TUNING AND PERFORMANCE EVALUATION FOR SURFACE MOUNTED AUDIO HAPTIC TRANSDUCER SYSTEMS

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1 INTRODUCTION

The use of audio haptic transducers as a means of augmenting the listening experience is becoming increasingly common in integrated sound systems. This is particularly apparent for sound systems designed in the gaming, automotive and virtual reality industries[1-3] where a heightened sense of listener immersion within a reproduced sound field is desired. Audio haptics can support such a heightened sense of immersion by rendering perceptible the reproduced sound via additional tactile sensory stimulation, facilitated by mechanical vibration of surfaces in contact with the listener. In such systems, it is important to maintain congruence between the audio rendered acoustically, and that rendered via haptics so that the tactile sensory response compliments the audition of sound rather than distracting from it[4]. A component of this congruence is the time alignment between the audio driven auditory and tactile sensations, which, in turn may be optimised through tuning of the responses of the haptics transducers applied within a system. Such optimisation becomes increasingly important as the transducer and/or complete system response becomes increasingly resonant and non-linear, thereby negatively impacting on the fidelity of the audio reproduction.

Recent research on audio haptics transducers[5,6] has included the definition and measurement of transducer response related metrics that can be used to assess transducer performance and system tuning strategies. However, these studies were conducted with audio haptic transducers under approximated ideal conditions (unloaded / simply supported, loaded / fixed), in order to form a means of characterisation and evaluation of different transducer designs and constructions on a comparative basis. This work follows a similar approach to that of a recent automotive-related case study[2] and extends the application of the previously defined haptic system tuning and characterisation methods to a further case study of an occupied (with listener) seat-based audio haptics solution. It is shown herein that the processes, through which haptics transducer tuning and performance evaluation have been conducted, in previous work, are readily extendible to realistic audio haptics systems in their intended occupied mode of operation.

2 EXPERIMENTAL ARRANGEMENT

The audio haptic system described and examined in this case study constitutes a custom, purpose-built system that employs a single commercially available haptic transducer (or “shaker”). In the interests of impartiality, a full description of the haptic transducer will not be provided. Instead, a set of general properties that sufficiently describe the unit for the purposes of this work are given in the following. This section documents the audio haptic system and the means by which it was measured for tuning and performance evaluation.

2.1 Audio Haptic System Overview

A reasonably large haptic transducer was selected for the purpose of this study owing to the need to effectively vibrate a seat pad, constructed of plywood with a foam and material overlay, in contact with an occupant (listener). This haptic unit is a moving magnet transducer design with a large moving mass (including the magnet) of approximately 0.38 kg and a power rating of 50 Wrms. It has an effective surface area (to be pressed against the surface to which it is mounted) of 132.7 cm^2 and a total unit weight of 1.23 kg. The interested reader is referred to previous works[5,6] in which the same haptic transducer was examined under the alias "Driver 3". During impulse response measurements (see Section 3), driving signals were provided via a single channel of a Meridian 557 amplifier[7]. For other instances of playback and measurement, a single channel of a Meridian 258 amplifier[8] was used to provide the driving signals.

The chair selected for use was a simple wooden-framed stackable office chair with seat and backrest support sections. Both the seat and backrest are constructed from a layer of ~1.5 cm thick plywood with a ~3.5 cm thick foam cushioned layer all contained within a thin material covering. The seat section of the chair has a width x depth of 0.45 x 0.52 m, giving a total seat surface area of 0.234 m^2. The audio haptic transducer was mounted to the underside of the seat section such that the circular effective surface area was in complete contact with the plywood layer and centred about the midpoint of the seat. A rigid connection was formed by bolting the haptic unit to the plywood using the 4 fixing holes provided on the unit chassis. In this way, the transducer was firmly affixed to the surface of the underside of the seat section.

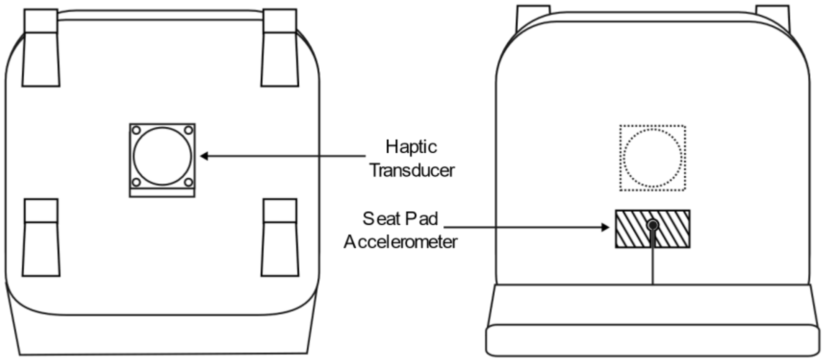

Figure 1: (Left) Plan view of the underside of the audio haptics system developed for this work with the central location of the haptic transducer shown. (Right) Plan view of the seat section showing the seat pad accelerometer location relative to the haptic transducer. NB: diagrams are not to scale and are for illustrative purposes only.

2.2 Measurement Procedure

All objective measurements detailed in this work were recorded using a Brüel & Kjær type 4375[9] accelerometer placed at the intersection of the upper side of the seat surface and the occupant when seated. To facilitate measurements while affording a level of comfort to the occupant, the type 4375 sensor was embedded within two 8 x 10 cm rectangular layers of Tecsound 100[10] material thus forming a seat pad accelerometer with the type 4375 sensor orientated to provide measurement along the vertical axis. This measurement device arrangement was positioned centrally on the seat surface in a left-right sense and slightly to the rear of the seat in a front-back sense. Figure 1 shows this arrangement diagrammatically with reference to the location of the haptic transducer. The justification for this measurement location stems from the assumed position of the centre of mass of an occupant (while seated) in the horizontal plane.

Displacement measurements were taken using a Brüel & Kjær type 2635[11] charge conditioning amplifier, the output of which was measured using an Audio Precision (APx) 525[12]. The APx 525 was simultaneously used as the stimulus source for response measurement. All displacement measurements were performed during audio playback with the haptics seat occupied by a listener. In this work, measurements were taken for a total of 4 different listeners to demonstrate the generality of the tuning and evaluation approach applied. Each listener was sat with similar posture with feet flat on the floor and back resting against the backrest. Further restriction of posture was deemed unnecessary for this work.

3 RESPONSE MEASUREMENTS

3.1 Impulse Response Measurement

Impulse responses (IRs) obtained from Exponential Sine Sweep (ESS)[13] measurements were used to examine the linear response of the audio haptic system when occupied. Two forms of ESS signal were defined for this purpose. Firstly, ESS signals were rendered (F_s = 192 kHz) for a range of different input power levels (1, 2, 4 and 8 Wrms, calculated using the nominal resistance of the transducer) covering a frequency range of 20 – 2 kHz over a time of 5 s. The upper frequency limit of the input stimulus is set such that the 1 kHz octave band is measured with 1 kHz being the upper frequency limit of the human somatosensory system[14]. The lower limit of 20 Hz is set to align with the lower limit of the human auditory system. Secondly, a further set of ESS signals were defined by filtering the original ESS signals with the resonance reduction filters described in the following section. These resonance reduction filters were defined via analysis of the impulse responses generated using the original ESS signals.

Frequency responses of a subset of the impulse responses measured are shown in Figure 2. These measurements are taken at a stimulus power of 4 Wrms for all 4 occupants with the displacement amplitude normalised for the purposes of comparing resonance characteristics.

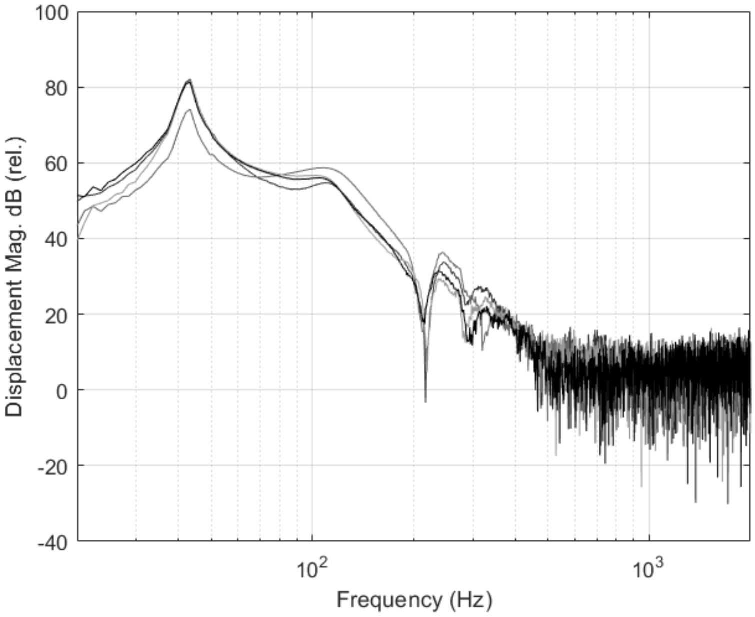

Figure 2: Frequency response (normalised displacement) of the audio haptic system as measured for 4 different occupants – derived from impulse responses in each case for an input power of 4 Wrms.

As shown above, the displacement responses consistently exhibit a large resonance at ~43 Hz and a less pronounced (wider Q) resonance at ~110 Hz. These resonance characteristics were observed for all levels of stimulus input power and were deemed common to all measurements and appropriate for forming the basis of resonance reduction filter definitions. A further finding drawn from the frequency responses is that the haptic system exhibits an operating range of up to 200 Hz with the response becoming increasingly inconsistent above this frequency. Section 4.1 provides a complete description of metrics and findings drawn from all impulse response measurements, including those produced with resonance reduction filtering.

3.2 Resonance Reduction and Measurement

As previously stated, and with reference to Figure 2, it is apparent that the general occupied system displacement response may be tuned towards a flat displacement magnitude in the frequency range of 20 – 120 Hz by attenuating the measured resonances. This tuning approach, referred to as resonance reduction, has been demonstrated in previous work[2,5,6] as an effective means of improving the transient response of haptic transducers. In this work, the use of resonance reduction is applied to demonstrably improve the transient response of the audio haptic system when occupied by a listener.

Two resonant features that are common to all occupied system impulse response measurements were selected for reduction. The first is the most prominent arising around 43 Hz and the second, less pronounced resonance present around 110 Hz. Resonance reduction filters, defined as negative gain 2nd-order biquadratic peaking filters, were defined for each resonance as follows: [Fc = 43 Hz, Q = 4, Gain = -12 dB]; [Fc = 110 Hz, Q = 0.5, Gain = -6 dB]. The parameters for the filter stages were defined using an average magnitude response of all 4 occupant responses and were relaxed as to not overfit the correction and/or completely flatten the resultant response. The original ESS stimulus signal was passed through the two resonance reduction filters and the system response remeasured using the filtered ESS signals. Measurements were conducted for input power levels of 1, 2, 4 and 8 Watts for all listeners (from hereon denoted “Occupants #1-4”). Impulse responses measured pre- and post- resonance reduction are depicted in Figure 3.

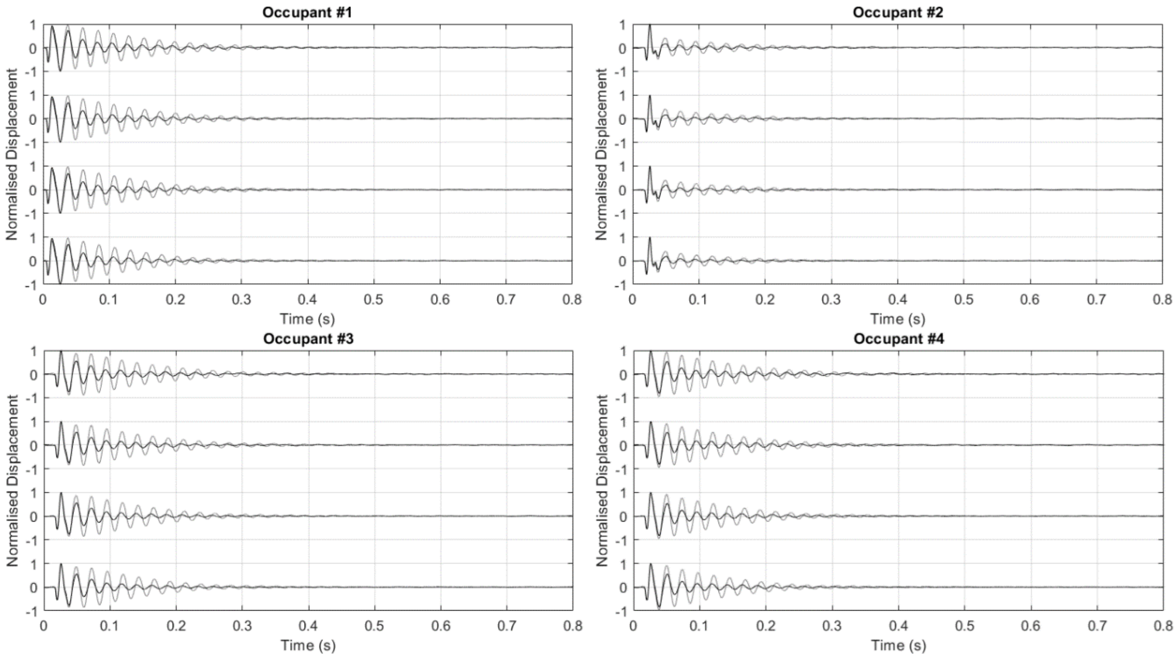

Figure 3: Impulse responses measured using ESS stimulus with (top to bottom, per panel) power 1, 2, 4 and 8 Wrms pre- (grey) and post- (black) application of resonance reduction filters.

It is apparent from Figure 3 that the resonance reduction filter stages are affecting the measured responses as expected in that the temporal decay envelopes of each response are shortened post-filtering. This is evident across all occupant responses and all levels of input stimulus power. Additionally, it is interesting to note the marked difference in response characteristics depending on the occupant, and particularly the comparatively short (quickly decaying) impulses collected for occupant #2. Such aspects are reflected in the impulse response metrics provided in Section 4.1.

3.3 Programme Material Measurement

In this work, impulse response measurements rendered using ESS signals exhibit the linear behaviour of the haptic system only. While it is possible to assess nonlinear quantities such as harmonic distortion using ESS signals[13], the use of programme material (actual music samples) can also reveal salient properties of the system. In this way, the system is measured such that nonlinear characteristics are preserved and the overall behaviour is recorded for analysis with likely use-case audio input. Programme material recordings demonstrate preservation of microdynamic modifications of input signals as well as the impact of resonance reduction as a means of improving system response linearity.

Two different excerpts of music from the genres of punk-rock (16s, Fs = 44.1 kHz) and movie score (orchestral – 13.5s, Fs = 44.1 kHz) were selected. The first excerpt demonstrates a punchy, transient-rich mode of system operation while the second demonstrates a more consistent, rumbly and less dynamic mode. Both excerpts were lowpass filtered using a 4th-order Butterworth filter with Fc = 200 Hz in order to align the input audio with the previously described operable bandwidth of the system. This provides 4 input excerpts (2 unfiltered, 2 filtered) for measurement. Furthermore, both excerpts underwent microdynamics modification to exaggerate the transient content in the case of the punk-rock excerpt and reduce the transients (enhance the steady-state portions) present in the movie score excerpt. The microdynamics processing was applied using the modified envelope follower method used in previous related work[5]. In this work, the lowpass filter used to define the amplitude envelope was a 3rd-order Butterworth filter with Fc = 30 Hz. This processing provided an additional version of each excerpt of programme material for evaluation of system response giving a further 4 input excerpts and a total of 8 overall. The results presented in Section 4.2 demonstrate how the use-case system performance may be objectively analysed using dynamically modified source audio.

4 RESULTS

4.1 Impulse Response Metrics

Fall Time and Transient to Late Energy Ratio (TLER) have been defined and shown to be appropriate metrics for haptic transducer response evaluation[2,5,6]. Both metrics are derived from measured impulse responses which, in this work, were recorded from an occupied seat-based audio haptic system under use-case conditions. Fall Time values are calculated from normalised energy curves derived from each impulse response. These energy curves are presented in Figure 4 for all measured impulse responses. Through comparison of the decay curves measured before the application of resonance reduction (RR) and those obtained with the resonance reduction applied, it is observed that the filtering process is increasing rates of decay.

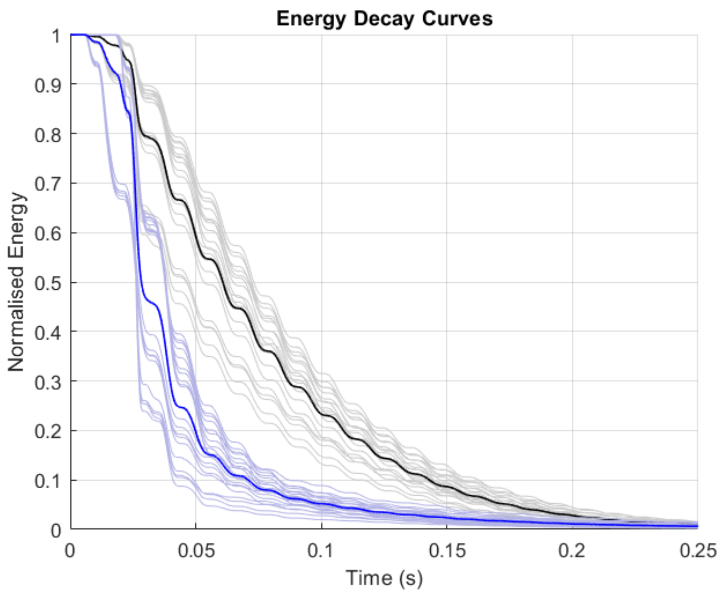

Figure 4: Energy decay curves derived from impulse response measurements pre-(grey) and post-(blue) resonance reduction filtering with bold black and blue traces representing the average unfiltered and filtered energy decay profiles respectively.

Table 1: Fall Time metric values as calculated from all measured impulse responses. Mean, minimum and maximum values are calculated across measurements of different input stimulus power levels.

	Mean Fall Time (ms)		**Fall Time [Min / Max] (ms)**	
Occupant	**Pre-RR**	**Post-RR**	**Pre-RR**	**Post-RR**
#1	119.42	53.99	[110.77 / 127.45]	[49.30 / 59.83]
#2	104.54	29.51	[95.87 / 108.23]	[26.09 / 37.72]
#3	125.92	55.78	[117.23 / 133.78]	[49.89 / 58.65]
#4	122.80	54.81	[116.40 / 128.18]	[47.98 / 62.20]

Table 2: TLER metric values as calculated from all measured impulse responses. Mean, minimum and maximum values are calculated across measurements of different input stimulus power levels.

	Mean TLER (dB)		**TLER [Min / Max] (dB)**	
Occupant	**Pre-RR**	**Post-RR**	**Pre-RR**	**Post-RR**
#1	-6.08	2.00	[-6.35 / -5.72]	[1.43 / 2.25]
#2	-2.52	4.39	[-2.78 / -2.14]	[3.82 / 4.68]
#3	-9.03	-2.32	[-9.41 / -8.71]	[-2.46 / -2.21]
#4	-8.60	-1.87	[-8.95 / -8.26]	[-2.05 / -1.78]

The mean Fall Time values, given in Table 1, quantify the differences in IR decay rates between original and tuned (with resonance reduction filtering) system conditions. It is readily apparent that the tuned condition achieves improved transient responses with faster slew from active to inactive states for all occupants measured. This overall trend in Fall Times, between original and tuned conditions, is consistent with the temporal IR characteristics displayed in Figure 3. It is also noted that the Fall Time values fully reflect the temporal characteristics of responses for each occupant with, for instance, the fast transient responses measured for occupant #2 represented by the lowest Fall Time mean values. Minimum and maximum Fall Time values calculated across all input power levels are provided for completeness and give an indication of how responses change depending on driving power. In all occupant cases, the maximum Fall Time was recorded for the lowest input power and the minimum Fall Time recorded for the highest input power. The exact mechanism behind this trend is currently unverified, however a possible reason is that higher input stimulus power levels yield more control over the large moving mass (overcoming inertia and restoring forces).

Table 2 provides the TLER calculated from original and tuned system responses using the response portion definitions provided in previous work[5]. A higher TLER value represents a system response with energy concentrated in the initial transient portion and less energy later in the response. In turn, a higher TLER suggests a faster transient response and a less resonant system with short decay. When taken together, TLER and Fall Time metrics give good insight into the temporal characteristics of system responses, and this is further evidenced in this work for evaluation of a realistic audio haptic system under use conditions. This claim is supported by the trends in mean TLER values which are consistently higher (while Fall Times are lower) for the tuned system signifying the impact of the resonance reduction filtering on system responses. The minimum and maximum values were recorded for the lowest and highest input stimulus power levels respectively which agrees with the findings drawn from Fall Time values. Ultimately, the tuned system is found to have quantifiably less resonance and, therefore, is expected to provide a more transparent reproduction of input audio as discussed in the following section.

4.2 Programme Material Metrics

The linear Crest Factor (CF) of each of the 8 programme material input excerpts are provided in Table 3 to provide context for the following analysis of measured displacements in response to these stimuli. A high crest factor signifies a larger dynamic range which is associated with transient exaggeration while a low crest factor represents a lesser dynamic range achieved when transient suppression is applied. Two key findings may be drawn from the CF values shown. Firstly, the dynamics modifications are producing expected trends in CF with the punk-rock excerpt having increased dynamic range and the movie score having decreased dynamic range (although less pronounced in the latter case). Secondly, the resonance reduction (RR) is shown to mildly affect the CF in all

Table 3: Linear Crest Factor (CF) values for each programme material input excerpt pre- and post-resonance reduction (RR) filtering.

	Unmodified Excerpt CF		**Dynamics Modified Excerpt CF**	
Excerpt	**Pre-RR**	**Post-RR**	**Pre-RR**	**Post-RR**
1. Punk-Rock (Punch)	4.80	4.67	**9.10**	**8.70**
2. Movie Score (Rumble)	3.67	3.94	**3.36**	**3.64**

Table 4: CF values of measured displacement signals in response to each dynamically modified programme material input excerpt (pre- and post-RR).

	CF Excerpt 1 (Modified)		**CF Excerpt 2 (Modified)**	
Occupant	**Pre-RR**	**Post-RR**	**Pre-RR**	**Post-RR**
#1	4.41	6.16	5.39	3.98
#2	5.83	8.14	4.77	3.53
#3	4.42	6.08	5.45	4.11
#4	4.36	6.19	5.41	4.30

excerpt cases as energy is being taken out of both transient (Excerpt 1.) and steady-state (Excerpt 2.) when the resonant frequencies appear in the audio. For brevity, the analysis of measured responses continues with reference to the dynamically modified stimuli only, noting that the same trends in metric values, reported herein, are also observed when analysing measurements of the unmodified input excerpts.

The Crest Factor values calculated from displacement measurements of the dynamically modified excerpts are presented in Table 4. It is observed that there is a better alignment between measured displacement CF and input audio CF (highlighted in bold in Table 3) for the tuned Post-RR case than for the original Pre-RR case for all occupant measurements. This indicates an increase in the transparency of audio reproduction and linearity within the audio haptic system when tuning is applied. It is revealing that in the majority of occupant cases, the CFs for excerpt 2 are higher than those for excerpt 1 which is contrary to the desired outcome of the dynamics modification for each excerpt. Post-RR CF values indicate much better preservation of the desired increase (for excerpt 1) and decrease (for excerpt 2) of input dynamic range.

To further this line of investigation, the measured displacement responses were compared to the original (Pre-RR) input stimuli in each case using normalised cross correlation. In this way, a value in the range [0 : 1] provides a measure of the agreement of input and output and, therefore, the linearity of the system (with a value of ‘1’ signifying a linear relationship). Table 5 provides these cross-correlation (XCorr) values. The application of resonance reduction tuning is shown to increase the linearity of the audio haptic system’s measured response due to the marked increase in XCorr values from the Pre-RR measurement cases to the Post-RR cases. This measured increase supports the claim that the applied tuning enhances the system’s overall capability to provide a transparent rendering of input audio content.

Table 5: Cross-correlation (XCorr) values calculated for each dynamically modified programme material input excerpt (pre- and post-RR).

	XCorr Excerpt 1 (Modified)		**XCorr Excerpt 2 (Modified)**	
Occupant	**Pre-RR**	**Post-RR**	**Pre-RR**	**Post-RR**
#1	0.40	0.63	0.36	0.58
#2	0.61	0.85	0.59	0.82
#3	0.38	0.61	0.32	0.58
#4	0.39	0.60	0.33	0.56

5 CONCLUSION

This case study has extended the use of a resonance reduction strategy and quantification metrics to the tuning and evaluation of a realistic audio haptic system under use-case conditions. A series of displacement measurements were taken of the system with 4 different occupants. These measurements included impulse responses and programme material with and without resonance reduction tuning and dynamics modification (in the case of programme material). Fall Time and TLER metrics were shown as capable of representing system responses in a temporal sense and change in system response when tuning is applied. Displacement measurements of programme material were examined in terms of dynamic range via Crest Factor metrics and the agreement between input audio and output displacement via normalised cross-correlation. It was shown that resonance reduction increases system linearity, thereby better preserving the intended dynamic characteristics of the input audio. By extension, this could positively impact the congruence between rendered auditory and haptic stimuli enhancing the sense of immersion provided by a complete system. However, this remains to be verified by subjective testing. Ultimately, this work gives further insight into how audio haptic system performance and the efficacy of tuning strategies may be measured and quantified.

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