THE EFFECT OF TEMPERATURE ON ACOUSTIC TRANSDUCER SENSITIVITY AND TRANSMITTING RESPONSE

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Abstract: *This study examines the effect of temperature on the receiving sensitivity and transmitting response of several underwater acoustic transducers and hydrophones: the Underwater Sound Reference Division (USRD) Type F30, F42A/D, H48, H52, and H56. The data were collected at the USRD over a five-year period, covering a frequency range of 1 Hz to 250 kHz and temperatures between 3°C and 35°C. The results reveal a notable inverse relationship between temperature and sensitivity below 1 kHz. For hydrophones with a preamplifier, the extent of the inverse correlation varies considerably at low frequencies where the preamplifier gain decays. Above 1 kHz the relationship is irregular, alternating between regions of no clear relationship, inverse relationship, and nonlinear relationship. The differences in sensitivity and transmitting response due to temperature follow similar trends. The findings of this study highlight the importance of calibrating transducers at the temperature they will be used for best accuracy. When temperature-matched calibration data is not available, the findings suggest extra uncertainty is present beyond that reported in calibration certificates.*

Keywords: *Received Sensitivity, Transmitting Response, Calibration, Temperature, Reciprocity, Comparison Calibration, USRD, Transducer, Hydrophone, Projector, NIST, APTF, LOFAC, Uncertainty, Piezoelectric, Coupling Gain, Electronic Impedance.*

1. INTRODUCTION

The Underwater Sound Reference Division (USRD) at the Naval Undersea Warfare Center (NUWC) Division in Newport, RI, provides underwater acoustic measurement and calibration services to government laboratories, industry, and academia both in the United States and internationally. It also operates a standards leasing program, disseminating calibrated acoustic transducers to U.S. and global customers. As the U.S. standardizing authority for underwater sound, the USRD offers measurement services traceable to the International System of Units (SI), with the National Institute of Standards and Technology (NIST) designated as the institute for sound in water [1]. USRD facilities include the Open Tank Facility (OTF), Low-Frequency Facility (LOFAC), and the Acoustic Pressure Tank Facility (APTF). These facilities and standards are supported by a research and development program focused on advancing underwater acoustic measurement techniques.

Previous research has investigated the effect of temperature on transducer sensitivity. Van Buren reported that the impact of temperature on sensitivity was a complex, frequency-dependent function. Ford et al expanded this work to 13 different transducers, showing that more complex designs exhibited larger temperature dependent differences than simple ones. Burghouwt expanded the data set to lower frequencies, showing temperature dependence was significant, particularly near the corner frequency of a built-in preamplifier. All studies have shown cases where the hydrophone's sensitivity is significantly affected. This study expanded the frequency range further, includes projectors, and investigates the contribution of preamplifiers at low frequency.

1.1. TRANSDUCERS

Understanding the design and material properties of the transducers is crucial for interpreting their temperature-dependent behavior. Key characteristics of the transducers analyzed in this research are summarized in Table 1, including housing material, piezoelectric element, preamplifier presence, oil fill, and frequency range. Images and more detailed descriptions are available in the USRD catalog [5].

Transducer	**Rubber**	**Active Element**	**Preamp (Y/N)**	**Oil Fill**	**Frequency Range**
H52	Butyl	Li_2SO_4	Y	Castor	20 Hz – 150 kHz
H56	Butyl	PZT-4	Y	Castor	10 Hz – 65 kHz
H48	Butyl	PZT-4	Y	Castor	1 Hz – 20 kHz
F42A	Polyurethane (PRC 1538)	PZT-4	N	N/A	1 kHz – 35 kHz
F42D	Polyurethane (PRC 1538)	PZT-4	N	N/A	6 kHz – 160 kHz
F30	Neoprene	Li_2SO_4	N	Castor	10 kHz – 150 kHz

Table 1: Summary of Transducer Materials.

1.2. PIEZOELECTRIC PROPERTIES

PZT-4, used in Type H48, F42, and H56 transducers, and lithium sulfate, used in Type H52 and F30 transducers, exhibit different temperature sensitivities.

1.2.1. PZT-4

The equation for sensitivity in PZT-4 for a sphere is displayed in equation 1 [7]:

$$\frac{V}{P_0} = \frac{b}{c^2 + c + 1}\left[g_{33}\left(\frac{c^2 + c - 2}{2}\right) - g_{31}\left(\frac{c^2 + c + 4}{2}\right)\right] \quad (1)$$

where V is the open-circuit voltage, P_O is the external pressure, c is the ratio of inner to outer radii, and g_{33} and g_{31} are the electromechanical constants. These constants can be expressed in terms of other material properties (Equations 2) [9].

$$g_{31} = \beta_{33}^T d_{31} = \frac{d_{31}}{\varepsilon_{33}^T}, \qquad g_{33} = \beta_{33}^T d_{33} = \frac{d_{33}}{\varepsilon_{33}^T}. \quad (2)$$

The piezoelectric charge constants d_{31} and d_{33} represent the polarization generated per unit of mechanical stress and ε_{33}^T is the dielectric permittivity. Previous research indicates that, from 0°C to 40°C, d_{31} and d_{33} vary minimally, with $d_{31} \approx -2d_{33}$ [10]. However, ε_{33}^T increases approximately linearly with temperature between 20°C and 40°C [11]. Given these relationships, the sensitivity ($\frac{V}{P_0}$) is approximately inversely proportional to ε_{33}^T, exhibiting a $\frac{1}{x}$ relationship with temperature for PZT-4.

1.2.2. LITHIUM SULFATE

Lithium sulfate used in Type H52 and F30 is also dependent on temperature for sensitivity. For frequencies well below the fundamental resonance of the crystals, the result is a constant equal to -0.0146 dB/°C [2]. This means that the sensitivity is decreasing constantly in the logarithmic scale as temperature increases.

1.3. CASING

All hydrophones in this study are encased in an elastomer to protect the active element from water, as shown in Table 1. The viscoelastic properties of these materials, particularly butyl rubber, are critical to understanding their performance, as these properties are influenced by both temperature and frequency. For example, historical USRD data [6] has demonstrated that temperature variations affect the sensitivity of butyl rubber-encased hydrophones in the 100-150 kHz range due to changes in the material's impedance. Viscoelastic materials exhibit increased molecular mobility at higher temperatures and lower frequencies, resulting in more elastic, rubber-like behavior. Conversely, they become stiffer and glass-like at lower temperatures and higher frequencies, as the reduced time for molecular relaxation restricts movement [12].

2. METHODS

The temperature sensitivity of underwater acoustic transducers was assessed through measurements at two facilities: LOFAC and APTF. LOFAC utilized both the coupler reciprocity method (for H48) and System K (for H52 and H56), while APTF conducted annual reciprocity calibrations. The lower-frequency measurements were performed at 3-5°C, 20°C, and 35-40°C, while the higher-frequency measurements were performed at 3°C, ambient (18°C-20°C), and 30°C. Table 2 summarizes the data collected, outlining the transducer type, facility, method, measured parameter (Free-Field Voltage Sensitivity (FFVS) or Transmit Voltage Response (TVR)), frequency range, number of unique serial numbers tested, total number of repetitions, and years of data collection. The F42A and F30 data represent repeated measurements of the same two units used as projector and reciprocal transducers in APTF. F30 data were only collected in 2022-2023, as it replaced a previous unit.

Unit	Facility	Method	Measurement	Frequency Range	# Units	Total # of Repetitions	Year(s) Collected
H48	LOFAC (Coupler)	Reciprocity	FFVS	1 Hz – 2000 Hz	3	3	2018-2021
H52	LOFAC (System K)	Comparison	FFVS	3 Hz – 2000 Hz	5	5	2019
H56	LOFAC (System K)	Comparison	FFVS	1 Hz – 1600 Hz	5	5	2023
H56	N/A	Coupling Gain	N/A	1 kHz – 80 kHz	1	1	2023
H52	APTF	Reciprocity	FFVS	1 kHz – 250 kHz	4	11	2018-2023
F42D	APTF	Reciprocity	FFVS	1 kHz – 250 kHz	3	9	2018-2023
F42A	APTF	Reciprocity	TVR	1 kHz – 40 kHz	2	38	2018-2023
F30	APTF	Reciprocity	TVR	40 kHz – 250 kHz	2	14	2022-2023
F42A	APTF	Electrical Impedance	N/A	1 kHz – 40 kHz	1	21	2018-2023

Table 2: Summarizing Testing Method for the Different Units.

3. RESULTS

These results show how the sensitivity of a hydrophone or transmitting response of a projector changes for a given change in temperature. The plots display the difference in sensitivity on the vertical axis for a corresponding change from ambient temperature (18-20°C) indicated in the legends. For low-frequency data (below 2 kHz), data are presented for three hydrophones (H48, H52, and H56). High-frequency results (above 2 kHz) were separated into projectors and hydrophones. The hydrophones included H52 and F42D, while the projectors comprised F42A and F30. As H52 had the largest population size, further evaluation was conducted to assess consistency for an individual serial number.

Multiple serial numbers of each model were tested, and the mean differences in sensitivity (or transmitting response) are indicated by the points in Figures 1-6. The standard deviation of the difference across the population of each model is indicated by the error bars. The standard deviation also accounts for measurement uncertainty from random sources. Measurement uncertainty from systematic sources cancels in the subtraction to calculate sensitivity and transmitting response differences.

3.1. LOW FREQUENCY

The low-frequency results consisted of data collected using the reciprocity coupler (H48) and System K (H52 and H56). Figure 1 illustrates the change in sensitivities for H48, H52, and H56 corresponding to a change from ambient temperature (20°C) to a hotter or colder extreme between 1 Hz and 2000 Hz.

The most notable temperature-dependent sensitivity change occurs in the H52 data from 1 to 60 Hz, as shown in Figure 1. When operating below the H52's rated lower limit of 20 Hz, the sensitivity variation with temperature is substantial and inconsistent across different H52 units. The mean sensitivity changes by 1 dB to 2.5 dB with temperature, and the variation between individual H52s can reach 4 dB. This variability suggests that some H52s exhibit minimal temperature sensitivity at lower frequencies, while others show significant changes. This spread coincides with the preamplifier roll-off, indicating that components controlling the time constant at the preamplifier input are susceptible to temperature variations. Given this correlation with the preamplifier, degradation of preamplifiers in some serial numbers may be a contributing factor. The H48 and H56 also exhibit this trend, albeit to a lesser extent, with the H56 showing 0.5 dB to 1 dB more variation than the H48. These data emphasize the importance of temperature-dependent calibration at low frequencies. Furthermore, a temperature correction derived for one serial number may not be applicable to another, especially below 60 Hz.

From 60 to 800 Hz (Figure 1), all units exhibit a consistent inverse relationship between temperature and sensitivity, with increasing temperature corresponding to decreasing sensitivity. While temperature increases result in negative sensitivity differences (red), temperature decreases result in positive sensitivity differences (gray and black). However, this effect is nonlinear, as the sensitivity difference is not directly proportional to the temperature change. For example, a 10°C temperature reduction (gray) produces a similar sensitivity difference to a 17°C temperature reduction (black) for the H52. These differences are consistent across different serial numbers and trials, as indicated by compact error bars that are less than 0.2 dB in many cases. Unlike the preamplifier roll-off effects below 60 Hz, the consistent temperature effects between 60 and 800 Hz suggest that a single temperature correction may be applicable across different serial numbers within this range. However, this observed relationship deviates from predictions based on the material properties of Li_2SO_4 (for H52) and PZT-4 (for H48 and H56) in section 1.2, which predicted different rates of decrease. It is important to note that the PZT-4 relationship for ε_{33}^{T} is reported for temperatures above 20°C, and the relationship may change below this temperature. Further research is needed to quantitatively connect these relationships.

At the top of Figure 1, the H48 temperature effects remain consistent up to 2000 Hz. The H48 was tested in the reciprocity coupler, designed to operate up to 2 kHz with limited noise. The H52 data only goes up to 800 Hz, as Burghouwt indicated the noise increases above that frequency, making it harder to discern meaningful temperature trends [4]. This system limitation is evident in the H56, where the data from 800 kHz to 1600 kHz appears more scattered, making it difficult to draw conclusions about temperature effects, which are similar in magnitude to the noise.

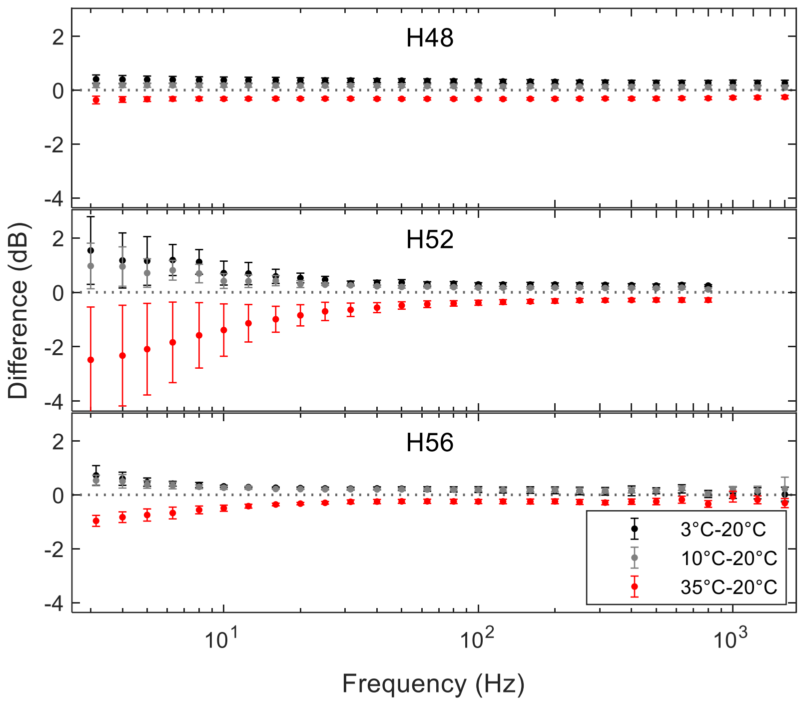

Figure 1: Comparing Mean Sensitivity Differences for Three Temperatures Compared to Ambient for H48, H52, and H56 at Low Frequency.

Figure 2 compares the change sensitivity and coupling gain across the indicated temperature differences for the Type H56. In the coupling gain measurement, an electrical signal is injected directly into the hydrophone's preamplifier and across the sensitive element using an input dedicated to this purpose. The ratio of this input signal over the resulting hydrophone output characterizes the gain of the circuit. Where the electrical properties of the preamplifier and sensitive element are controlling factors, the change in the coupling gain should predict the change in the sensitivity. The coupling gain under-predicts the sensitivity change by about 0.25 dB in the preamplifier roll-off region, and by 0.3 dB to 0.5 dB above that region. Where temperature dependent calibration is unavailable, coupling gain is a valuable prediction tool to reduce what would otherwise be a much larger error in the roll-off region.

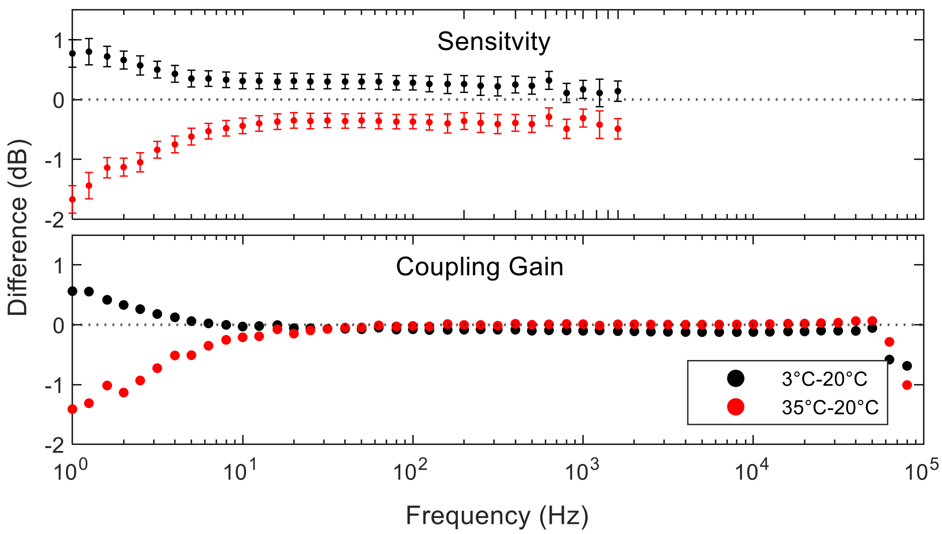

Figure 2: Comparing Sensitivity and Coupling Gain Difference for Two Temperatures Compared to Ambient for H56 SN 27

3.2. HIGH FREQUENCY

The consistent relationship between temperature and sensitivity observed at lower frequencies does not hold across the entire frequency range, as illustrated in Figure 3 for H52 and F42D devices between 1 kHz and 125 kHz. For both H52 and F42D, sensitivity and temperature exhibit an inverse relationship below 7 kHz, similar to that seen in the low frequency data above 60 Hz. This relationship disappears between 7 kHz and 35 kHz, where the overlapping red and black data points (and error bars) indicate no clear correlation. Inverse proportionality re-emerges between 35 kHz and 70 kHz. Above 70 kHz, the relationship becomes increasingly nonlinear, with sensitivity decreasing under both positive and negative temperature changes from ambient[1].

Consequently, to minimize calibration uncertainty, each unit should ideally be calibrated at its operating temperature, as a simple temperature correction formula is insufficient. Below 100 kHz, the temperature-induced sensitivity changes are within 0.5 dB, comparable to the measurement uncertainty of a calibration in this frequency range. However, the non-zero means calculated across multiple trials and units suggest a small, temperature-dependent change in sensitivity. Using these hydrophones at a temperature other than the calibration temperature would introduce an additional uncertainty of approximately 0.2 dB to 0.5 dB. Above 100 kHz, the effect is more pronounced, potentially adding up to 3.5 dB of uncertainty when operating at a different temperature. This unpredictable behavior above 100 kHz may be attributed to the temperature-dependent properties of the rubber housing materials, as discussed in Section 1.3, highlighting the need for further research on the combined effects of high frequencies and temperature on these materials.

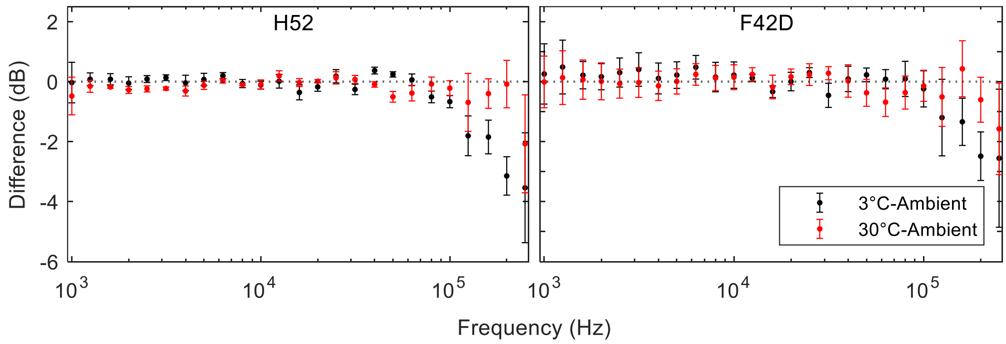

Figure 3: Comparing Mean Sensitivity Difference for Two Temperatures Compared to Ambient for H52 and F42D at High Frequency.

Analysis of the H52 dataset, comprising 11 calibrations spanning 5 years and 4 serial numbers, demonstrates the consistency of the sensitivity-temperature relationship across the H52 model range. Figure 4 compares serial number 47 (right graph) to the aggregated results of the other three serial numbers (left graph). Isolating other serial numbers and comparing them with the remaining three shows a similar trend. The similarity between these graphs below 100 kHz, in both pattern and error bar size, suggests a consistent sensitivity-temperature variation across H52s. This implies that the results from a single unit can be extrapolated to other H52 units, potentially simplifying testing procedures and reducing the need for extensive testing of multiple units.

[1] In these datasets ambient temperature is 18°C or 20°C.

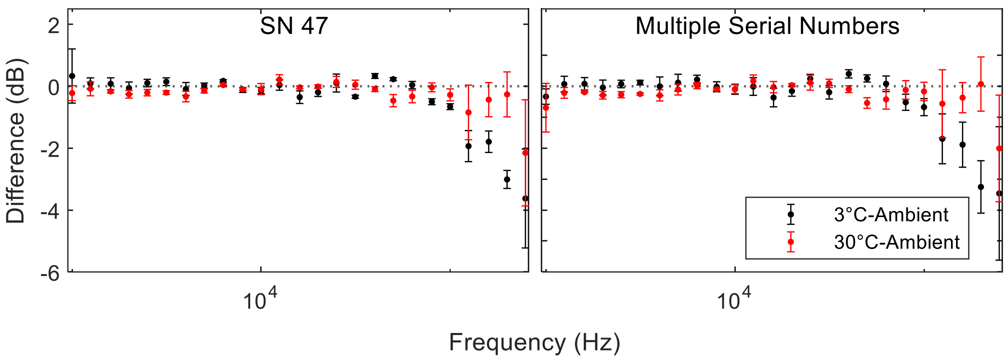

Figure 4: Comparing Mean Sensitivity Difference for Two Temperatures Compared to Ambient for One Serial Number (H52 SN 47) to Multiple Serial Numbers.

Figure 5 presents the results for the difference in transmit response compared to ambient conditions at various temperatures. The Type F42A (left graph) results exhibit a similar pattern to the sensitivity differences observed for the similarly constructed Type F42D hydrophone in this frequency range. In contrast, the Type F30 projector exhibits a larger temperature difference at 40 kHz, with the temperature difference decreasing from 40 to 63 kHz. Above 70 kHz, the uncertainty increases significantly. Separating the serial numbers (middle and right graph) reveals inverted behaviors, where one unit displays higher sensitivity at hotter temperatures, while the other displays lower sensitivity compared to ambient. This contrasts with the H52, where each serial number displayed the same pattern, suggesting that, for the Type F30 transducer, temperature effects cannot be extrapolated from one unit to another. Therefore, each unit requires individual testing to characterize its temperature dependence.

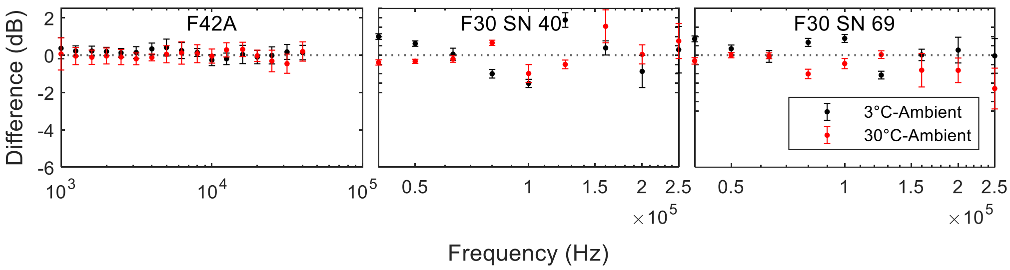

Figure 5: Comparing Mean Transmitting Response Difference for Two Temperatures Compared to Ambient for Projectors F42A (left), F30 SN 40 (middle) and SN 69 (right).

Since electrical impedance can indicate unit stability, the temperature-induced deviation in decibels was analyzed for the electronic impedance of the Type F42A projector, encompassing 21 calibrations spanning 5 years. Figure 6 compares the difference in transmitting response for the Type F42A with the difference in electrical impedance across the indicated temperatures. The difference, reported in decibels, remains relatively constant from 1 to 30 kHz, with 3°C exhibiting an electrical impedance 0.1 dB greater than ambient and 30°C exhibiting an electrical impedance 0.3 dB less than ambient. Similar to the coupling measurement, electrical impedance appears to be one of the variables influencing temperature variation, but not the only factor influencing change in transmitting response. The differences in transmitting response and electronic impedance are closely correlated up to approximately 10 kHz, above which the temperature dependence of the transmitting response inverts until around 20 kHz. Thus, while electrical impedance measurements can provide insights into the effects of temperature on a unit, they cannot replace the need for calibrating specific units at their intended operating temperature.

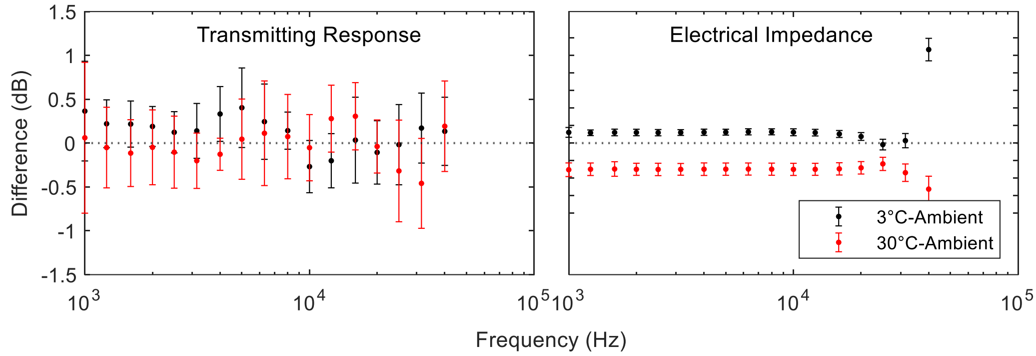

Figure 6: Comparing Mean Electrical Impedance Difference to Transmitting Response at Two Temperatures Compared to Ambient for F42A SN 141.

4. CONCLUSION

This study demonstrates the complex and often unpredictable effects of temperature on the sensitivity and transmitting response of USRD underwater acoustic transducers. The relationship between temperature and sensitivity is inverse below 1 kHz. Above 1 kHz there are regions of no clear relationship, inverse relationship, and nonlinear relationship, suggesting the contribution of factors beyond the temperature dependence of the lithium sulfate and PZT-4 piezoelectric properties. The findings reveal that the temperature dependence varies with transducer type and material, frequency, and the presence of preamplifiers, precluding the use of simple temperature corrections.

A key conclusion is that accurate underwater acoustic measurements require careful temperature management and, ideally, calibration at the intended operating temperature. Particularly below 20 Hz (with preamplifier-equipped hydrophones) and above 100 kHz, relying solely on nominal calibration data can introduce 1 dB to 3.5 dB of calibration error, significantly greater than the calibration uncertainty provided on USRD calibration certificates. At low frequencies when preamplifier roll-off is a controlling factor of the hydrophone sensitivity, a coupling gain style measurement can characterize all but about 0.25 dB of this error. At high frequencies, impedance measurements can predict some of this error.

Ultimately, this research reinforces the need for caution when interpreting underwater acoustic data acquired at temperatures different from the calibration temperature. Further research in methods for accounting for temperature effects on sensitivity and transmitting response could reduce the need for time-consuming and expensive testing, at least for some consistent and well-understood hydrophones, increasing the availability of accurate underwater acoustic measurements across a wide range of applications.

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