisons of measurements in the APV with those in other facilities (eg USA, China);
- Perform a systematic assessment of commercial designs of hydrophone and identify devices suitable as reference devices for simulated ocean conditions, in particular at frequencies greater than 200 kHz;
- Develop experimental techniques to enable the characterisation of materials in the form of panels as a function of temperature and pressure using parametric array and/or linear acoustics.

8. ACKNOWLEDGEMENTS

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The APV facility could not have been established at NPL without the expertise provided by the NPL Design and Engineering Services Office, in particular Mr Peter Lovelock and Mr Geoff Stammers. We would also like to thank the project manager for the project to commission the facility at NPL, Mr. Kevan Dodd.

Our considerable appreciation also goes to the staff of USRD-NUWC in the USA for their help and advice, in particular Dr. A. Lee Van Buren, Mr Bill Carlsen, Mr Tony Paolero and Mr Bob Drake.

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10. APPENDIX 1

Feature	Description
Frequency Range	1 kHz to 2 MHz
Free volume Provided by Acoustic Lining	1.9 m diameter and 4.1 m long
External Dimensions	2.5 m diameter and 7.6 m long
Access Ports	Two ports 2.4 m apart: one port having access diameter 0.84 m and the other 0.50 m
Measurement Distance	One fixed stage and two movable to give distance range 0.8 m to 2.5 m. Rotation of main shaft through 360 °. Rotating the device on the movable carriage by ±30°
Device Handling	Overhead crane with continuous fine control of speed, comprehensive safe support system for large lid during monitoring procedures, and a versatile lifting platform to aid device attachment
Maximum Weight	For devices under test 350 kg
Hydrostatic Pressure	20 kPa to 6895 kPa, normal rate of change variable from 35 kPa per minute to 1500 kPa per minute (5 psi to 220 psi per minute)
Temperature	2 °C to 35 °C
Environmental Noise	Lower than sea state zero
Cable Specification	Electrical lead-through to take cables from 5 mm to 20 mm diameter and integral connectors up to 38 mm diameter
Signal Power	Analogue Associates MA 5000VZ amplifier (5 kW, DC to 25 kHz); Brüel & Kjær 2713 100 W amplifier (DC to 1 MHz); ENI 240L 200 W amplifier (20 kHz to 10 MHz)
Device Mounting	Full information on the device/flange mounting arrangements is available on request

11. APPENDIX 2

A2.1 DESCRIPTION OF THE USRD TRANSDUCERS

A2.1.1 F27

The USRD F27 is a general purpose unidirectional transducer for underwater acoustic calibrations in the frequency range 1 kHz to 40 kHz. The transducer is designed for operation in the temperature range 1 °C to 35 °C and at hydrostatic pressures of up to 35 MPa. The active element consists of fifty-five lead metaniobate discs, each of 25.4 mm diameter and 5.6 mm thick. The discs are cemented to a 25.4 mm thick tungsten backing plate. The elements are arranged in a circular array of approximate diameter 214 mm. The front face is covered with butyl rubber and the transducer is oil filled. The transducer has a nominal transmitting voltage response of 118 dB re 1 µPa·m/V at 10 kHz and a nominal low frequency capacitance of 10.4 nF at the end of 12 m of cable. The transducer is reversible and reciprocal, and the response exhibits high stability with temperature and hydrostatic pressure.

A2.1.2 F30

The USRD F30 is a general purpose unidirectional transducer for underwater acoustic calibrations in the frequency range 10 kHz to 150 kHz. The transducer is designed for operation in the temperature range 0 °C to 35 °C and at hydrostatic pressures of up to 24 MPa. The active element consists of a rectangular array of 12 lithium sulphate crystals, each of 12.4 mm by 12.7 mm by 1.59 mm. The elements are supported by rubber pads and the transducer has an oil-filled housing. The array is 50 mm high and 38 mm wide. The transducer has a nominal transmitting voltage response of 136 dB re 1 µPa·m/V at 50 kHz and a 30:1 transformer reduces the impedance to a nominal value of 100 Ω at 20 kHz. The transducer is reversible and reciprocal, and the response exhibits high stability with temperature and hydrostatic pressure.

A2.1.3 H52

The H52 hydrophone is designed as a standard hydrophone for the frequency range 20 Hz to 150 kHz. The hydrophone is designed for operation in the temperature range 0 °C to 35 °C and at hydrostatic pressures of up to 52 MPa. The active element consists of 8 lithium sulphate crystals mounted on rubber supports in a castor oil filled butyl rubber boot. A solid-state preamplifier provides low output impedance and a 10 dB voltage gain. The hydrophone response exhibits high stability with temperature and hydrostatic pressure.

A2.2 VARIATION OF RESPONSE WITH PRESSURE AND TEMPERATURE

Before delivery to NPL, USRD calibrated the three transducers in the Acoustic Pressure Tank Facility (APTF) at USRD-NUWC. Calibrations were undertaken at temperatures of 6 °C, 18 °C and 30 °C and at hydrostatic pressures of 0.14 MPa, 3.0 MPa and 7.0 MPa. The receive sensitivity calibration data was provided at logarithmic frequency intervals in the range 1 kHz to 200 kHz for the H52. Transmitting voltage response data was provided for the F30 over the same frequency range, and TVR data was provided for the F27 in the range 1 kHz to 40 kHz.

Since the frequency intervals for the data were not always the same for calibrations performed at different temperatures and pressures, it was not straightforward to determine the difference in sensitivity with pressure and temperature (and hence the coefficients). To evaluate the calibration data at a common set of frequency points, each set of calibration data was fitted with a cubic spline approximation containing a sufficient number of interior knots to reduce the RMS residual to 0.1 dB or less, thus providing a very close fit to the data. The fitted curves were then evaluated at 1 kHz intervals. This procedure was carried out using the NPLFIT software.

For each frequency, the data at the three temperatures was then used to derive a coefficient of variation with temperature for that frequency by using a linear least squares fit, the coefficients being derived from the slope of the linear fit and expressed in dB/°C. This was done for each of the three hydrostatic pressures, producing three values for the temperature coefficients. These were then averaged to provide one value of the temperature coefficient at each frequency. The standard deviations of the three values were also used to derive uncertainties which were expanded to provide a confidence level of 95%. This procedure was then repeated for the data at the three hydrostatic pressures, with the pressure coefficient being derived at each of the three temperatures and averaged in the same way, providing a coefficient expressed in dB/MPa.

There are a number of potential problems that might be envisaged with the above approach. Use of a linear fit provides quite a crude estimate of the variation in response with temperature (or pressure). It is possible that the transducer response will vary nonlinearly with temperature or pressure, but to estimate such a variation accurately requires more than the three data points available. However, the choice of a linear approximation should not introduce too great an inaccuracy if, as is the case for the examples here, the response generally varies monotonically with pressure or temperature and only by relatively small amounts over the range of interest. It is intended that NPL will characterise the reference transducers more fully in due course, providing more accurate values for the coefficients.

Another potential problem is that there is an implicit assumption that the variations with temperature and pressure are independent (ie uncorrelated). Hence the three pressure coefficients derived at three separate temperatures have been averaged to provide one value (and vice versa). Similarly, uncertainties have been calculated assuming that the three values are three independent estimates of the same coefficient. This may not be a valid assumption and there may well be correlation between the pressure and temperature coefficients. However, since at most frequencies the variations in response for these transducers is relatively small, it is believed that the errors introduced by this assumption are not too great. In any case, the existence of correlation should cause an increase in uncertainties (for example, if the temperature coefficient varies considerably as the pressure is changed).

To assess this, the correlation was calculated for the pressure and temperature coefficients for each transducer, with a parameter calculated which is zero for no correlation, +1 for positive correlation (peaks line up, troughs line up) and –1 for negative correlation (peaks line up with troughs). For the three transducers, the correlations were: -0.32 for the H52, -0.24 for the F30 and -0.72 for the F27. This would seem to indicate a degree of negative correlation.

The coefficient for each transducer are plotted in the following figures along with the uncertainties. Large values of uncertainties may indicate inaccuracies in the original calibration data, or may indicate unaccounted for correlations in the pressure and temperature coefficients.

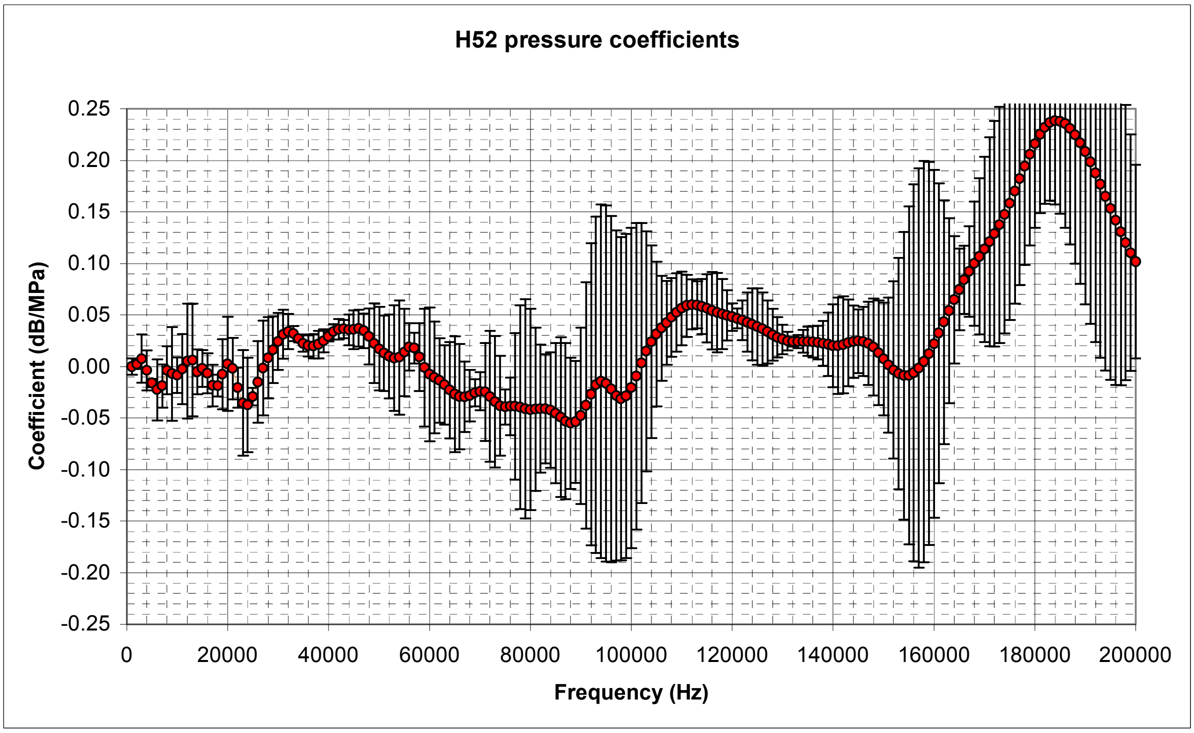

Figure A2.1: Coefficients of variation of receive sensitivity with hydrostatic pressure for the H52 (error bars are uncertainties expressed for a confidence level of 95%)

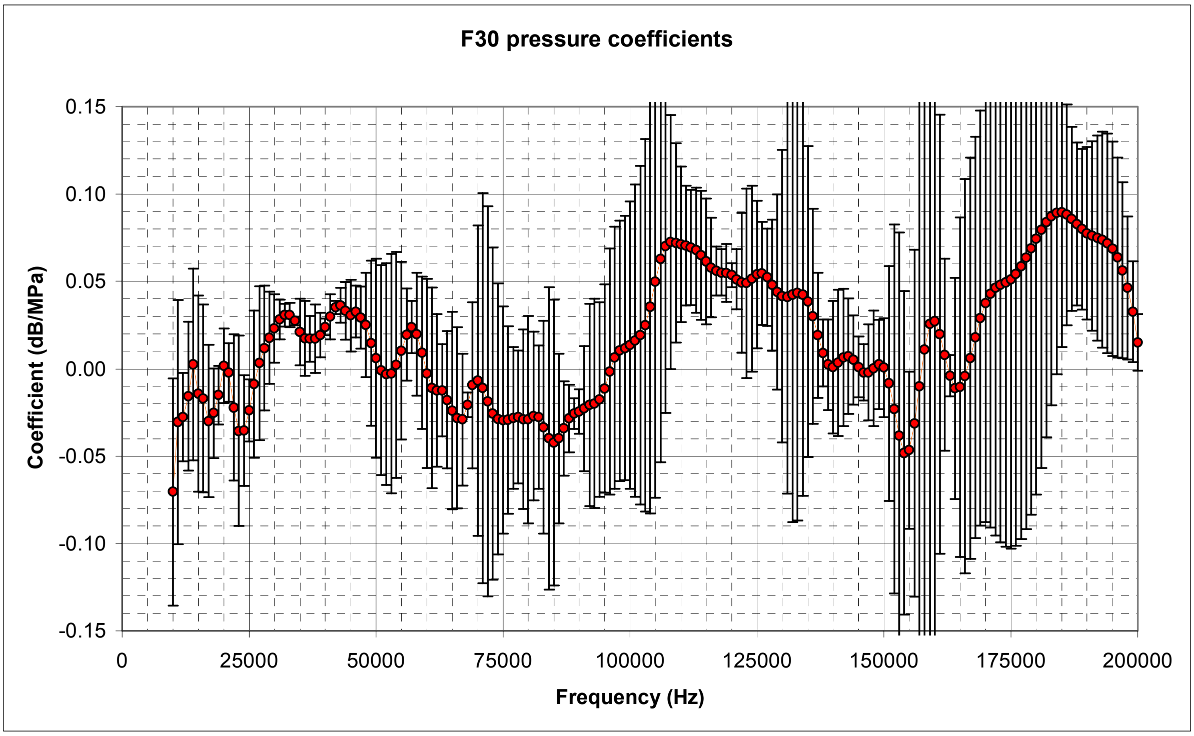

Figure A2.2: Coefficients of variation of TVR with hydrostatic pressure for the F30 (error bars are uncertainties expressed for a confidence level of 95%)

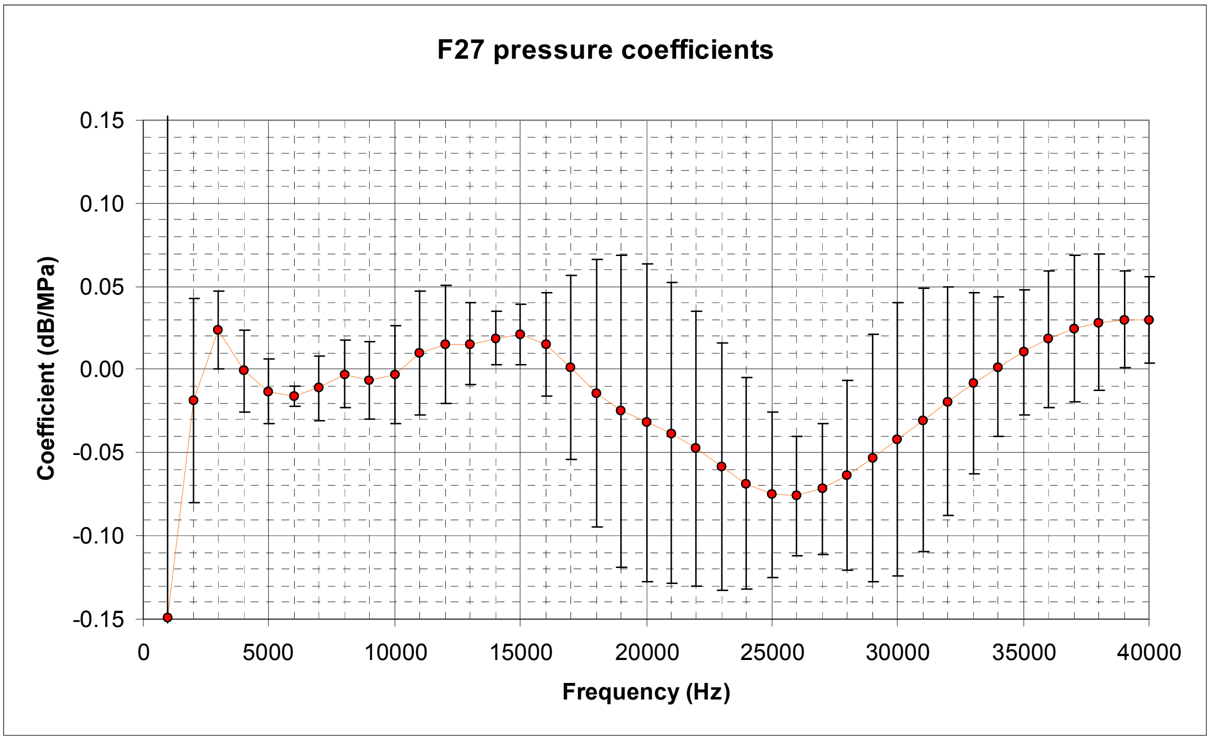

Figure A2.3: Coefficients of variation of TVR with hydrostatic pressure for the F27 (error bars are uncertainties expressed for a confidence level of 95%)

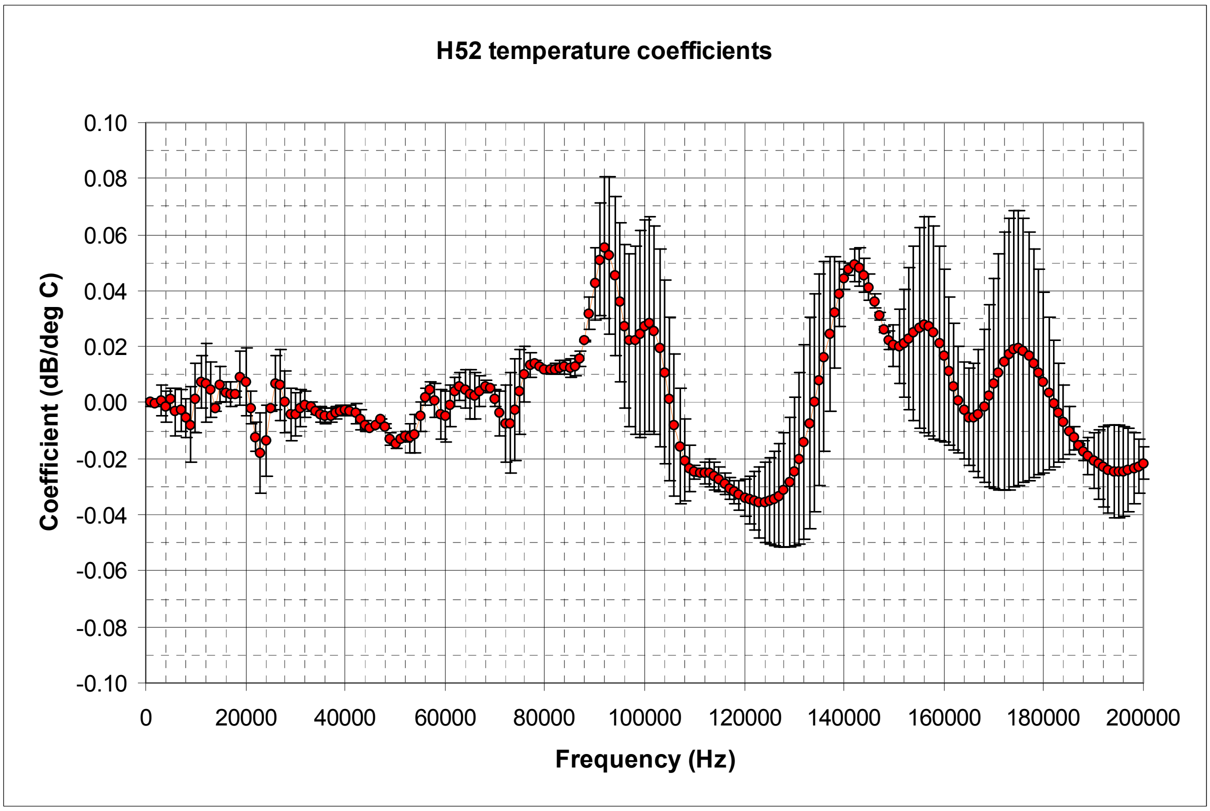

Figure A2.4: Coefficients of variation of receive sensitivity with temperature for the H52 (error bars are uncertainties expressed for a confidence level of 95%)

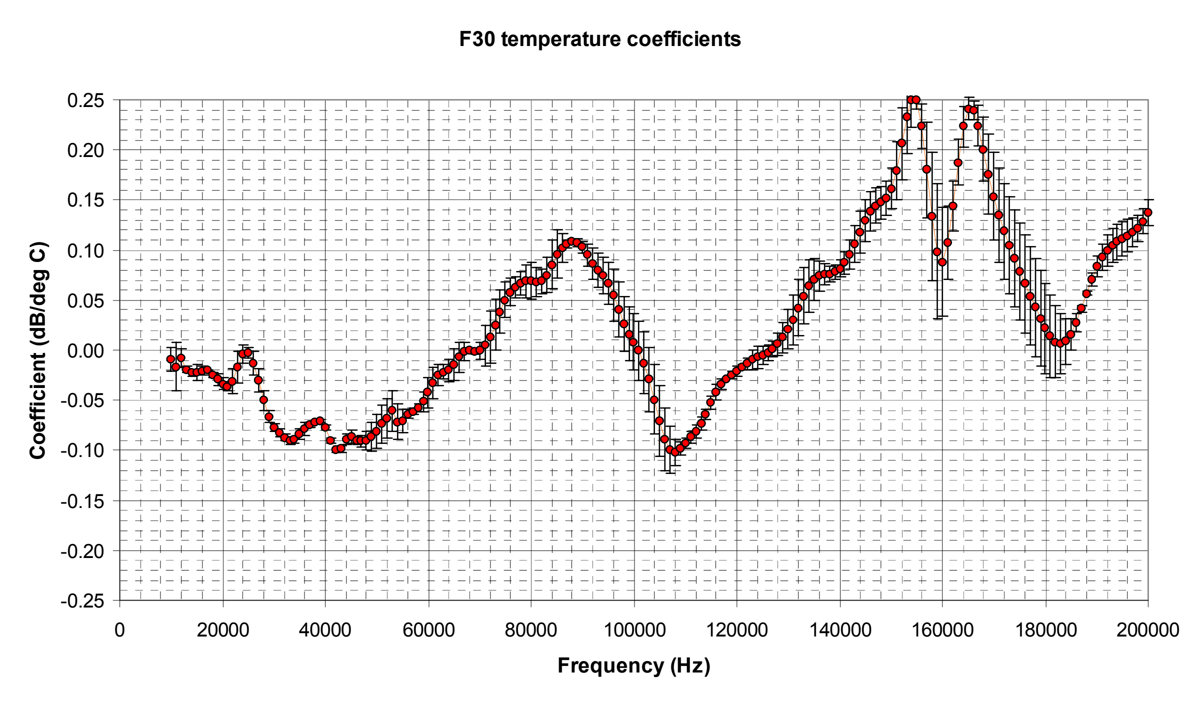

Figure A2.5: Coefficients of variation of TVR with temperature for the F30 (error bars are uncertainties expressed for a confidence level of 95%)

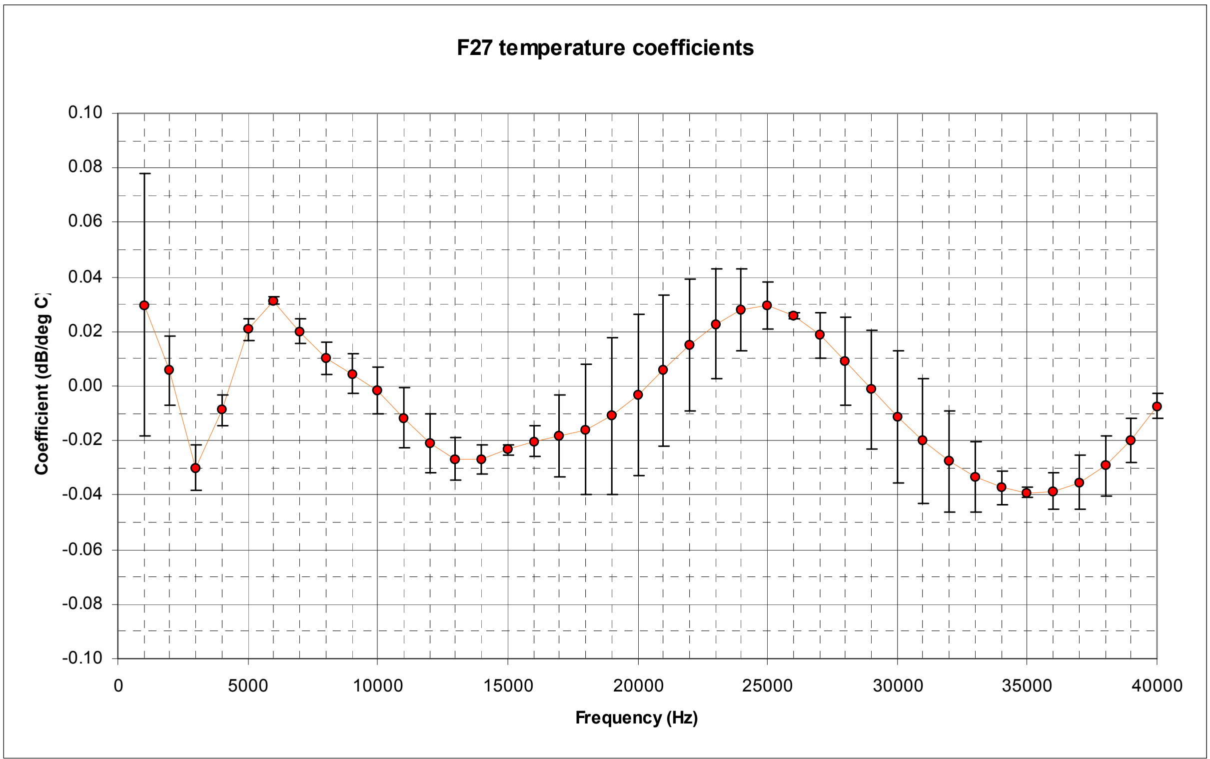

Figure A2.6: Coefficients of variation of TVR with temperature for the F27 (error bars are uncertainties expressed for a confidence level of 95%)