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Impact of Voice-Coil Temperature on Electroacoustic Parameters for Optimized Loudspeaker Enclosure Design in Small-Signal Response

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ABSTRACT

The study of electroacoustic parameters in relation to loudspeaker temperature has predominantly focused on large-signal conditions (i.e., high-power audio signals), with limited attention to their behavior under small-signal conditions at equivalent thermal states. This research addresses this gap by investigating the influence of voice-coil temperature on electroacoustic parameters during small-signal operation. The frequency response of the electrical input impedance and the radiated acoustic pressure were measured across different voice-coil temperatures. The results revealed temperature-dependent changes in all parameters, including natural frequency in free air f_s , mechanical quality factor Q_{MS} , electrical resistance R_E , electrical inductance L_E , and equivalent compliance volume V_{AS} . Notably, R_E and L_E increased linearly with temperature, while f_s decreased and V_{AS} increased, suggesting a combined effect of air mass and variation in compliance. These shifts point to thermally induced changes in both the electrical and mechanical domains, likely amplified by viscoelastic creep in the suspension. Finally, simulations of sealed and bandpass enclosures showed measurable shifts in frequency response and bandwidth under thermal variations, reinforcing the importance of considering temperature effects when selecting electroacoustic parameters for enclosure design.

1 Introduction

Exactly a century has passed since Rice and Kellogg [1] introduced the first hornless electrodynamic loudspeaker, radiating directly into free air, an innovation that laid the foundation for modern loudspeaker design and remains dominant in sound reproduction systems

[2, 3]. Modeled via electrical, mechanical, acoustic, and thermal analogies, this system has enabled advanced analysis and simulation [4, 5, 6]. Despite their extensive use, this type of loudspeakers face inherent limitations, particularly in efficiency, due to thermal dissipation, restricting acoustic output, and introducing

undesired non-linearities [7, 8].

A well-documented phenomenon is the increase in electrical resistance (R_E) of the voice-coil with increasing temperature [9, 10, 11, 12, 13], which increases approximately 0.4% per 1 °C. This results in measurable decreases in sensitivity (up to 6 dB when the temperature doubles) and performance, including: (1) a reduction in reference efficiency (η_0), (2) a rise in the electrical quality factor (Q_{ES}), and (3) increased input impedance (Z_E), all of which affect the shape of the transfer function, power handling, and voltage sensitivity [13, 14].

Although thermal effects are well characterized under large-signal conditions [6], where non-linear and time-dependent effects dominate, their impact in small-signal conditions has been less explored. Small-signal measurements, where the system is assumed linear, are commonly used to determine Thiele-Small (TS) parameters for enclosure design. However, voice-coil temperature during these measurements may significantly affect the TS parameters.

This study builds on our previous work [15, 16] by evaluating how variation in voice-coil temperature influences the TS parameters and consequently the electroacoustic performance of the loudspeaker under small signal conditions. We propose a framework for analyzing these effects and identifying thermally stable TS parameter sets, suitable for accurate enclosure design.

2 Materials and Methods

The methodological approach of this study is based on established theoretical models of loudspeaker behavior in the electrical, mechanical, acoustical, and thermal domains. This includes modeling input electrical impedance, the temperature-dependent variation of voice-coil resistance [17], and dual-path thermal dissipation frameworks [10]. Furthermore, small signal mechanical and acoustic responses are characterized based on classical modeling [4, 18], while enclosure behavior is supported by classical work on sealed and bandpass designs [19, 20, 21, 22]. These models form the basis for the experimental design, parameter estimation, and simulation strategies described below.

The loudspeaker chosen for testing was a *Peerless* model *SLS-P830667* with an 8" diameter, specifically selected for its typical characteristics as a voice-coil woofer. Its overhung design allowed for direct measurement of the voice-coil, which was visible (see Figure 1).

The voice-coil temperature was monitored throughout the experiment using a non-contact infrared thermometer *Smart Sensor* and an infrared thermographic camera model *HTI HT – 02D*.

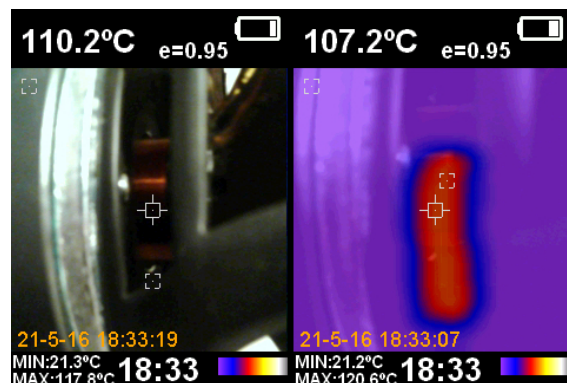


Fig. 1: Thermal images of the loudspeaker in operation. Left: Visible image. Right: Infrared image.

The experimental method involved gradually increasing the temperature of the voice coil using a Samson Servo 120a voltage source audio amplifier. This procedure is referred to as the "burning stage" (BS) of the experiment. The test signal to increase the temperature in BS was a sine waveform of 192 Hz where the electrical current and power dissipation are maximum with 3.655 V_{RMS} at the loudspeaker terminals for the given loudspeaker sample. A Scarlett 2i4 Focusrite USB audio interface model was used to generate the signal to test the device. The electrical input impedance of the loudspeaker was measured using the DATS V3 system (*Dayton Audio*, Indiana, USA). Figure 2 shows the setup for the measurements.

In addition, the acoustic frequency response of the loudspeaker was measured using the acoustical measurement software *Room EQ Wizard* (REW) and a measurement microphone *Behringer ECM8000*, which was used in the near-field of the loudspeaker at low frequency of the piston range ($ka < 1$), following the methods of [23], as shown in Fig. 3.

2.1 Measurement of the input electrical impedance at different temperatures

Electrical measurements were initiated by first recording the loudspeaker under ambient temperature conditions. Subsequently, the loudspeaker was subjected to an excitation with a high audio level signal of +30 dBu

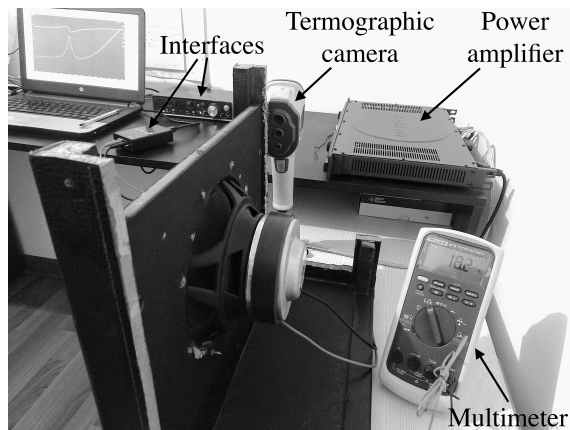


Fig. 2: Setup of the electrical and thermal measurements of the loudspeaker.

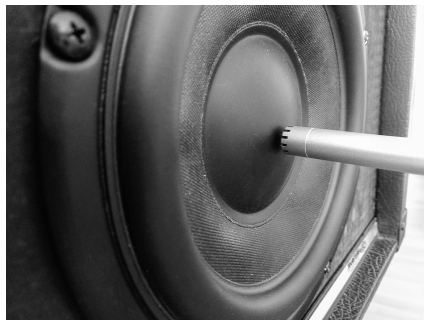


Fig. 3: Setup of the near-field measurement at different loudspeaker voice-coil temperatures.

(24.5 V_{RMS}) measured at the loudspeaker terminals until the voice-coil reached 130 °C. Higher temperatures can be used, but to avoid system failure (damage on the loudspeaker or/and audio amplifier), the 130 °C was considered reasonable for the experiment following the recommendations in [8]. Once the desired coil temperature was reached, 19 simultaneous measurements (electrical impedance and acoustic pressure) were made as quickly as possible in the first instant of time (due to the rapid exponential decay of the temperature) with a nominal audio level of +4 dBu (1.23 V_{RMS}). The temperature recordings of the loudspeaker's voice-coil revealed that it took 65 seconds to obtain the first 14 impedance recordings. Subsequent impedance measurements were taken in progressively longer and varying time intervals, at which differences of 3 °C were expected to be recorded, reflecting a slower decay rate as the temperature decreased, as shown in Fig. 4. The

final impedance record, at 23 °C, was captured approximately 48 minutes after the first measurement.

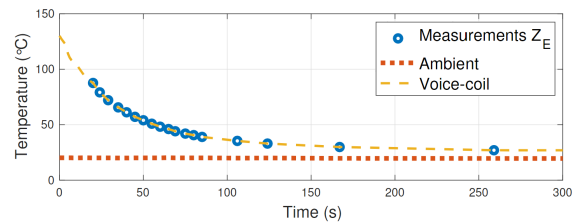


Fig. 4: Recording of loudspeaker temperatures for the first 18 input electrical impedance measurements.

2.2 Obtaining parameters, curve fitting, and simulations at different temperatures

TS and electromechanical parameters were obtained from each of the 20 input electrical impedance measurements conducted for different temperature variations of the voice-coil. The voice-coil at ambient temperature (20 °C) was used to obtain the volume compliance of the driver suspension (V_{AS}) and the electromechanical parameters through the added-mass method, following the criteria established by [24]. In the case of the remaining 19 measurements, where the temperature of the voice-coil varied, the specified mass method described by [25] was used. This approach was chosen because using the added-mass method would have required repeating the impedance measurement, which would have been complex and could introduce inaccuracies, particularly in controlling the different variables from the previous measurement, such as maintaining the same coil temperatures. Consequently, it was assumed that the mass of the loudspeaker diaphragm M_{MD} (31.5 g), measured using the added mass method for the coil at ambient temperature, would remain constant throughout the variation of the temperature of the loudspeaker coil.

The relationship between the loudspeaker parameters was determined and analyzed through curve fitting analysis once they were obtained for the different voice-coil temperatures. Different models were used for curve fitting analysis to describe the behavior of the parameters as a function of temperature. The linear model was used only for highly linear correlations ($r \geq 0.95$). For the remaining loudspeaker parameters, the power model and the exponential model were utilized.

Subsequently, the goodness of fit of the curves was evaluated using the adjusted coefficient of determination ($\bar{R}^2$) and the sum of squares of error (SSE). To validate the results obtained from the fitted curves, a comparison was made with classical loudspeaker temperature models for R_E . This comparison also extended to Q_{ES} and η_0 , as described in previous works [6, 9, 10, 12, 26].

Following this, simulations of the input electrical impedance, displacement, velocity, and volume velocity emitted by the diaphragm, acoustic frequency response, and loudspeaker efficiency were obtained from estimated TS parameters for different temperatures of the voice-coil. Measurements of the input electrical impedance and acoustic frequency response of the loudspeaker were used for comparison with these simulations.

2.3 Acoustic measurement frequency response at different temperatures

For the acoustic measurement, the loudspeaker was again initially measured at room temperature. Subsequently, the frequency response of the loudspeaker was measured and recorded for different voice-coil temperatures. This was achieved measuring as quickly as possible after being excited, resulting in 17 measurements through the natural exponential decay of the temperature.

The variation of the frequency response with respect to the increase in the temperature of the voice-coil was analyzed. The responses in the 1/24 octave were smoothed and the relative levels of the frequency responses at different temperatures of the voice-coil were determined with respect to the voice-coil at ambient temperature. Finally, to analyze the slopes of the rise and useful band of the loudspeaker, the power model was utilized to fit the best straight line describing their behavior for each frequency response as the temperature of the voice-coil increases.

2.4 Enclosures design based on voice-coil temperature

The voice-coil at both ambient and elevated temperatures was used to design and simulate a sealed (closed-box) and bandpass system. The latter was set at approximately the temperature at which the TS parameters reached a stable value (45 °C). For the sealed enclosure, a single volume of enclosed air V_{AB} was optimized

to achieve a highly efficient system (absorbent material was not taken into account). Similarly, the procedure was applied to a fourth-order bandpass loudspeaker system with a fixed volume of enclosed rear air V_{AB1} , while the front air volume remained vented V_{AB2} . Due to the characteristics of the loudspeaker, the design of a vented enclosure was not considered in this study.

To carry out the experiment and the proposed criterion for enclosure design, the TS parameters were measured using the added mass method for the voice-coil of the loudspeaker at ambient temperature (26.4 °C) and then heated to simulate and compare the responses at elevated temperature (49.9 °C). To achieve this without requiring additional instrumentation, the voice-coil was heated using a small localized heat source placed near the diaphragm. Due to the low thermal capacitance of the voice-coil, its thermal time constant is rapid. In contrast, the measurement of the warm voice-coil was conducted after ten minutes of heating when it stabilized, considering the high thermal capacitance of the magnetic structure and its thermal time constant. The temperature of the magnetic structure was not accounted for in this research.

3 Results

This section provides results obtained from various loudspeaker measurements and simulations.

3.1 Electrical input impedance of the loudspeaker at different temperatures

Fig. 5 (top and bottom) shows the measurements of the electrical input impedance of the loudspeaker at various temperature values of the voice-coil. A consistent increase in magnitude across the entire bandwidth was revealed when temperatures increased, except for a frequency range between 57 and 100 Hz. At higher frequencies, the impedance is dominated by the voice-coil inductance and seems to be independent of each other as the temperature increases. As the temperature of the voice-coil increased, the phase response exhibited upward and downward fluctuations throughout the frequency range. Notably, it was found to have two pivot points: at DC and for a frequency of around 200 Hz. This fact may indicate that effective moving mass and voice-coil inductance are independent of rising temperature.

These results illustrate the influence of temperature on the given loudspeaker's electrical response, particularly the variations in magnitude and phase, underscoring the importance of considering thermal effects in understanding and optimizing loudspeaker performance. These results are key for estimating the proper TS parameter of our method in the following sections.

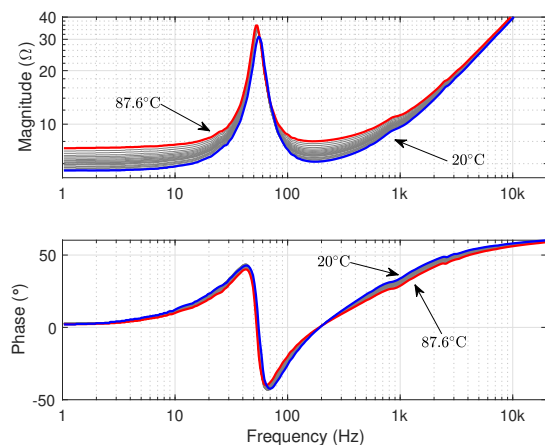


Fig. 5: Loudspeaker input electrical impedance measured at different voice-coil temperatures. Top: Magnitude. Bottom: Phase.

3.2 Parameters, curve fitting, and simulations at different temperatures

The parameters for different voice-coil temperatures were fitted using linear and non-linear regression techniques and are pictured in Fig. 6. In particular, the parameters Q_{ES} , Q_{TS} , R_E , L_E , and η_0 were modeled as linear functions, where the electrical quality factor Q_{ES} increased by $0.004/^{\circ}\text{C}$, the total quality factor Q_{TS} increased by $0.003/^{\circ}\text{C}$, electrical resistance R_E increased by $0.030 \Omega/^{\circ}\text{C}$, electrical inductance L_E increased by $0.0014 \text{ mH}/^{\circ}\text{C}$, and reference efficiency η_0 decreased by $0.00098 \text{ } \%/^{\circ}\text{C}$. On the other hand, f_S and V_{AS} were modeled as power functions, while Q_{MS} was modeled as an exponential function.

The goodness-of-fit results shows that all fitted models explained more than 95% ($\bar{R}^2 > 0.95$) of the total variation of the data over the average. Furthermore, the sum of squares of error (SSE) indicated that the discrepancy between all data and the fitted models was very low ($\text{SSE} \ll 1$), as shown in Fig. 6.

The results of the simulation of the electrical impedance of the input of the loudspeaker at different temperatures of the voice-coil are shown in Fig. 7 (top). It can be observed that the measured response is very well fitted by the lossless inductance model, except for the high-frequency range. In this band, the magnitude of the electrical impedance increases with increasing frequency and the temperature of the voice-coil. For example, at 20 kHz, the variation in the magnitude of the actual response is 2.2Ω , while in the simulated response it is 12.3Ω .

Fig. 7 (bottom) shows the displacement results indicated that as the temperature of the voice-coil increased, the loudspeaker's displacement decreased. The coil temperature was increased by 67.6°C from the ambient temperature, resulting in a maximum variation of 0.15 mm at the lower limit of the low frequency, a minimum variation of 0.02 mm near f_S and a subsequent maximum variation of 0.67 mm above f_S . Similarly, the velocity and volume velocity emitted by the diaphragm also decreased with increasing temperature of the voice-coil. The minimum variation occurred near f_S , with values of 0.006 m/s for the velocity and $0.00013 \text{ m}^3/\text{s}$ for the volume velocity, respectively. Maximum variations were observed at 100 Hz, with values of 0.03 m/s and $0.00079 \text{ m}^3/\text{s}$ for velocity and volume velocity, respectively. Comparable displacement and velocity behaviors of the loudspeaker diaphragm were reported in [27].

Figure 8 (top) shows the results of the simulated sound pressure level measured at one meter on the axis for an input voltage of $2.83 \text{ V}_{\text{RMS}}$ showed that with increasing temperature, the bandwidth increased and its sensitivity decreased minimally against the maximum measured increase of temperature by 0.13 dB at 48 Hz, and decreased a maximum of 2.30 dB at 230 Hz. At high frequencies, the sensitivity variation tended to be constant concerning the increase in the temperature of the voice-coil of the loudspeaker. Finally, the results of the loudspeaker efficiency showed that it decreased with f_S as the temperature of the voice-coil increased, reaching a maximum variation of 0.19% and a constant variation of 0.05% in the band between 200 and 1000 Hz for an increase in temperature by 67.6°C . In addition, the sensitivity did not vary at high frequencies with increasing voice-coil temperature. However, at frequencies below f_S , the efficiency increased with increasing voice-coil temperature, reaching a maximum variation of 0.13% and tends to remain unchanged for

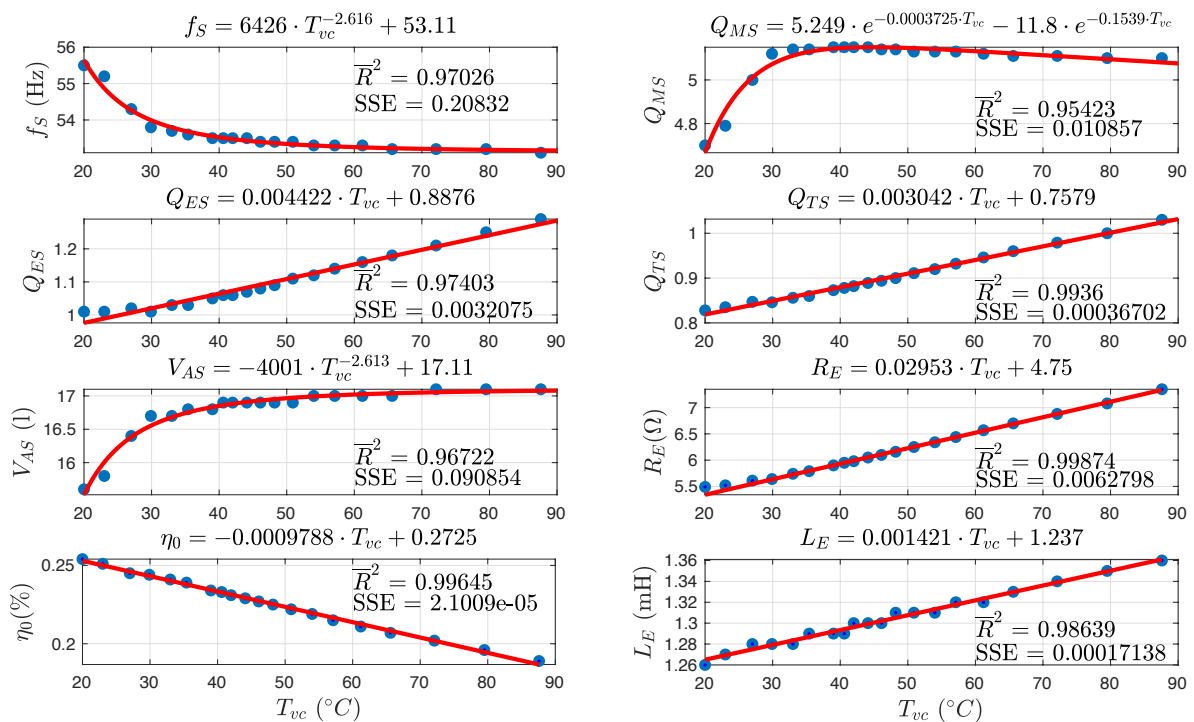


Fig. 6: Curve fitting of loudspeaker parameters as a function of voice-coil temperature for $T \in [20, 90]$, through linear, potential, and exponential models, with their respective adjusted coefficients of determination ($\bar{R}^2$) and the sum of the square of errors (SSE).

very low frequency by increasing the temperature by 67.6 °C, as shown in Figure 8 (bottom).

3.3 Frequency response at different temperatures

Figure 9 shows that the measured sound pressure level tended to decrease with increasing temperature, at least up to 660 Hz, which was the maximum frequency in the near field. In the frequency range below mechanical resonance, a maximum relative level of -2.63 dB was reached by increasing the temperature of the voice-coil by approximately 100 °C. At the same temperature increase, the relative level reached a minimum of -0.77 dB in the f_s region. Furthermore, upon f_s in the proper band of the loudspeaker, the relative level again reached a maximum of -2.96 dB. The entire frequency range analyzed exhibited a maximum estimated relative level of -3.46 dB at 577.2 Hz.

However, the power models fitted for the frequency range below f_s indicated that the rise in slope increased

as the temperature of the voice-coil increased. In this range, a temperature increase of 100 °C led to an increase in the slope of 1.5 dB / Oct. In contrast, the slope decreased as the temperature of the voice-coil increased for the frequency range above f_s . In this range, a temperature increase of about 100 °C decreased the slope by 0.3 dB/Oct.

3.4 Enclosures response considering temperature

Given the above analysis, we propose to select a specific set of TS parameters to design a loudspeaker enclosure. The criterion for selecting the TS parameters is when the temperature increases to a stable value on the curves f_s , Q_{MS} , and V_{AS} shown in Fig. 6. This range indicates when the TS parameters have reached a warming point that can be stable enough for a confident enclosure design. The loudspeaker reaches a plateau temperature at ≈ 50 °C. Using the set of TS parameters at this temperature, a closed and a bandpass enclosure

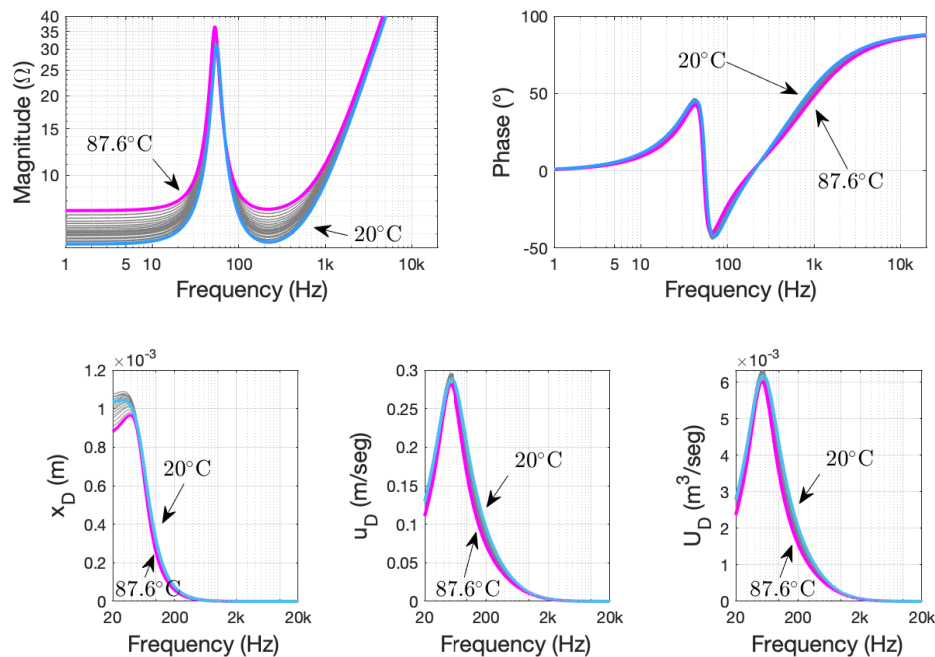


Fig. 7: Simulation of the loudspeaker's electrical, and mechanical responses at different measured voice-coil temperatures. Top: Electrical input impedance. Bottom: Diaphragm displacement and velocities.

are compared with designs at room temperature. The simulation results are shown in Fig. 10.

The closed-box in Fig. 10 (top) revealed that while maintaining the same sealed enclosure volume ($V_{AB} = 22$ L), a slight reduction in the low-frequency response was observed. This decrease could be attributed to the influence of the warmer voice-coil condition on f_S and Q_{TC} . However, for the bandpass enclosure in Fig. 10 (bottom), the volume of the rear sealed enclosure ($V_{AB1} = 6$ L) remained the same for the bandpass loudspeaker system. Consequently, the design based on the warm voice-coil condition exhibited a slightly lower total system quality factor Q_4 , vented front box volume V_{AB2} , and bandpass width Δf compared to the results obtained at ambient temperature, from 213.9 to 179 Hz, due to the increase in the lower cutoff frequency from 38.1 to 40 Hz and the decrease in the upper cutoff frequency from 252 to 219 Hz.

4 Discussion

The results presented here highlight the sensitivity of the TS and electroacoustic parameters to temperature changes, even under small-signal conditions. A

methodological novelty in this study lies in the use of a controlled excitation stage to induce temperature elevation, followed by low-level measurements to preserve linearity while capturing thermal effects.

The observed variations in parameters such as R_E , L_E , f_S , Q_{MS} , and V_{AS} , among others, confirm that temperature influences not only the electrical domain but also mechanical and acoustic properties. In particular, the decrease in f_S and the increase in V_{AS} suggest that both the suspension compliance and the effective mass of air adjacent to the diaphragm are thermally modulated. These combined effects lead to shifts in mechanical resonance, which are critical in tuning enclosure responses.

For loudspeaker enclosure design, these thermal shifts imply that enclosure tuning based on TS parameters measured at room temperature may not translate accurately to real-world operating conditions, especially under sustained thermal load.

Although the mechanical mass M_{MD} was assumed constant, the behavior of f_S and V_{AS} suggests a temperature-dependent increase in compliance, possibly due to softening of suspension materials, reduction in air density

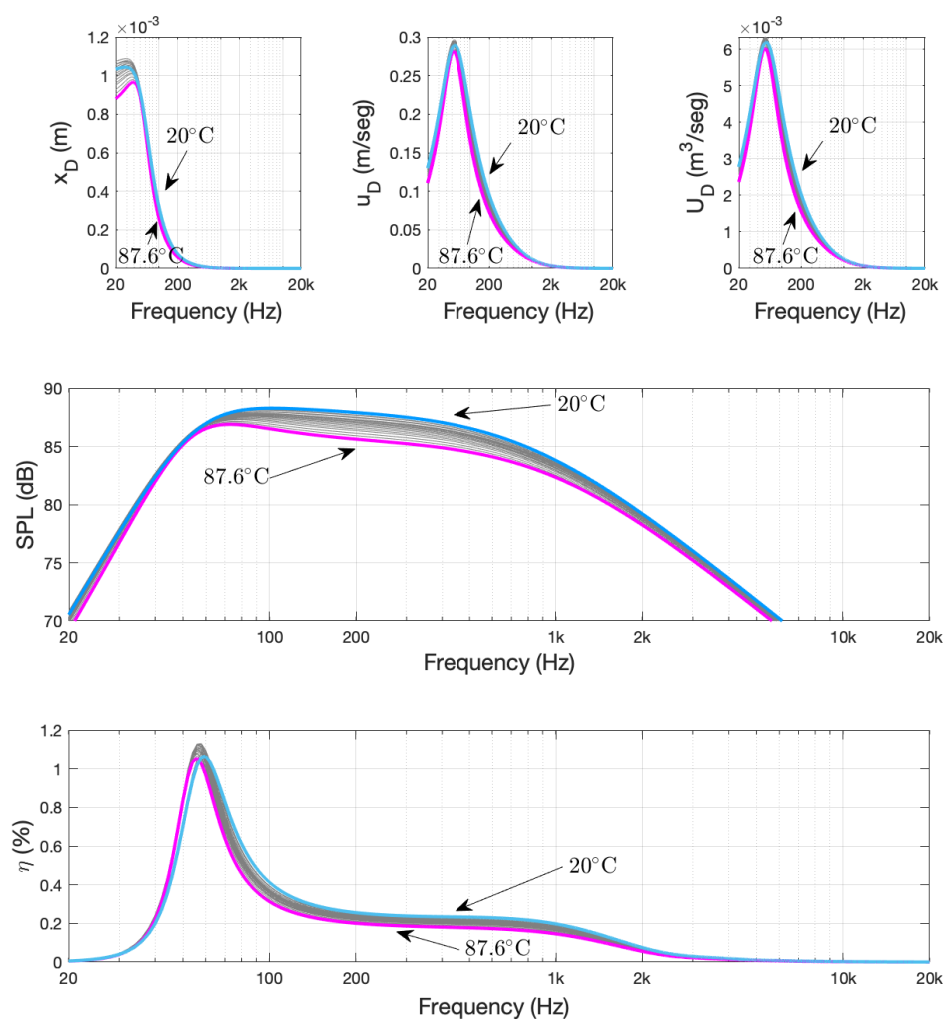


Fig. 8: Simulation of the loudspeaker's acoustic response, and efficiency at different measured voice-coil temperatures. Top: Sound pressure level. Bottom: Efficiency.

near the diaphragm, or thermally activated viscoelastic effects such as creep. Although the creep effect is typically associated with long-term static load or high excursion [28, 29, 30], our findings suggest that temperature alone, without high excursions, can induce viscoelastic relaxation in the suspension system.

From a practical perspective, we observed that around 50 °C, several TS parameters, such as f_s , Q_{MS} , and V_{AS} , reach a thermal plateau. This temperature can serve as a reference point for enclosure designers to select more stable and realistic parameters, minimizing performance drift during operation.

The simulation results showed that these thermal effects translate into measurable shifts in the frequency response and bandwidth of sealed and bandpass enclosures. Although sealed systems showed mild low-frequency attenuation, bandpass systems were more affected, exhibiting reduced bandwidth and altered tuning. This reinforces the importance of integrating thermal considerations into enclosure design practices, particularly for applications that involve extended playback or high ambient temperatures.

Although not directly measured in this study, it is worth noting that temperature also affects the speed of sound in the air inside the enclosure. This may lead to minor shifts in the tuning frequency of acoustic resonators, especially in vented or bandpass designs with narrow tolerances.

5 Conclusions

This study demonstrates that thermal variations in the voice-coil can significantly affect the TS parameters, even during small-signal operation. This challenges the common assumption that small-signal measurements are immune to thermal influence, and highlights the need for temperature-aware characterization.

By integrating controlled excitation, infrared thermography, and regression-based modeling, we provided a practical methodology to evaluate the thermal dependencies of electroacoustic parameters and incorporate these variations into enclosure design strategies.

We identified that key parameters such as R_E , L_E , f_s , Q_{MS} , and V_{AS} undergo consistent and predictable

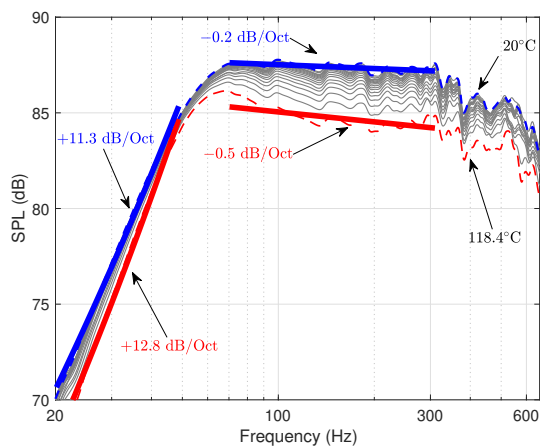


Fig. 9: Near-field frequency response of the loudspeaker and power model tuning to describe the loudspeaker's rise and bandwidth slopes at different voice-coil temperatures.

changes with temperature. These were modeled with high precision, allowing for an accurate simulation of loudspeaker behavior under thermal conditions.

A thermally stabilized region was identified around 50 °C, where multiple parameters reach a plateau. This temperature can serve as a practical reference point for selecting TS parameters in enclosure design, improving robustness, at least, in sealed and bandpass systems.

The enclosure simulations confirmed that systems optimized at ambient temperature may deviate from expected performance once operating temperature increases. The account of thermal stabilization helps to achieve more reliable tuning of volume, resonance, and bandwidth in design enclosures.

Future work may benefit from incorporating non-linear and dynamic thermal models to capture transient effects and material hysteresis. Expanding this methodology to other loudspeaker types and enclosure geometries will also help generalize the proposed design approach.

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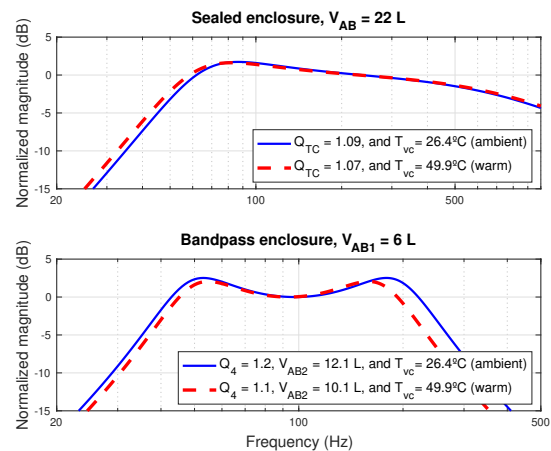


Fig. 10: Frequency responses of a sealed and bandpass system for designs assuming a single enclosed air volume, based on parameters measured with voice-coil at ambient and warm temperatures. Top: Sealed enclosure. Bottom: Bandpass enclosure.

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