VARIATION IN FREE-FIELD RESPONSE CHARACTERISTICS OF HYDROPHONES WITH TEMPERATURE AND DEPTH

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1. ABSTRACT

Hydrophones are commonly used to make traceable measurements of acoustic fields in water. However, the free-field calibration of hydrophones is most often performed in a laboratory tank at water temperatures and depths that are not representative of the conditions found in the sea. Data describing the variation in hydrophone performance parameters with water temperature and depth of immersion have been difficult to obtain and are not readily available from manufacturers.

With the recent commissioning of the Acoustic Pressure Vessel (APV) at NPL, hydrophone performance parameters, such as frequency response, electrical impedance and directivity, may now be determined as a function of temperature and depth. The APV facility enables free-field calibration and testing of hydrophones and projectors in the range from a few kilohertz to 1 MHz at water temperatures from 2 °C to 35 °C, and applied hydrostatic pressures of up to 7 MPa (simulating ocean depths of up to about 700 m).

This paper provides a brief description of the calibration methodology used for measurements in the APV, and then presents the results of the characterisation of a number of commercially available hydrophones as a function of temperature and applied hydrostatic pressure. The results demonstrate that some devices exhibit a strong dependence of performance on environmental conditions, with variations in sensitivity of up to 4 dB observed as the hydrostatic pressure is increased to 7 MPa, and with similar variations also observed as the water temperature is changed. It is shown that for some hydrophones, the variation in electrical impedance with temperature and applied pressure can be a good indicator of the variation that may be expected in the absolute sensitivity.

2. INTRODUCTION

2.1 REQUIREMENT FOR UNDERWATER CALIBRATION

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 [1], and for the measurements to be meaningful, they must be traceable to common standards of measurement [2,3]. 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 [4,5].

NPL currently provides a range of both calibration and testing services for the underwater acoustics community under the DTI National Measurement System (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.

2.2 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. However, the relatively small size of the pressure vessels used restricts the range of measurements that may be undertaken, precluding the making of free-field acoustic measurements. Acoustically "transparent" pressure pots are also used in large laboratory test tanks and open water facilities, but the transparency to the acoustic field is an approximation which is valid only at low frequencies [1].

The NPL acoustic pressure vessel addresses the requirement for free-field acoustic testing of transducers at simulated ocean conditions. Commissioned in 2000, the acoustic pressure vessel (APV) is now in full operation at the National Physical Laboratory [6-8]. 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.

3. MEASUREMENT METHOD

3.1 TECHNICAL DESCRIPTION OF THE APV

The pressure vessel shown schematically in Figure 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 "petal" sections of steel, each section having a decreasing thickness toward the central areas where each domed end section is reduced to a thickness of two inches. 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 water required to fill the chamber has been added. Also highlighted in Figure 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 [9] 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 materials since these tend to exhibit an acoustic performance which is dependent on the particular environmental conditions.

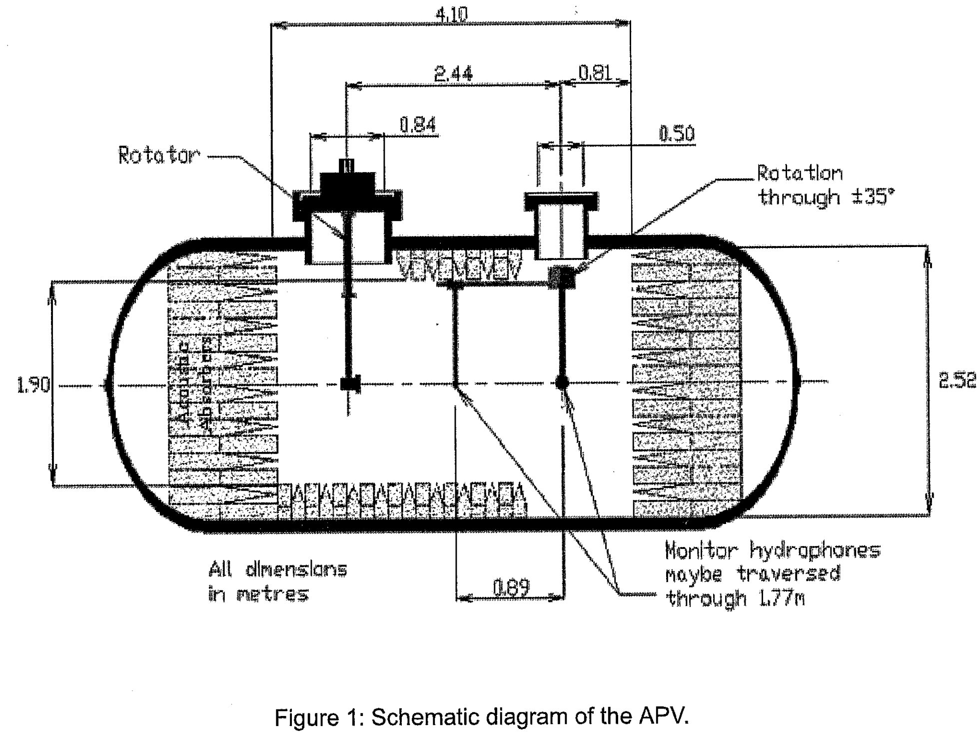

Figure 1: Schematic diagram of the APV.

There are two circular ports situated on top of the test chamber, which 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 its 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°. 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.

The ability to provide acoustic and mechanical isolation from plant equipment and ground borne noise is 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. It is possible to achieve environmental conditions lower than sea state zero within the tank when employing the air mounts.

A versatile operator control and monitoring system incorporating all non-acoustic tasks is run through a PC-based control system, 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 piece of plant equipment in the field, displaying vital information such as tank water levels, flow rates, pressures and temperatures along with valve and pump conditions.

3.2 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 [10]. 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. 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.

4. RESULTS

4.1 ELECTRICAL IMPEDANCE

4.1.1 MEASUREMENTS

The electrical impedance or admittance is an important parameter describing the behaviour of underwater electroacoustic transducers [1, 11]. 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.

The impedance analyser used in the pressure vessel facility is the Hewlett Packard HP4294A. 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 a different position to avoid a direct reflection.

4.1.2 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). 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.

Figure 2 shows an admittance plot of a B&K 8105 hydrophone measured over the frequency range 75 kHz to 175 kHz. The measurement has been made at 0.1 MPa, 0.5 MPa, 1 MPa and 7 MPa, and finally a repeat measurement has been made at 0.1 MPa. It can be seen that there is a relatively large change as the pressure increases up to 1 MPa, but then the hydrophone remains fairly stable as the pressure increases up to 7 MPa.

One possible explanation for this behaviour may be that there is some compliant material in the hydrophone moulding, which is effectively fully compressed by the time the pressure reaches 1 MPa. At higher pressures, relatively little further compression takes place resulting in only a small further 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.

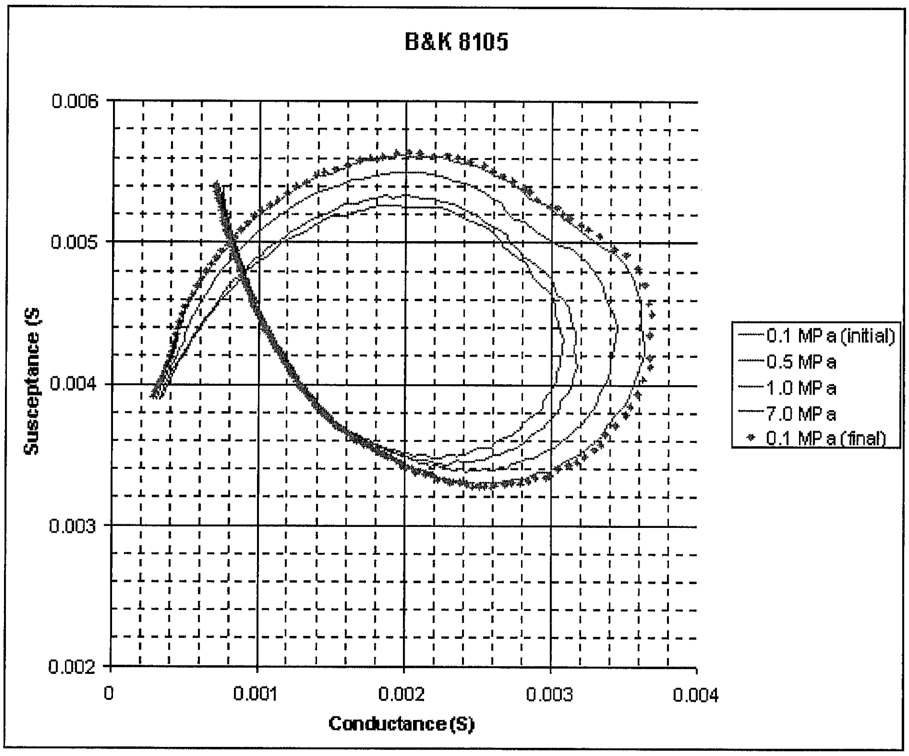

Figure 2: Admittance plot of B&K 8105 hydrophone, 75 kHz – 175 kHz.

With the pressure vessel depressurised, the conductance and susceptance of a B&K 8103 hydrophone was measured, over the frequency range 100 kHz to 370 kHz, 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. Figure 3 shows conductance versus frequency for these temperatures. From this figure we can see that, 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.

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.

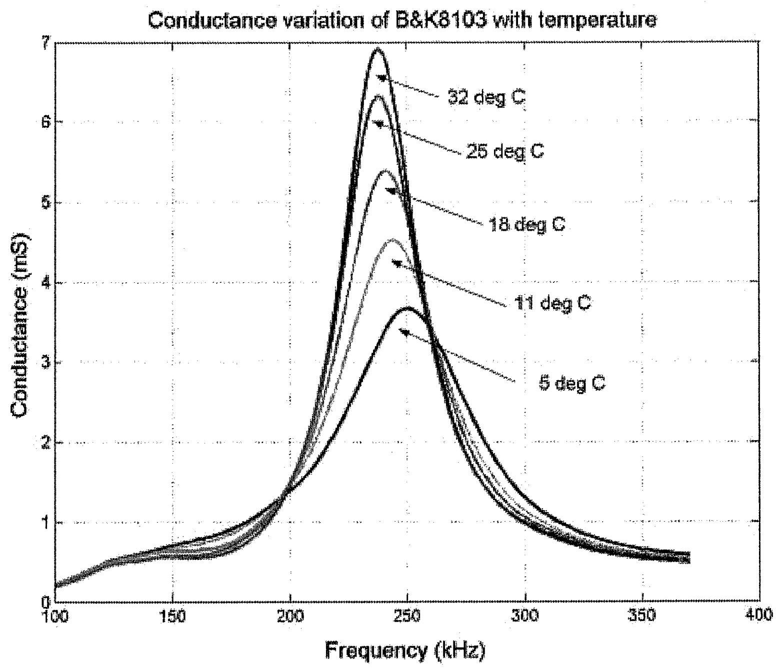

Figure 3: Variation of conductance with frequency at five temperatures for a B&K 8103.

4.2 DIRECTIONAL RESPONSE

4.2.1 MEASUREMENTS

While the performance of many sonar systems used in the ocean depends on the directional properties of their transducers and arrays [1,12], 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.

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.

4.2.2 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 reference hydrophone. The discrete scanning method was used, with measurements taken at one degree intervals. Figure 4 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 slight shift in the position of the sidelobes. 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.

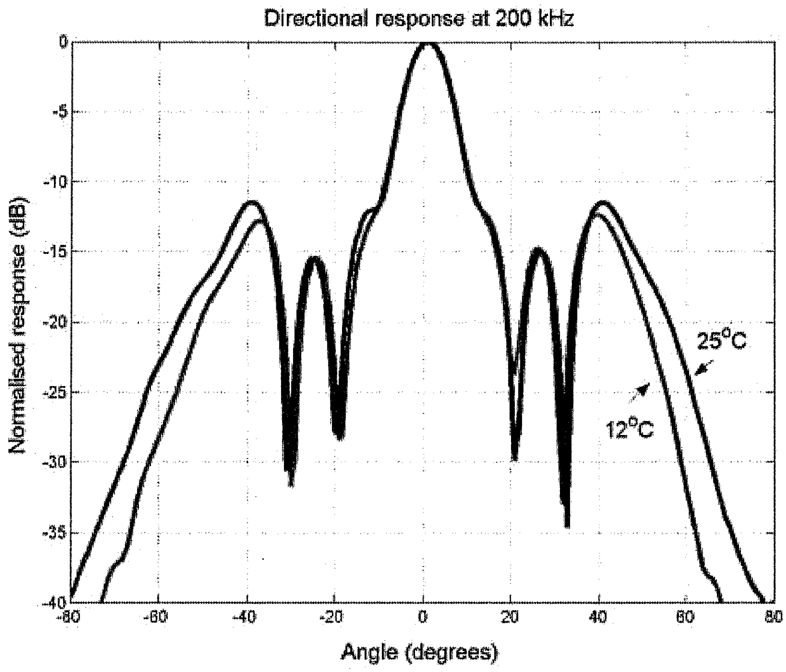

Figure 4: Directional response of the piston transducer at 200 kHz.

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 making 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.

4.3 RECEIVE SENSITIVITY

4.3.1 MEASUREMENTS

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, whether 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 [10,13] 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

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.

With the test chamber at the desired environmental condition, the impedances of both the projector and hydrophone were measured (unless the hydrophone had 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.

4.3.2 RESULTS

Figures 5 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 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. 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. 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 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 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, 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.

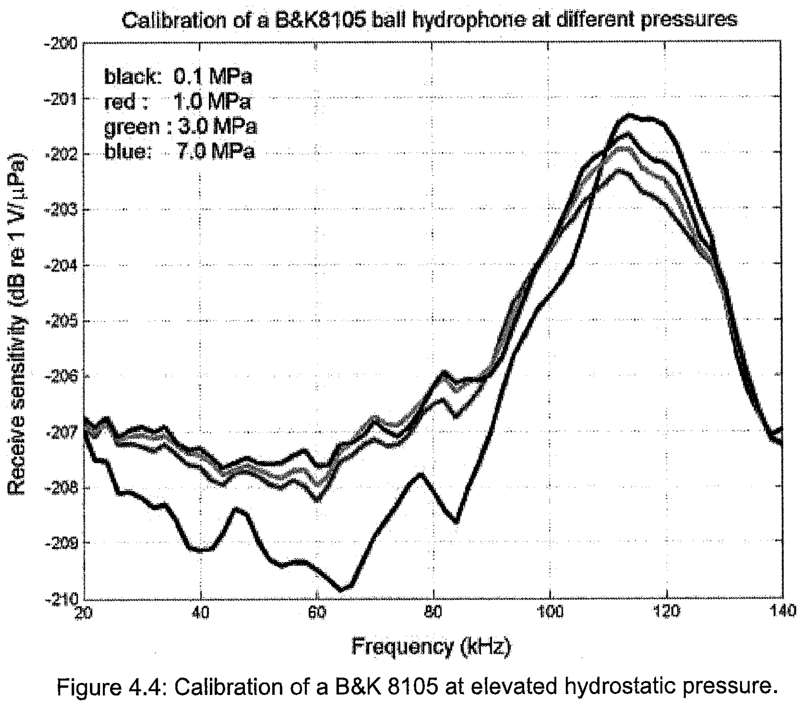

Figure 4.4: Calibration of a B&K 8105 at elevated hydrostatic pressure.

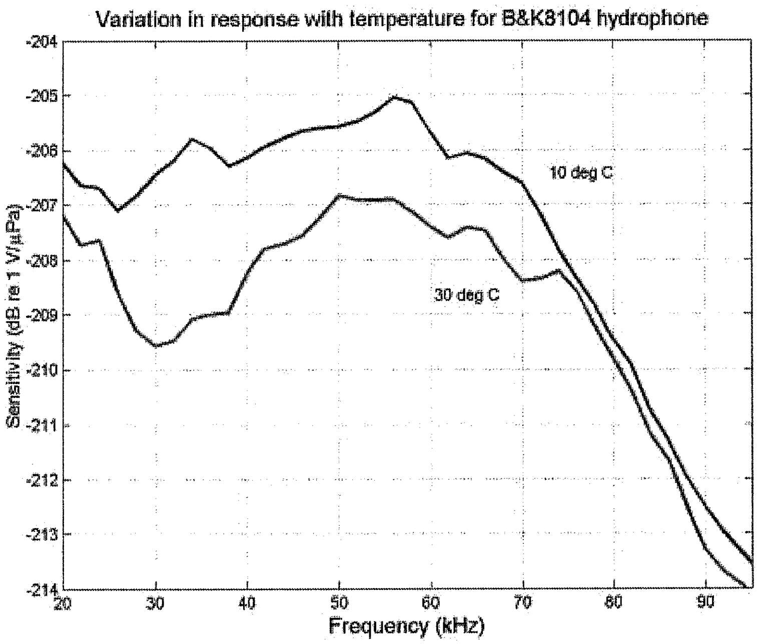

Figure 4.5: Calibration of a B&K 8104 at different temperatures.

4.4 SUMMARY

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 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 and it is clear that even hydrophones of relatively simple design can exhibit significant variations in response with hydrostatic pressure and temperature. 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.

One conclusion that may be made from the results of measurements so far is that changes in the electrical impedance are in some 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, transducers are required that may be used as reference transducers at frequencies greater than 200 kHz.

4.5 ACKNOWLEDGMENTS

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