OBJECTIVE ASSESSMENT OF COLORATION IN ACTIVE ACOUSTIC SYSTEMS: REAL-ROOM MEASUREMENTS WITH TIME-INVARIANT FILTER EQUALIZATION

S Neeten Amadeus Acoustics, Vienna, Austria
C Frischmann Rohde Acoustics, Salzburg, Austria
V Werner Amadeus Acoustics, Vienna, Austria
F Kaiser Amadeus Acoustics, Vienna, Austria

1 INTRODUCTION

Active Acoustic systems are employed to enhance venue acoustics. In the tuning of such systems, engineers contend with two performance limits: stability and coloration. Stability is quantified by the Gain Before Instability (GBI), the maximum gain before the system self oscillates. Coloration, however, is often audible long before this limit is reached. A fixed safety margin below this limit, however, is an unreliable predictor of audible coloration. This paper therefore introduces an objective method to measure and quantify system-induced coloration using cepstral analysis. The method is validated with measurements in three different acoustic environments, analyzing the coloration of active acoustic systems. The outcome shows the effectiveness of equalization applied to the signal processing to increase the GBI and decrease the coloration.

2 THEORY

2.1 Stability of Active Acoustic Systems

Active acoustic systems employ matrix-based signal processing algorithms that integrate input from multiple microphones and distribute output to a network of loudspeakers, enabling real-time modification of a room’s acoustic response. Such systems can be separated into recursive, in-line and hybrid systems. In-line systems rely on source-focused miking techniques combined with artificial reverberation processing to enhance acoustic conditions within the performance space. These systems are designed to operate well within the GBI limit. Recursive systems, on the other hand, use controlled feedback to modify the room’s natural acoustics and operate closer to the instability limit. A hybrid system combines both approaches. The measurements in this paper are obtained, using a hybrid system. Even below the GBI, uneven frequency distribution across all frequencies in feedback loops can cause unwanted, audible coloration. An increased color free stability margin provides the tuning engineer with greater flexibility in configuring specific acoustic presets, allowing for increased strength, adaptable energy distribution and adjustable overall system color. This equalization process thus constitutes the system’s technical tuning, establishing a stable and neutral foundation. Subsequently, an artistic tuning is performed, often with musicians, to tailor the acoustical geometry to the client's needs. After the artistic tuning, a second measurement iteration is recommended to cater for performed changes in spatial and energetic distribution. In advance to this process, individual speaker calibration should be carried out to prevent tonal coloration caused by differences in speaker mounting conditions. This is also an essential prerequisite if the active acoustic system is to be used for immersive applications.

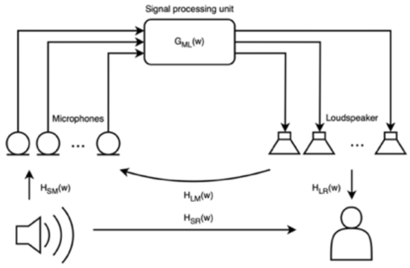

Figure 1: Signal flow of active acoustic systems[1]

Figure 1 shows the basic signal flow of an active acoustic system. The transfer functions **H**(ω) describe the acoustic transfer functions and $\mathbf{G}_{ML}(\omega)$ describes the transfer function of the processing unit. The indices are Microphones (M), Loudspeaker (L), Acoustic Source (S) and Receiver (R).
The Convolution of the signal processing $\mathbf{G}_{ML}$ with the room transfer function $\mathbf{H}_{LM}$ is responsible for the stability of such systems. Following the Nyquist Criteria for Multichannel systems, the system is stable if following expression is fulfilled:

$$|\boldsymbol{G}_{ML}(\omega) * \boldsymbol{H}_{LM}(\omega)\,| < 1$$

A more detailed investigation of instability in multichannel active acoustic systems has been presented in previous research. Eigenvalue analysis of the loop transfer matrix $\mathbf{G}_{ML}(\omega) * \mathbf{H}_{LM}(\omega)$ has proven to be a powerful tool for assessing stability, as it directly reveals the frequency-dependent modes that approach or cross the instability threshold. Gain before instability, including its implications for multichannel system design is detailed described by Poletti[2]. Improving the GBI requires a suitable filter design for the signal processing function $\boldsymbol{G}_{ML}(\omega)$ as exemplified in previous work[3]. In this research a filter design is applied on the microphone input channels to flatten the loop gains over the frequency range to increase the stability. This approach not only increases the system's stability but is also crucial for minimizing the audible coloration caused by dominant, narrow-band peaks in the loop response.

A safety margin is applied to the GBI to avoid audible coloration and is further explored in the next chapter. While time-variant signal processing, such as frequency shifting or phase modulation, can be employed to increase the GBI, these methods may introduce their own audible artifacts and significantly affect the musical performance as well as the decay characteristics of acoustic instruments. For this reason, such methods should be avoided in any context involving acoustic music [4,5]. As this work focuses exclusively on the effects of time-invariant filter equalization, these time-variant approaches are not considered further.

2.2 Coloration in Active Acoustic Systems

A variety of objective metrics have been proposed to quantify coloration in active acoustic systems. For example, Nielsen[6] bases his measure on deviations in the modulation-transfer characteristics of the room impulse response. Meynial and Vuichard[7], by contrast, focus on the late-decay RIR spectrum and define coloration as the standard deviation of the residual amplitudes against a Rayleigh distribution. This metric has been further investigated from a psychoacoustic perspective and shows a strong correlation with perceived coloration[8,9]. However, this metric is sensitive to several practical factors[9]. In particular, it depends on the FFT size and exhibits variability due to random fluctuations in repeated impulse response measurements. A further limitation is the assumption of ideal diffuse-field conditions. This may not hold in many real-world spaces, where late reverberation can deviate from the Rayleigh distribution even in the absence of active system coloration[10]. Such deviations occur because every room introduces its own baseline coloration due to its unique modal response and reverberation characteristics. Consequently, it is essential to distinguish this inherent room coloration from the coloration specifically introduced by the active acoustic system during analysis.

Determining the appropriate safety margin below the GBI is a critical challenge. The goal is to set an overall loop gain that provides an acoustic enhancement without causing audible coloration. Published literature offers a wide range of recommendations for this margin, with suggested values spanning from 5 dB to 17 dB. The required value depends strongly on parameters such as the number of decorrelated channels and the type of signal processing applied[11]. A margin of 5 dB was found out, to be a good threshold resulting in no audible coloration for the tested setup[7].
While findings like the -5 dB threshold provide a useful reference, a single value for the safety margin is insufficient as it fails to describe the spectral distribution and perceptual nature of potential coloration. This necessitates a more detailed, frequency-dependent metric. Therefore, this paper introduces an objective method based on cepstral analysis to visualize and quantify coloration across the relevant frequency range.

3 OBJECTIVE MEASUREMENT OF COLORATION

3.1 Objective Coloration Measurement

Cepstral analysis has previously been proposed for assessing room coloration[12,13], where it was used to detect the effects of strong, individual reflections in passive rooms, where coloration caused by reflections manifest in distinct peaks in the cepstral domain. The present work focuses on quantifying the specific spectral irregularities that arise from system-induced coloration. The proposed method can be broken down in the following steps and was introduced by Frischmann[14].

3.2 Time-Frequency Analysis and Cepstral-Liftering

First, each recorded impulse response is transformed to a time-frequency representation using a spectrogram, as shown in Figure 4 (upper row). The real cepstral coefficients are computed according to the definition:

$$C_r = \mathcal{F}^{-1}\{\log(|\mathcal{F}\{h(t)\}|)\}$$

$\mathcal{F}$ denotes the Fourier transform and *h(t)* the impulse response of the microphone signals. High-time liftering is then applied by setting the first coefficients to zero. This step effectively removes the slowly varying spectral envelope, thereby isolating the coloration. The optimal lifter length is dependent on the existing room acoustics and needs separate examination. To see the impact of the coloration in the time-frequency domain the cepstral coefficients are transformed back to the frequency domain:

$$f(\omega)_{lifter} = e^{\mathcal{F}\{C_r\}}$$

The resulting liftered spectrogram $f(\omega)_{lifter}$ denotes the liftered spectrum, visualized in Figure 4 (middle row). The remaining energy in the liftered spectrogram corresponds to the coloration, caused by the room or the enhancement system. The Spectral Flatness Measure is used to assess how coloration evolves over time and to quantify its perceptual prominence. The Spectral Flatness is computed by dividing the geometric mean of the power spectrum by its arithmetic mean.

$$Flatness = \frac{\sqrt[N]{\prod_{n=0}^{N-1} f(\mathrm{n})_{lifter}}}{\frac{1}{N}\sum_{n=0}^{N-1} f(\mathrm{n})_{lifter}} \qquad Flatness\,[dB] = 10 * log_{10}(Flatness)$$

A Spectral Flatness close to 0 dB indicates a flat spectrum with no coloration. A value approaching negative dB values indicate a tonal, “peaky” spectrum, the characteristic of coloration. To reduce impact of the fluctuations for every time frame, the Spectral Flatness is computed with a running average over multiple frames. The resulting curve, overlaid in the spectrogram in Figure 4 (middle row), reveals the temporal evolution of the coloration. The vertical line indicates the time frame with the most prominent coloration. This analysis is performed within a frequency of 50 Hz – 4 kHz, as system loop gain above 4 kHz is typically low due to air absorption and system filtering, making significant coloration unlikely.

3.3 Spatial Averaging and Critical Moment Analysis

While the Coloration analysis introduced in 3.2 can be performed on each microphone channel this work employs spatial averaging of the power spectrograms of all channels to assess the overall system coloration. For special microphone setups with non-uniform distribution or microphones placed in acoustically different areas, it makes sense to compute the coloration for small groups of microphone channels or to exclude specific channels. Otherwise, information about the coloration could be lost, due to the spatial averaging over all channels. For the final quantitative assessment, the spectrum corresponding to the time frame of minimum Spectral Flatness is extracted. This spectrum is then averaged with its immediate temporal neighbours (the preceding and subsequent frames) to yield a more robust estimate. The resulting spectrum is then processed in two stages. First, it is resampled onto a logarithmic frequency axis. Afterwards, a smoothing filter is applied to the spectrum, which effectively retains prominent peaks while reducing small-scale variance. The final spectrum is assumed to represent the moment of most prominent coloration and is used for further analysis. The time frame is marked with a vertical line in Figure 4 (middle row). The corresponding spectrum is shown in Figure 4 (bottom row).

3.4 Room Correction

To isolate the coloration added by the enhancement system, two conditions are measured: first, the baseline coloration of the passive room, and second, the total coloration with the system active. (Figure 7). By subtracting the baseline spectrum from the total spectrum, the corrected coloration purely caused by the system is obtained, as shown in Figure 7 (right). The final objective metric is the Spectral Flatness Measure calculated on this corrected spectrum. The Spectral Crest Factor is another measure to quantify the prominence of peaks in the coloration spectrum. It Is defined as the ratio of the maximum peak value to the RMS value.

4 MEASUREMENTS

The measurements were conducted in three different environments, further explained in the next chapter. Acoustic room parameters were measured based on the ISO 3382-1, using six different microphones distributed throughout the room. The coloration analysis was conducted using the microphones and loudspeakers integrated in the active acoustic system. The system employed in this setup offers an interface for routing the excitation signal directly through the active acoustic system's loudspeakers in order to excite the room. The system microphones are used to measure the closed-loop path and form the basis of the coloration analysis outlined earlier. The following analysis first examines the effect of system equalization on acoustic parameters and coloration when operating at a fixed -6 dB margin below the GBI. We demonstrate that this approach is limited, as the increased stability of the equalized system fundamentally alters its performance at a fixed margin. In order to facilitate a more meaningful comparison, the unequalized and equalized systems are analyzed with both adjusted to yield an equivalent level of objective coloration.

4.1 Measurement Environments

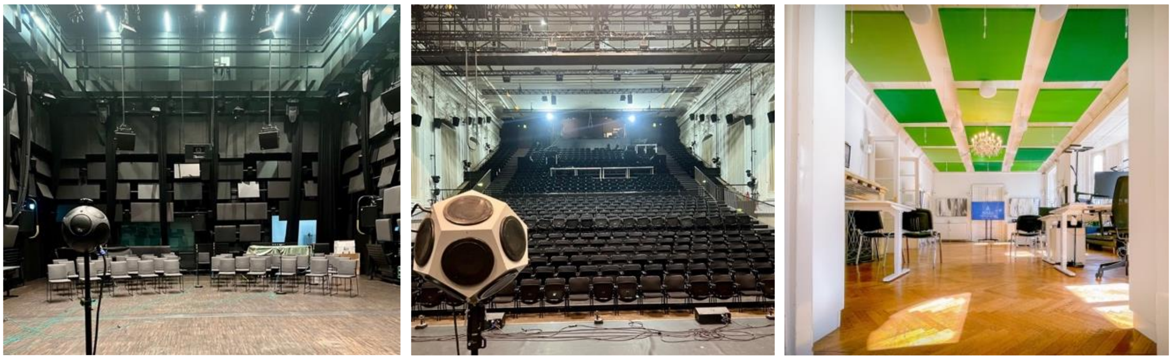

Figure 2: Klangtheater at the University of Music and Performing Arts, Vienna (left); Halle E&G at Museumsquatier, Vienna (middle); Amadeus Hub, Showroom of Amadeus Acoustics, Vienna (right)

The proposed method was validated in three different acoustic environments, each equipped with an Amadeus Active Acoustics system. The first venue is the Klangtheater at the University of Music and Performing Arts in Vienna. It is a multi-purpose hall with a size of 170 m^2 and a capacity of up to 99 persons, primarily used for electro-acoustic music, orchestra rehearsals, jazz and chamber concerts. The installed system comprises 12 DPA 4098 microphones, 58 d&b 5S loudspeakers, and 6 d&b 18S subwoofers.

The second measurement environment was the Halle E at the Museumsquartier in Vienna. This flexible, multi-purpose venue offers up to 850 m² of space and a maximum seating capacity of 1144 persons. Its adaptable seating configuration allows it to host a wide range of functions, including operas, gala events, and corporate functions. The acoustic enhancement system utilizes 32 Electro-Voice SL12-2V loudspeakers distributed around the audience area. Additional ceiling and stage coverage is provided by several Kling & Freitag CA1215 loudspeakers. The entire setup is complemented by a d&b audiotechnik Y-Series main PA system, supported by frontfill and infill speakers. A number of Audio-Technica U853 microphones are suspended above the audience. On-stage sound is captured by six DPA 4017 shotgun microphones, with the option to expand the setup using six additional AKG CK98 microphones. Additionally, five Schoeps MK41 microphones can be deployed at the front edge of the stage for focused pickup. The last environment is a 50 m² office space located at the Amadeus Acoustics headquarter in Vienna, which also serves as a room for acoustic demonstrations and system tests for improvements. The installed active acoustic system features 24 Genelec 4410A loudspeakers positioned around the room, supported by four Genelec F Two subwoofers. Additionally, eight SoundTube IPD-RS62-EZ loudspeakers are suspended from the ceiling. As system microphones, 12 DPA 4098 are suspended from the ceiling.

4.2 GBI Based Comparison

In this analysis, the different equalization stages were compared by operating the system at a fixed margin of -6 dB below the GBI. The GBI was determined by increasing the system loop gain in 0.1 dB steps. After increment, the room was excited by a noise burst and the system response was monitored for any sign of instability. After the GBI was found, the gain was reduced by 6 dB.

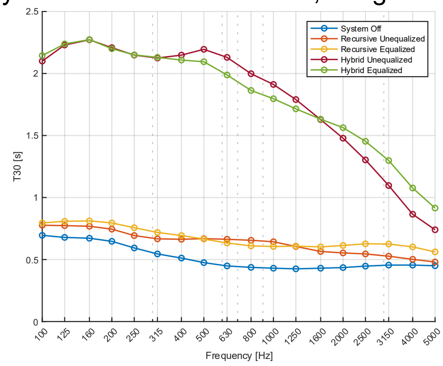

Figure 3: Reverberation Time (T30) at the Klangtheater.

Figure 3 shows the reverberation time (T30) for several system configurations. The “System off” curve describes the passive room acoustic. The active part is divided in a pure recursive part (without additional signal processing) and a hybrid mode (Adding algorithmic processing to the recursive matrix). Both modes were measured in an unequalized and equalized state. The result indicates that the equalization has a minimal effect on the overall reverberation time but may contribute to a more linear decay slope across the frequency spectrum. Figure 4 illustrates the coloration analysis for the hybrid configuration, comparing the unequalized (left column) and equalized (right column) states. In the unequalized condition, a prominent resonance is clearly visible around 1.4 kHz in the spectrogram as well as in the coloration plots. This spectral peak was clearly audible during on-site evaluation, rendering the configuration perceptually unsuitable. In contrast, the equalized state demonstrates a substantially more uniform energy distribution, as reflected in the reduced Spectral Flatness variance over time (middle row). At the time frame corresponding to the most prominent coloration, highlighted by the vertical marker, the Spectral Flatness Measure increases by 0.8 dB relative to the unequalized case, indicating a less colored and more spectrally balanced response. As seen in the bottom right plot, the distinct peak at 1.4 kHz is reduced, resulting in a perceptual suitable configuration for use. The reduction of this peak leads to a decreased Spectral Crest factor of 2.2 dB. This comparison underscores the limitation of relying on a fixed GBI margin as the sole criterion for tuning active acoustic systems. The increased system loop gain introduced by equalization results in a higher excitation level, which manifests visually in the top row as an apparently longer reverberation time.

However, this effect is primarily due to increased system energy and should not be misinterpreted as a degradation in decay characteristics. Finally, it is important to note that in the context of coloration analysis, narrowband spectral peaks are more perceptually significant than spectral dips and should therefore be prioritized in the tuning process.

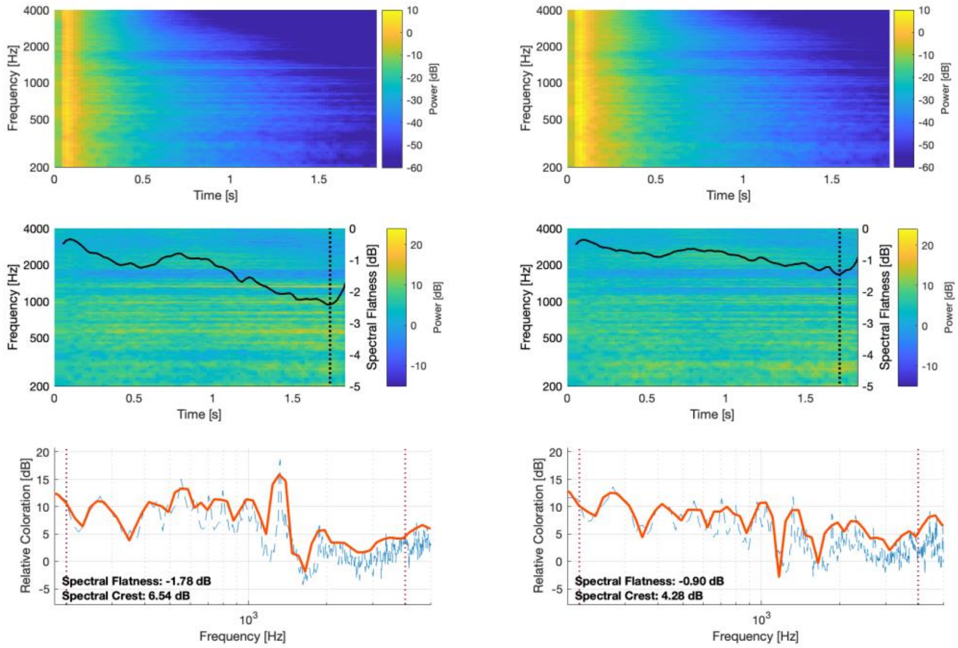

Figure 4: Coloration Analysis Klangtheater Hybrid; Spectrogram (upper row), liftered spectrogram and Spectral Flatness over time (middle row), critical time analysis (bottom row). Unequalized (left), Equalized (right)

4.3 Coloration Based Comparison

A hybrid configuration was evaluated in the Amadeus Hub, with the resulting reverberation times and corresponding coloration analysis for the system off, unequalized, and equalized states shown in Figure 5 and Figure 6, respectively. The Amadeus Hub is an office space with acoustically dry characteristics, exhibiting negligible coloration. Consequently, the baseline room correction step was not required for this analysis. For a direct comparison, the gain of the 'Unequalized' and 'Equalized' system states was adjusted until their objective coloration measures were comparable. To achieve this similar level of coloration, the Unequalized system required a large stability margin of 9.7 dB. In stark contrast, the Equalized system could be operated with a much smaller margin of only 4.9 dB. This demonstrates that for an equivalent level of objective coloration, the equalized system can run at a significantly higher gain, resulting in a higher Reverberation time as s seen in Figure 5. Furthermore, the spectrograms (upper row) illustrate that the decay of the equalized system is more spectrally balanced.

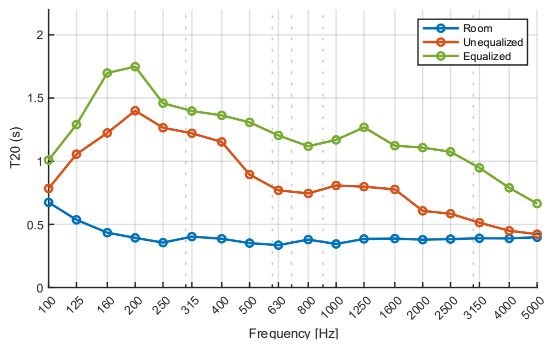

Figure 5: Reverberation Time (T20) at the Amadeus Hub

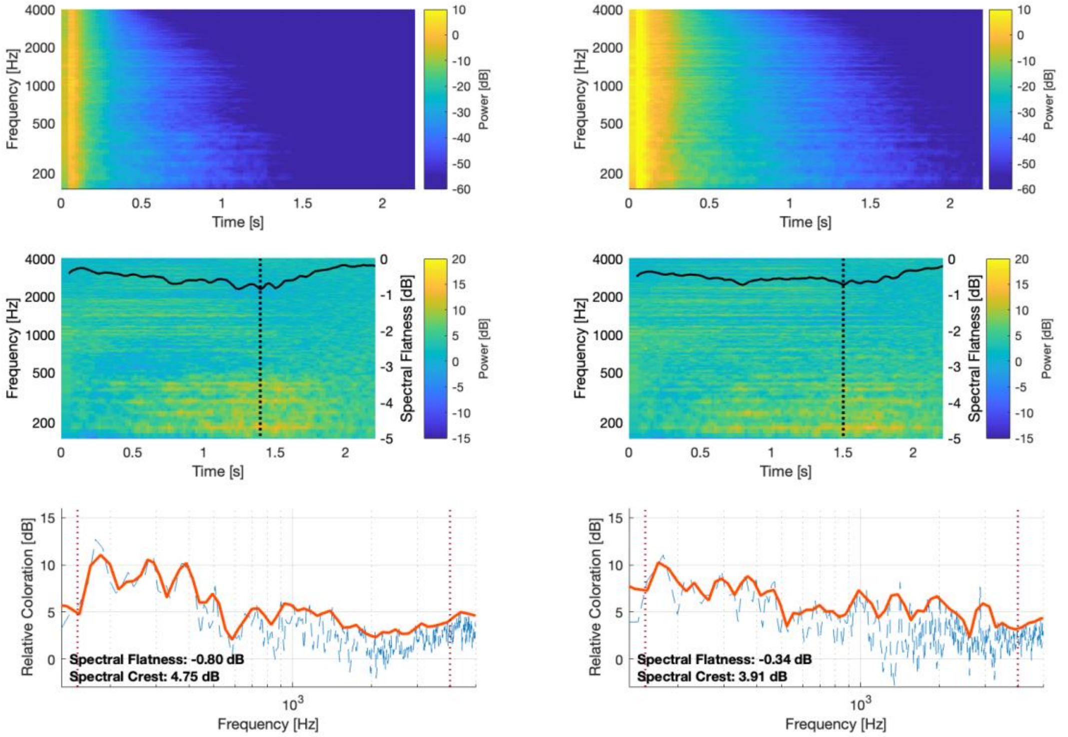

Figure 6: Coloration Analysis Amadeus Hub Hybrid; Spectrogram (upper row), liftered spectrogram and Spectral Flatness over time (middle row), critical time analysis (bottom row). Unequalized (left), Equalized (right)

4.4 Baseline Correction

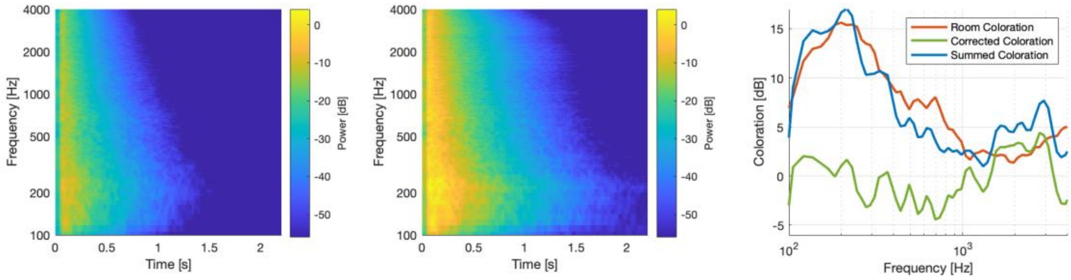

Figure 7: Baseline Correction at Halle E; Spectrogram Room (left), Spectrogram system on (middle), Coloration comparison (right)

Figure 7 demonstrates the baseline correction process used to isolate system-induced coloration from the inherent coloration of the room. The measurements were conducted in Halle E, that exhibits inherent low-frequency coloration between 100 Hz and 400 Hz, as shown in the passive room response (red curve). When a non-optimized active acoustic preset is activated (blue curve), its inherent spectral coloration compounds with the existing coloration of the room, potentially leading to perceptually undesirable interactions. To decouple these two effects, the passive room's coloration spectrum is subtracted from the total coloration spectrum of the active system. The resulting corrected curve (green) represents the coloration purely attributable to the active system itself. This allows for targeted analysis; for instance, the broad peak between 1.5 kHz and 3 kHz in the corrected spectrum corresponds to a region of uneven spectral decay that is also clearly visible in the accompanying spectrogram. While this work focuses on correcting system-induced artifacts, this same principle can be extended to use the active system to compensate for the inherent acoustical deficiencies of the room itself.

5 CONCLUSION

This paper has demonstrated that a fixed stability margin below the Gain Before Instability (GBI) is an insufficient predictor of audible coloration in active acoustic systems. To address this, we introduced and validated an objective measurement methodology based on cepstral liftering and the analysis of a corrected coloration spectrum. Key metrics such as the Spectral Flatness Measure and Spectral Crest Factor, when calculated on this isolated spectrum, provide a more meaningful assessment of system-induced coloration. The real-world measurements confirmed that with appropriate filter equalization, a system can operate significantly closer to its GBI limit while exhibiting less objective coloration than its unequalized counterpart. This finding underscores the importance of spectral uniformity in the loop gain structure. Effective equalization, therefore, provides tuning engineers with greater flexibility, allowing for more acoustic enhancement without introducing unwanted artifacts.

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