IMPACT OF IMPEDANCE MISMATCH ON CROSSTALK CANCELLATION WITH MICRO-SPEAKER ARRAYS

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ABSTRACT

Crosstalk Cancellation (CTC) is an audio technology designed to deliver binaural sound from loudspeaker arrays. Recently, its application has been extended to portable devices with miniature loudspeakers, hereafter referred to as micro-speakers. This paper investigates the effect of manufacturing inconsistencies causing variations in micro-speaker characteristics on CTC performance using numerical simulations. A lumped element model, based on measured electrical impedance of several identical micro-speakers, is used as the transfer functions between the array input signals and the loudspeaker diaphragm velocity. This, together with a rigid sphere acoustic head model or measured Head-Related Transfer Functions (HRTFs), is used to simulate the pressure signals at the listener's ears. Key findings reveal the sensitivity of CTC to specific parameter variations.

Keywords: crosstalk cancellation, micro-speakers, binaural audio, electroacoustic modeling, head-related transfer function

1. INTRODUCTION

The widespread use of mobile devices, including smartphones, laptops and tablets, has led to a significant increase in the integration of miniature speakers, or micro-speakers, to deliver high-quality audio in portable electronics. Advances in digital signal processing have led to the testing of sound and noise control technologies in portable devices with embedded micro-speakers [1], including binaural 3D audio reproduction over loudspeakers – a technique known as Crosstalk Cancellation (CTC) [2–4].

A potential challenge in using micro-speakers for such applications is the variability introduced by manufacturing inconsistencies, which can lead to discrepancies between expected and actual performance [5, 6]. This paper investigates the effect of micro-speakers manufacturing variations on CTC performance by analysing a set of micro-speakers of the same model, produced by the same manufacturer. These variations are assessed by measuring the electrical impedance of the micro-speaker voice coils, and a lumped element model is used to estimate key parameters such as voice coil resistance, inductance, suspension damping, compliance and the electrodynamic transduction coefficient (force factor). The effect of parameter variations on the transfer function relating input voice coil voltage to diaphragm velocity is analysed and the resulting impact on CTC performance is assessed. This is done by combining the transfer function with both rigid sphere and measured Head-Related Transfer Functions (HRTFs) to investigate how variations in micro-speaker parameters affect the reproduced pressure at the listener's ears.

2. THEORETICAL FRAMEWORK

2.1 Micro-speaker lumped element model

The electrical impedance of the blocked voice coil, Z_{EB}, at a given frequency ω is modelled as

$$Z_{EB} = R_E + j\omega L_E, \tag{1}$$

where R_E is the DC voice coil resistance, and L_E is its ideal inductance without considering the losses generated

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by eddy currents at higher frequencies [7]. The mechanical impedance describing the diaphragm and voice coil dynamic is computed as:

$$Z_{MD} = R_{MS} + j\omega M_{MD} + \frac{1}{j\omega C_{MS}}. \tag{2}$$

In Equation (2), the parameter M_{MD} models the mechanical mass of the diaphragm and voice coil assembly, C_{MS} defines the mechanical compliance of the diaphragm suspension, and R_{MS} models the mechanical losses in the suspension [8]. The micro-speaker is mounted in a closed-box enclosure. Therefore, the total mechanical impedance, Z_M, can be modelled by introducing the rear-acoustic loading radiation impedance as follows [9],

$$Z_M = Z_{MD} + j\omega M_A + S_D^2 \frac{\rho_0 c^2}{j\omega V_c}. \tag{3}$$

where ρ_0 is the air density, c is the speed of sound, S_D is the effective radiating area of the micro-speaker diaphragm, V_c is the cabinet's volume, and M_A represents the effective mass of acoustic loading on the speaker diaphragm. By combining Equations (1) and (3), the electrical voice coil impedance is given by [8, 9]:

$$Z_E = Z_{EB} + \frac{(Bl)^2}{Z_M}, \tag{4}$$

where the force factor, Bl, is the electro-mechanical transduction coefficient representing the force exerted on the diaphragm by the magnetic motor [8]. It can be further shown [9] that the ratio between the velocity of the diaphragm and voice coil assembly, u_D, and coil input voltage, v_E, is given by:

$$\psi \triangleq \frac{u_D}{v_E} = \frac{Bl}{Z_{EB} Z_M + (Bl)^2}. \tag{5}$$

Assuming that the loudspeaker radiates sound omnidirectionally, Equation (5) can be used to express the ratio of acoustic pressure, p, to input voltage [9]:

$$\frac{p}{v_E} = j\omega\rho_0 S_D \psi \cdot G(\boldsymbol{r}, \boldsymbol{r}_s) \triangleq \Gamma \cdot G(\boldsymbol{r}, \boldsymbol{r}_s), \tag{6}$$

where $G(\boldsymbol{r}, \boldsymbol{r}_s)$ is the Green's function modelling the acoustic field produced by the speaker located at $\boldsymbol{r}_s$ at point $\boldsymbol{r}$. In this work, Equation (6) and the transfer element Γ are used to model the micro-speaker transfer function and investigate the effect of parameters variations on Crosstalk Cancellation.

2.2 Crosstalk Cancellation

Crosstalk Cancellation (CTC) is a method for reproducing binaural audio over loudspeakers, achieved by sound field control via inverse filtering [4, 10]. A single listener, L-channel CTC system ensures accurate binaural reproduction by controlling the sound pressure at two control points (the listener's ears) using L loudspeakers. The system may be described in the frequency domain as [4]

$$\boldsymbol{p} = \boldsymbol{C}\boldsymbol{H}\boldsymbol{d}, \tag{7}$$

where $\boldsymbol{p}$ is the pressure reproduced at the listener's ears, $\boldsymbol{C}$ is the $2 \times L$ plant matrix describing the system's complex frequency responses between the L loudspeakers and the left and right ear, $\boldsymbol{H}$ is the $L \times 2$ matrix of the CTC filters, and $\boldsymbol{d}$ is the target pressure to be reproduced. The CTC filters $\boldsymbol{H}$ are typically obtained by minimising the squared error norm $\|\boldsymbol{p} - \boldsymbol{d}\|^2$. To ensure causality, a modelling delay is usually introduced during filter design [3]; for simplicity, this delay term is omitted here. Solving this minimisation problem involves inverting the plant matrix $\boldsymbol{C}$. Since $\boldsymbol{C}$ is generally non-square, the filters are computed using the Moore-Penrose pseudoinverse [10].

The computation of the CTC filters, $\boldsymbol{H}$, with an accurate plant matrix, $\boldsymbol{C}$, is often impractical as it requires a thorough calibration and measurement process. Therefore, system models are commonly used, making assumptions about the listener's Head-Related Transfer Function (HRTF) and loudspeaker radiation. For instance, loudspeakers could be modelled as monopole sources [2, 11]. However, errors in the reproduced signals and a degraded binaural effect can result from inaccurate plant models [4]. Moreover, at certain frequencies, the plant matrix undergoing inversion may be ill-conditioned. Thus, to control the loudspeaker gains and the sensitivity of the pseudoinverse solution to errors in the plant matrix, Tikhonov regularisation is used to compute the CTC filters as [11]

$$\boldsymbol{H} = \boldsymbol{C}^H[\boldsymbol{C}\boldsymbol{C}^H + \beta \boldsymbol{I}]^{-1}, \tag{8}$$

where β is the regularisation parameter, $\boldsymbol{I}$ is the 2×2 identity matrix and $[\cdot]^H$ denotes the Hermitian transpose. In Equation (8), β determines the relative weight assigned to the electrical power required to drive the loudspeakers – referred to as control effort and defined as $\|\boldsymbol{H}\boldsymbol{d}\|^2$. As β changes from zero to infinity, the solution changes from minimising only the performance error to minimising the control effort [3].

In this paper, Equation (8) is used to calculate the CTC filters employed to drive L micro-speakers arranged in a linear configuration, adopting a rigid sphere head model for the plant matrix, $\boldsymbol{C}$, as outlined in [12]. To include the micro-speaker characteristics, Equation (7) is modified as follows,

$$\boldsymbol{p} = \boldsymbol{G}\boldsymbol{\Gamma}\boldsymbol{H}\boldsymbol{d}, \quad (9)$$

where $\boldsymbol{\Gamma}$ is a $L \times L$ diagonal matrix populated with transfer elements Γ as defined in Equation (6), $\boldsymbol{G}$ is the matrix of Green's functions modelling the acoustic field between the array speakers and the listener's ears, and $\boldsymbol{d} = [1, 0]^T$ is the target binaural signal [4]. In this work, $\boldsymbol{G}$ contains the transfer responses associated with a rigid sphere head model or Neumann KU 100 HRTFs [13], and is hereafter referred to as *forward* plant matrix.

2.3 Crosstalk Cancellation system description

The CTC system under consideration consists of $L = 5$ sources and two control points corresponding to the ears of a dummy head. The sources considered, all of the same model and from the same manufacturer, are rectangular microspeakers with diaphragm dimensions of 9.2 mm × 32.2 mm, giving an area of $S_D = 2.9$ cm^2. Each transducer is mounted in a cabinet with a volume of approximately $V_C = 13.0$ cm^3. Figure 1 illustrates the listener and loudspeakers configuration.

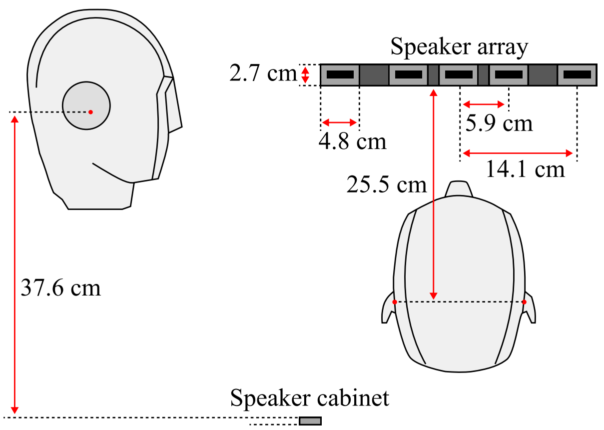

Figure 1: Graphical representation of the CTC system (side and top view).

3. SENSITIVITY ANALYSIS OF PARAMETERS

This section illustrates how the parameters of the model introduced in Equation (4) are estimated from measured voice coil electrical impedances and how they affect the transfer function ψ defined in Equation (5).

3.1 Parameter estimation

The voice coil impedance of 12 micro-speakers was measured between 100 Hz and 20 kHz using the method described in [14]. The resulting data were then analysed using the function introduced in Equation (4) for the least-squares estimation of the Thiele-Small (T-S) parameters of the micro-speakers. Table 1 presents the mean value of the fitted parameters, along with their corresponding percent Relative Standard Deviation (RSD), and maximum mismatch ($m_{\%}$), equivalent to three deviation standards. The total mass $M_{MT} = M_{MD} + M_A$ represents the mechanical mass of loudspeaker diaphragm assembly including air load and voice coil, and f_0 the resonance frequency of the micro-speakers.

Table 1: Estimated mean, percent Relative Standard Deviation (RSD), and maximum mismatch ($m_{\%}$) of model parameters.

Parameter	Mean value	RSD (%)	$m_{\%}$
R_E	3.7 Ω	3.3%	9.9%
L_E	0.025 mH	0.8%	2.4%
Bl	3.5 N/A	2.5%	7.5%
R_{MS}	4.8 Kg/s	6.4%	14.4%
C_{MS}	0.015 mm/N	5.9%	17.3%
M_{MT}	3.7 g	4.8%	14.4%
f_0	678.8 Hz	2.3%	6.9%

The table shows that the estimated parameters with the largest variation are the suspension resistance and compliance, followed by the mechanical mass and electrical resistance. This result is consistent with the level of manufacturing imperfection reported in other studies [6, 9, 15, 16], where it is observed that C_{MS}, R_{MS}, and R_E are typically the micro-speaker parameters that are the most subject and sensitive to variations in the production line. It is further noted that the estimated voice coil DC resistance, resonance frequency, and mechanical mass align with the specification provided in the micro-speaker data sheet.

Figure 2 shows the measured voice coil impedance and the reference impedance curve calculated using the mean values from Table 1. The figure clearly illustrates the manufacturing inconsistencies in micro-speakers across the entire frequency range. It should also

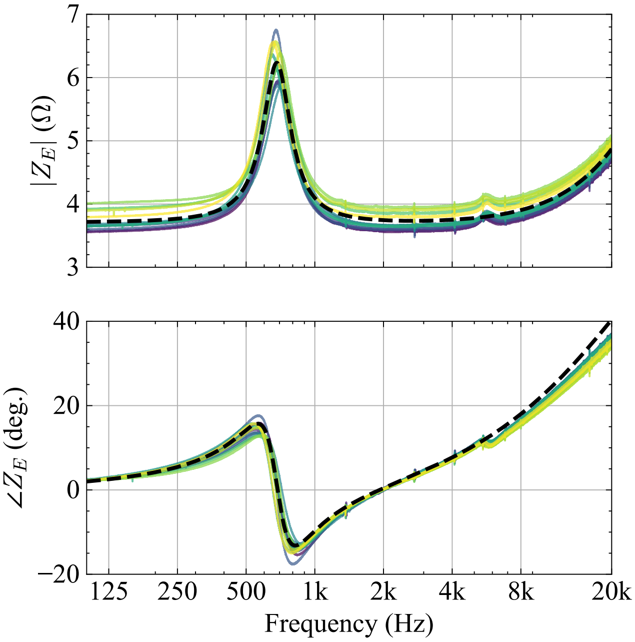

Figure 2: Measured (coloured, solid) and average (black, dashed) voice coil electrical impedance. The average curve is computed using the mean parameters of Table 1.

be noted that the lumped element model considered replicates the impedance curve well, but is unable to reproduce the resonance peak at 5.5 kHz, which might be a higher-order mechanical vibration mode of the micro-speaker [7].

3.2 Effect of parameter variations on ψ

Each parameter of the micro-speaker model has a different effect on the transfer function ψ (Equation (5)) and thus on the radiated acoustic pressure (Equation (6)). Figure 3 illustrates the effects caused by variations of individual parameters on the magnitude and phase of ψ. The black solid and dashed lines respectively represent the magnitude and phase of ψ calculated using the mean parameter values from Table 1, with $\rho_0 = 1.204$ kg/m^3 and $c = 343$ m/s. Deviations from the mean are indicated by the shaded areas, transitioning to blue for negative variations and red for positive variations.

The variation of the voice coil resistance R_E is inversely proportional to the variation of the magnitude of ψ. Without altering the system's resonance frequency, increasing R_E reduces both the magnitude of ψ and the radiated acoustic pressure. Significant phase variations primarily occur at high frequencies. The electrical inductance L_E affects ψ only at high frequencies, with a smaller effect compared to R_E. Conversely, the variation of the magnitude of ψ is directly proportional to the variation of the force factor Bl, with limited phase variations. The suspension resistance R_{MS} modifies the sharpness of the resonance peak without changing its frequency, where higher mechanical losses due to the suspension reduce the radiated sound. The phase response is only slightly affected by large variations in R_{MS}. Differently to the previous cases, the resonance frequency of the system is significantly influenced by changes in C_{MS} or M_{MT}, as expected. An increase in these parameters will lower the resonance frequency and alter the phase response of ψ. These observations align with the results discussed in [17].

4. EFFECT OF PARAMETER VARIATIONS ON CROSSTALK CANCELLATION

This final section examines how mismatches in loudspeaker impedance – resulting from variations in selected T-S parameters between different micro-speakers – affect the CTC level achieved by the system, based on the model introduced in Equation (5). The tuning of the regularisation parameter, the modelling of the inverse filters, and the evaluation of CTC performance are discussed, followed by simulation results based on two forward plant matrices, $\boldsymbol{G}$.

4.1 CTC filters and CTC level

The CTC filters are computed as shown in Equation (8), using a rigid sphere head model to design the plant matrix. This choice is motivated by the variability introduced by micro-speaker manufacturing variations, as observed in Figure 2. Such inconsistencies can lead to inaccurate plant models when using speakers different from those used during the calibration process. In these cases, regularisation would improve the robustness of the system to loudspeaker variations, but also reduces the CTC performance in the ideal case. Additionally, previous research has shown that CTC levels obtained with measured HRTFs and those derived from rigid sphere head models are comparable [4]. Therefore, for simplicity, in this work the plant matrix elements used for the CTC filter design utilise a rigid sphere head model. The mathematical formulation for the responses follows [12], with the head radius set to 87.5 mm.

To determine the appropriate level of regularisation, the control effort was analysed. Specifically, a frequency-independent regularisation parameter of $\beta = 0.00023$ was

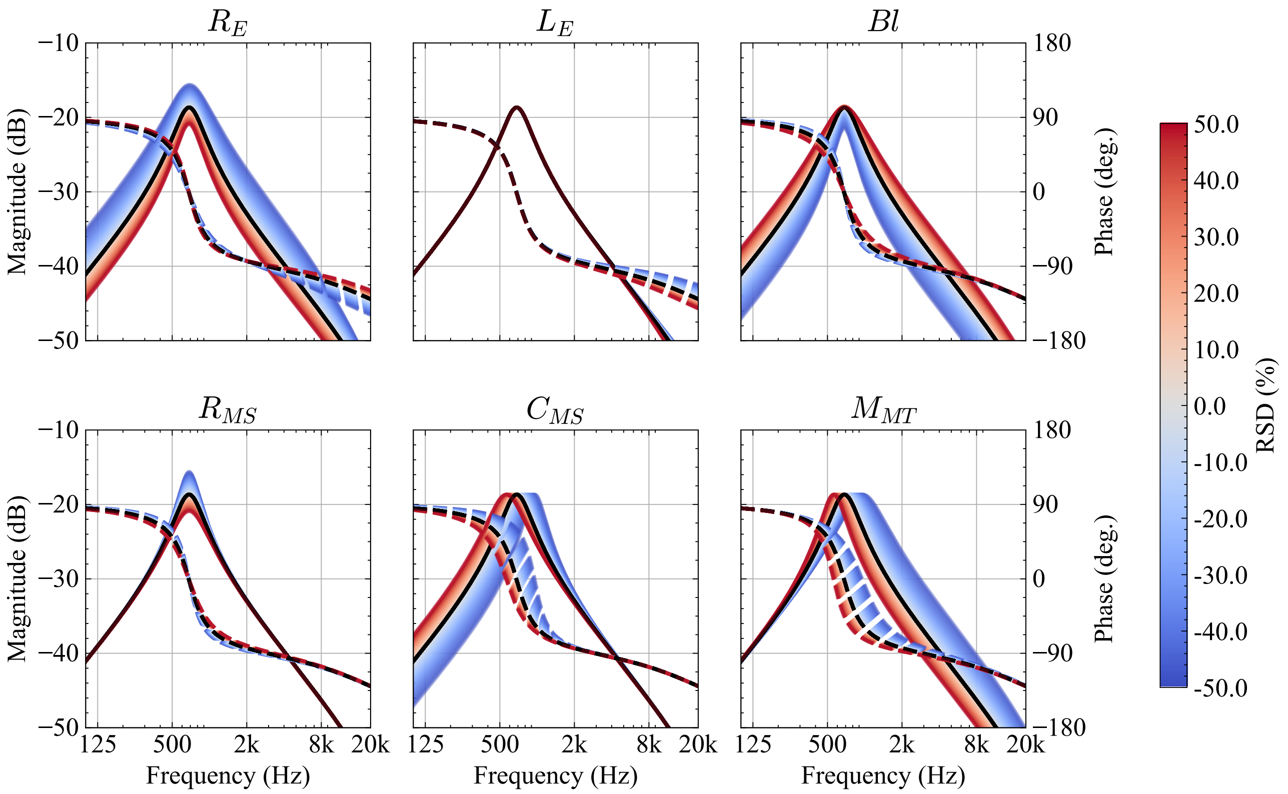

Figure 3: Effect of parameter variations on the magnitude and phase of the transfer function ψ. The black line represents ψ computed using mean parameter values (solid for magnitude, dashed for phase). Shading transitions toward blue for negative variations, measured in terms of the percent Relative Standard Deviation (RSD), and red for positive variations.

chosen to ensure that the control effort variation remained within 18 dB over the 100 Hz to 20 kHz range.

The performance of the system is evaluated using the CTC level, defined as the ratio of the squared reproduced pressures at the listener's ears for a target binaural signal $\boldsymbol{d} = [1, 0]^T$ [4]:

$$\text{CTCL} = 10 \log_{10} \left(\frac{|p_1|^2}{|p_2|^2} \right). \tag{10}$$

The CTC level quantifies the amount of CTC achieved between the listener's ears. In general, a minimum CTC level of 20 dB is required to achieve the desired binaural effect [4].

4.2 Simulation outline

The behaviour of the system under parameter variation was simulated for different levels of percentage mismatch. Previous studies [9,15,16] indicate that the parameters most subject to manufacturing variations in microspeakers are C_{MS}, R_{MS} and R_E. Specifically, these studies suggest that the suspension compliance has an imperfection tolerance of about $\pm 30\%$, while the mechanical and electrical resistances typically vary within $\pm 10\%$. For these reasons, and given the levels of variation reported in Table 1, the T-S parameters R_E, R_{MS}, C_{MS} and M_{MT} are selected for analysis.

The simulation follows this procedure: a single T-S parameter is selected, and a set of $L = 5$ random values is generated for a given percentage mismatch level. The manufacturing imperfections are assumed to follow a normal distribution with a mean μ – the nominal values from Table 1 – and a standard deviation σ given by

$$\sigma = \frac{m_{\%}}{3 \cdot 100} \mu. \tag{11}$$

In Equation (11), $m_{\%}$ represents the maximum deviation from the mean that the random value of the T-S param-

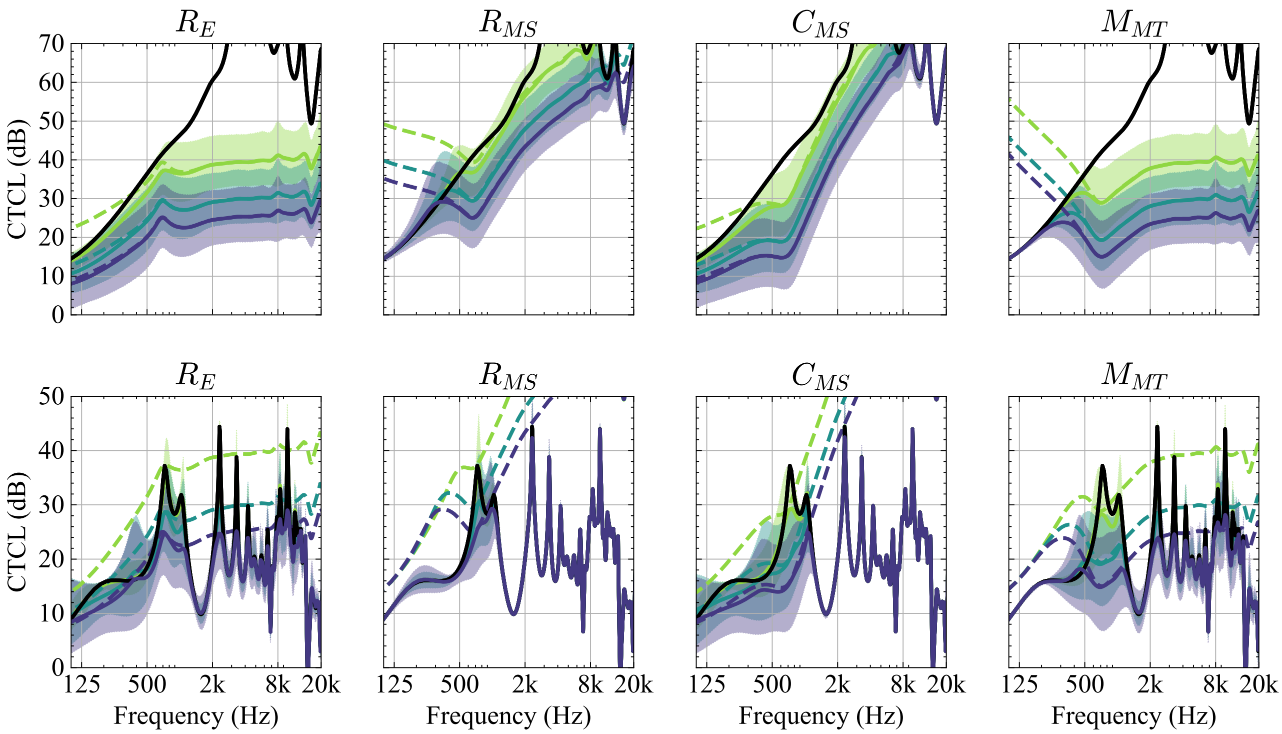

Figure 4: Average CTC level for different parameter mismatch values and forward plant matrix choices. Top: forward plant modeling with rigid sphere HRTFs; bottom: forward plant modeling with KU 100 HRTFs. Mismatch values: 0% (—), 10% (—), 30% (—), 50% (—). Dashed lines show CTC levels with reduced regularisation ($\beta = 10^{-9}$) in the first row and with rigid sphere forward plant matrix in the second. Shaded regions indicate the 10th to 90th percentiles.

eter can assume. Therefore, 'thirding' $m_{\%}$ ensures that nearly all randomly generated values are within three standard deviations. The selected values for maximum mismatch are $m_{\%} = 10\%$, 30% and 50%. This latter value is considered because, in addition to discussed manufacturing imperfections, further variations can occur during sound reproduction due to the non-linear and time-variant behaviour of micro-speakers, which significantly affects their response [5, 7, 18]. While keeping all other parameters fixed at their nominal mean values, the generated random parameters are used to compute five distinct transfer functions, ψ and Γ. These modified transfer functions populate the diagonal transfer function matrix $\mathbf{\Gamma}$. In this way, the effect of parameter variations on the CTC level can be examined by computing and analysing the reproduced pressure, as described in Equations (9) and (10). This procedure is repeated 10^4 times for the four selected parameters and across all percentage mismatch values to ensure statistical reliability of the results. Finally, the retrieved CTC levels are averaged.

4.3 Performance Analysis

The results of the simulation are illustrates in Figure 4, which shows the average CTC level obtained for the three different parameter mismatch values and four model parameters, for the two distinct forward plant matrix choices. The top row of the figure displays the results corresponding to the choice of a rigid sphere forward plant matrix, while the bottom row corresponds to the KU 100 HRTF plant matrix. Dashed lines are introduced in the plots. In the first row they represent the CTC levels obtained by reducing the regularisation parameter to $\beta = 10^{-9}$. In the second row, they show the CTC level obtained using the rigid sphere forward plant matrix (with $\beta = 0.00023$). The averaged CTC level is compared with the performance level obtained without introducing any parameter variation (black line). Moreover, the statistical dispersion of the CTC level obtained for each simulation is illustrated with shaded regions, whose boundaries define respectively the 10th and 90th percentiles.

4.3.1 *Forward plant modeling with rigid sphere HRTFs*

Figure 4 shows that when the same rigid sphere head model used to compute the CTC filters is also used to design the forward plant matrix, the CTC level achieved by the system, when no mismatch is considered, is well above the 20 dB threshold over most of the frequency range considered. At low frequencies, especially below 200 Hz, the plant matrix is highly ill-conditioned, resulting in poor CTC levels regardless of parameter mismatch. In this range, β regulates the stability of the solution and prevents energy loss, but at the cost of reduced control performance. When parameter variations are introduced, a reduction in the CTC level is observed. The reductions are consistent with the variations in the transfer function ψ observed in Figure 3. In particular, changes in R_E and M_{MT} affect the CTC level over the entire frequency range, especially above the resonance frequency, where losses of more than 20dB occur above 2kHz. Variations in mechanical resistance mainly affect and reduce the CTC level about and below the resonance frequency, while variations in C_{MS} lead to reductions at frequencies below resonance. The results obtained with reduced regularisation (dashed lines) highlight an important property of the system: at low frequencies, the performance degradation is driven by regularisation rather than impedance mismatch. This proves that regularisation imposes a performance limit on the system, regardless of parameter variations.

4.3.2 *Forward plant modeling with KU 100 HRTFs*

When the reproduced pressure is derived by modeling the forward plant matrix with KU 100 HRTFs, the CTC level significantly reduces compared to the case in which the rigid sphere head model is employed. The forward plant matrix is not accurate and the system results in a lower CTC performance, in line with what is observed in [4]. Nonetheless, similar trends to those observed in the previous case occur. T-S parameter variations reduce the CTC level in proportion to the parameter mismatch, matching the variations in the transfer function ψ. It is further noted that at certain frequencies the CTC level matches that of the rigid sphere (dashed lines), indicating that the reduction is driven by the largest mismatch – whether from regularisation, head model differences, or variations in micro-speaker parameters. For the chosen level of regularisation, errors from mismatched head models dominate over most of the frequency spectrum, while CTC degradation due to parameter mismatch is mainly confined to mid-low frequencies, especially below 1 kHz and about resonance. At these frequencies, the performance loss due to parameter mismatch is less severe than in the previous case, even for large variations. This suggests that in practice, even with extremely poor manufacturing tolerances, parameter mismatches have a negligible effect on CTC performance, provided that the CTC filters and the forward plant matrix are designed with different models.

5. CONCLUSIONS

The increasing integration of miniature loudspeakers in mobile devices has enabled the use of advanced audio technologies, such as Crosstalk Cancellation (CTC), to improve the audio experience on these devices. However, manufacturing inconsistencies in micro-speakers can introduce variability that affects performance. This paper has investigated the effect of these variations on CTC using a lumped element model to design two transfer functions: one for diaphragm velocity to voice coil input voltage, ψ, and the other for acoustic pressure to input voltage. Manufacturing variations in 12 micro-speakers were measured, revealing a maximum variation of up to 20% in the Thiele-Small parameters. The effect of parameter mismatch on CTC was investigated by analysing different model parameters considering typical manufacturing variations.

The CTC filters have been designed using Tikhonov regularisation with a rigid sphere head model. The reproduced pressure was computed using a forward plant matrix whose entries are populated either with the same rigid sphere responses used for the CTC filters, or with measured HRTFs. The results have shown that when a rigid sphere head model is used, the CTC level variations due to parameter mismatch are more pronounced, as the ideal CTC level is very high and there are no errors in the sound path transfer responses. The variations are consistent with those observed in the transfer function ψ. At low frequencies, the degradation in performance is driven by regularisation rather than impedance mismatch, highlighting that regularisation sets a performance limit independent of parameter variations. When KU 100 HRTFs are used, the CTC level is significantly reduced due to the differences in the head models. At some frequencies, the CTC level is equal to that of the rigid sphere, indicating that the reduction is dominated by the largest mismatch – whether from regularisation, head model differences or micro-speaker parameter variations.

The results presented in this paper suggest that CTC performance may be further compromised when multiple mismatches are combined. Future research could also explore the effects of extending the micro-speaker model to account for non-linear behaviour, as well as analysing the effects of varying the number of loudspeakers in the array, or testing the system's robustness across different listener positions.

6. ACKNOWLEDGMENTS

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