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In room acoustic simulation of television type reproduction environments

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ABSTRACT

The quality of sound reproduction in living spaces are determined by the attributes of the loudspeaker, and the acoustic qualities of the reproduction space. This is also true for the special case of television set reproduction. In order to improve reproduction quality, the ability to predict the acoustic response of a television set in specific room environments is advantageous. In this work, a combined finite element/geometric acoustic simulation regime is prepared and specialised for television set installations. A television set is characterised as an acoustic source based on a set of anechoic measurements. Typical television set installation conditions can be problematic for conventional transparent source models, and so a counter strategy is proposed to improve a classic image source model by additionally utilising semi-anechoic measurements. The simulation techniques are evaluated by comparing simulated with measured in-room responses for a characterised television set source in wall-mount and table-top installation conditions with a conventional loudspeaker source reference case.

1 Introduction

Whilst the acoustic characteristics of a certain loudspeaker are fixed, the room characteristics and loudspeaker placement can vary for each installation and can have a favourable or unfavourable effect on the sound quality. There are numerous types of approaches and frameworks for simulation of in-room acoustic response. Vorländer [1] provides a comprehensive overview of the subject. Within these are there are two main categories of approach: those requiring numerical calculation of the wave equation, such as finite elements (FE), which are most suitable for low frequencies; and those based on assumptions of geometric acoustics (GA) [2] such as image source method (ISM) [3] and stochastic ray tracing (SRT) [4], often combined as a 'hybrid' approach, which are most suitable for mid-high frequencies. In each case, the room is modelled as a closed entity of representative shape and boundary conditions, with the response calculated between the loudspeaker source and receiver, which are typically modelled as points in space, characterised by their free-field acoustic response, and considered acoustically transparent.

The ability to model, simulate and predict the acoustic response of a loudspeaker in a certain installation condition in a specific room is obviously advantageous

for engineering purposes, whether for auralisation purposes or for more generic room impulse responses (RIR) or room transfer functions (RTF). It is also true for television (TV) set reproduction. Modern TV set design trends are now well established to have their acoustic transducers hidden within the structure [5]. Commercial pressures for an ever-slimmer form-factor necessitates a design such that the transducer radiates via a coupled cavity or 'slot' located most typically on the bottom edge on the TV set. This, together with the large size and aspect ratio of a TV set, can mean that the directional characteristics of the acoustic radiation are markedly different to that of a standard compact-sized, front-facing loudspeaker. Additionally, this 'downfiring' architecture ensures that the sound initially reaching the listener is more heavily influenced by the acoustically reflective surfaces in the vicinity of the TV set, and thus the installation condition of the TV set forms an important part of the sound design and evaluation process [6].

2 Analysis of TV installations

There are two types of installation condition, which encapsulate the majority of TV set installations, namely 'wall-mount' and 'table-top'. Wall-mount whereby the TV set is in very close proximity to the wall (e.g. 12 cm or less), and table-top, whereby the TV set is self-supported on a table top, still within a relatively close proximity to a wall (e.g. 30 – 50 cm). Figure 1 shows the initial part of the impulse response of a TV set which can be representative of two such installations, measured in semi-anechoic conditions. For comparison, each plot also includes an impulse response curve measured in comparable conditions in a fully anechoic chamber, and time aligned. The left plot represents a wall-mount installation. The right plot represents a table-top installation. The centre plot shows an intermediate 'free-stand' case, i.e. table-top without the table. For each of the curves, the initial peak or 'direct-sound' consists of a dual peak, followed by a train of delayed, attenuated peaks from primary and secondary reflections. Aside from predictable primary reflections based on arrival times of image sources there also begins a series of secondary reflection events due to the multiple acoustic paths to the microphone from behind the TV screen and the various reflections occurring between the TV screen and wall therewith. This pattern of delayed peaks in the impulse response are manifested as periodic distortions in the magnitude response, perceived as coloration [7]. Although TV sets are often tuned in the frequency domain using parametric equalisation, appropriately for performance in all expected types of installation, anecdotally it is said that table-top installations have a 'brighter' timbre compared with wall-mount installations.

3 Problems for TV room simulations

Considering the importance of the initial reflections to the listener perception, the evidence of Figure 1 may be problematic for in-room simulation of TV sets. When applying the transparent source model, to a receiver in an (ISM) simulated room, the direct and back wall reflection events occur as a simple summation of the free-field characterisation of the source and the respective first-order image source. The existence of secondary reflection events between the (TV set) source and (back wall) reflectors suggest that important information is lost when applying this model. The TV set obviously acts as an acoustical obstacle for certain primary reflections which are not accounted for. Indeed, the close proximity of the source to the wall is a problem for GA propagation models regardless of the existence of secondary reflection events. The plane-wave reflection model will not accurately characterise the spherical radiation characteristic of a source close to a reflecting surface at grazing incidence.

With a modification to a standard application of ISM, it may be possible to improve the simulation result for the case of TV set installation by utilisation of semi-anechoic measurement data, as a source for early reflection data. Since the direct propagation and back-wall reflection events are well defined, and easily identifiable in an ISM simulated impulse response, it can be possible to identify, and manually replace these events with equivalent data derived from semi-anechoic measurements.

4 Outline of investigation

In this paper, we report a simulation approach for a TV sets in a room based on conventional approaches except for the modification previously described, to mitigate some of the problems of TV set simulation. Briefly, we apply a combination approach, modelling low frequencies using a frequency domain FE approach, and high frequencies using GA methods. The two regimes

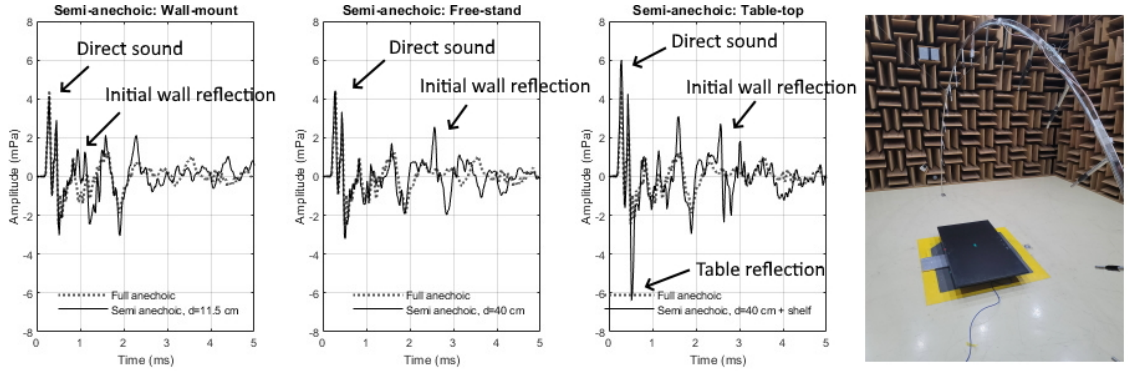

Fig. 1: Time aligned early part of impulse response of 55" TV set measured. (a) 'wall-mount' (actually floor) (b) 'free-stand' (c) 'table-top' with shelf installed in the lower part with a 6 cm gap. In each case, the impulse response shown is the 'on-axis' or normal to the wall with microphone at 1.5 m from the wall. A fully anechoic measurement taken in comparable conditions is included for comparison.

combined in the frequency domain at the simulated room's Schroeder frequency [2] using a loudspeaker type crossover to generate a full bandwidth RTF, with a RIR constructed using an inverse fast Fourier transform (iFFT). Source characterisation of the TV set is based on a full set of free-field response measurements conducted in a fully anechoic chamber. The measured data applied in the FE simulation eventually as a weighted sum of multipole sources, with the weights determined by a spherical harmonic fit to measured data. For the geometric simulation part, the measured set of impulse responses are arranged as an interpolation table. The simulation techniques evaluated by comparison with a measured in-room response. Two TV installation conditions are tested – wall-mount, table-top. A loudspeaker based in-room response is also measured and simulated as a reference case.

5 TV source measurement

The TV set analysed in this investigation is a 55-inch model (Samsung LS03) equipped with 4 loudspeakers in a 2.0.2 architecture i.e. a down-firing main stereo pair for general reproduction + up-firing pair for surround sound reproduction, which are disregarded in this investigation. The loudspeakers are single-transducer, full-range loudspeakers in a slot architecture with bass reflex. The dimensions of the TV set are 123.5 x 70.5 x 2 cm. The radiating aperture of the slot loudspeaker is 9.5 x 0.3 cm. The centre of the aperture is on the bottom edge at a distance of 27.5 cm from the centre. To avoid measurement errors of phase due to the variable latency of the TV set operating system, the measurement system uses a direct connection to the TV set loudspeaker. This means that various audio blocks such as parametric equalisation were by-passed. In this investigation, only the right (R) loudspeaker was analysed.

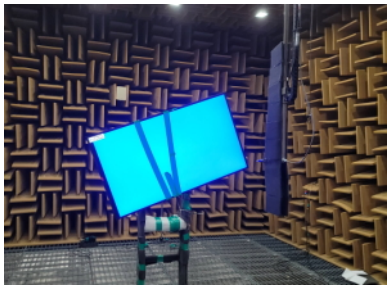

Fig. 2: Measurement setup of TV set source in fully anechoic chamber

TV impulse responses were measured in a fully anechoic room, as shown in Figure 2 using a front-pole $N = 19$, Gaussian sampling scheme [8]. The TV set was supported by a measurement jig, which enabled rotation around a first vertical axis using a turntable and a second axis normal to the screen centre. Measurements were taken at $r = 1.5$ m orbit around first axis at 10° separation with the microphone also normal

to the screen centre. The TV set was then rotated by 10° around the second axis, and another set of measurements taken around a second orbit using the turntable. This process repeated until a total 18 orbits of measured to complete the sampling grid, with 614 unique points. This measurement set is the basis the for the main source characterisation for both GA and FE simulation method.

For this type of source characterisation based on sampled free-field measurements on a spherical grid, it is preferable that the measurement centre aligns with the source acoustic centre, or centre of the acoustically effective dimension. Unfortunately, our measurement jig was unable to support, stably a TV in this set-up. Consequently, the far field condition of $r \gg \lambda$ [9, Eq. 3.54], for acoustic wavelength λ, already in violation for a large region of low frequencies at 1.5 m, is stretched further to a minimum measurement distance of 1.14 m to the acoustic centre.

Additional sets of measurements were also carried out in a semi-anechoic chamber, in a set up previously introduced in section 2. The setup, as shown in Figure 1, consists of a turntable, on which a TV set attached, in the centre of a 1.5 m semi-circular 17-microphone array of 10° separation. By rotating the turntable between 0° - 170° at 10° separation, and measuring impulse responses at the 17 locations, an equivalent, almost hemispherical, sampling grid of impulse response measurements can be achieved. For these measurements the spherical centre of the measurement grid was a point on the vertical centre line of the TV set with a -7 cm vertical offset, the closest point the TV fixture would accommodate to the loudspeaker location.

It should be remarked that with the back wall reflection, our semi-anechoic measurement setup do not meet distance conditions for far-field. Not only the $r \gg \lambda$ condition at low frequencies but $r \gg l^2/\lambda$ [9, Eq. 3.53] at high frequencies, based on an acoustically significant dimension l as twice the distance between the TV and the wall. Additionally, both of these sampling grids can reliably characterise acoustic sources without spatial aliasing up to spherical harmonic order $N = 19$ with the related condition $kr < N$ [8].

6 Spherical harmonic analysis

For a sound source, which is spatially compact such that it may be considered as centred on a point in space

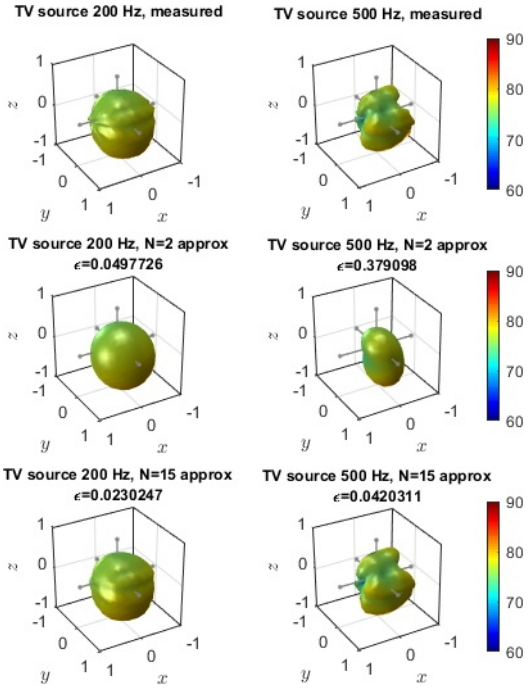

Fig. 3: Selected balloon plots of TV set source directivity, with order limited spherical harmonic approximations at $N = 2$, and $N = 15$

$\mathbf{x}_0$, radiating with time-harmonic dependence $e^{j\omega t}$, the free-field sound pressure p at $\mathbf{x} = (x, y, z)$, can be represented as

$$p(\omega, \mathbf{x}) = \sum_{n=0}^{N} \sum_{m=-n}^{n} C_{mn}(\omega) H_n^m(\mathbf{x} - \mathbf{x}_0) \qquad (1)$$

H_n^m represents a propagation model for an out-going wave, expressed in spherical coordinates $\mathbf{r} = (r, \theta, \phi)$ – radius, azimuth and colatitude.

$$H_n^m(\mathbf{r}) = h_n^{(2)}(kr) Y_n^m(\theta, \phi) \qquad (2)$$

$h_n^{(2)}$ is a spherical Hankel function, k is the wavenumber, and Y_n^m are spherical harmonic functions, which in this project are defined in the same way as Gumerov and Duraiswami [10]. C_{mn} is a set of coefficients which uniquely define the source directional characteristics up to a certain order N.

The directivity of a sound source, with sound pressure measured on various sample points of a sphere centred

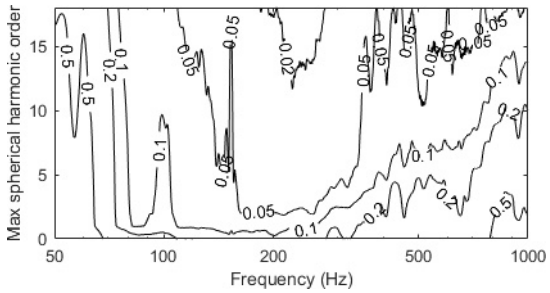

Fig. 4: Contour plot of error in TV set source approximations based on maximum spherical harmonic order

on the source location can be characterised by exploiting the orthogonality of Y_n^m and applying modal decomposition on Eqn. 1 to determine C_{mn} absolutely [11]. This approach is applied in this investigation to obtain C_{mn} coefficients for a Genelec 8020 loudspeaker based on measurements published in the BRAS repository [12].

For the case of the TV source measured in section 5, the measurement centre and the sound source centre are not the same, thus a different approach is required. Here a least-squared (LSQ) error fitting approach is taken, whereby a matrix equation is assembled, and inverted, where each row is Eqn. 1 applied at a different measurement point, with $p(\omega, \mathbf{x})$ obtained from a fast Fourier transform (FFT) of the impulse response measurement. One of the problems of LSQ error fitting approach is that higher order fittings may generate spurious artifacts due to the over representation of high order modes. To avoid this we followed the approach of Duraiswaini et al. [13] and applied Tikhonov regularisation.

Figure 3 shows a set of directivity balloon plots for the TV source at 200 Hz and 500 Hz, and two approximations based on a spherical harmonic fit, $N = 2$ and $N = 15$. Figure 4 is a comprehensive error analysis, up to the maximum order available based on the measurement sampling grid and the frequency range of application, calculating ε defined as the L^2 norm of the residual between the measured data and the approximation. Eventually the acoustic sources are represented in the FE simulation based on a $N = 2$ spherical harmonic fit, applied as multipole sources, which, based on Figure 3, 4, and a crossover frequency of 550 Hz, seems acceptable. For some frequencies such as 500 Hz, a high order representation can significantly improve the approximation, however for many others such as 200 Hz there is no significant gain in accuracy. Note that a poor signal to noise ratio for the measurement at the lowest frequencies can be an explanation for the high amount of error recorded in that region.

7 Modal field simulation (FE)

The principal, constraint on any model involving the numerical solutions of wave equation is that the discretised simulated space has sufficient resolution for a mathematically well represented distributed waveform. For approaches which use a 3D volumetric mesh such as FE method, the number of degrees of freedom to be solved increase with $\mathcal{O}(f^3)$ in order to maintain accuracy. In the low frequency / modal field region, the acoustic wavelength is comparable with the with room dimensions. For smaller rooms at lower frequencies these simulations are within the capabilities of a modern workstation, although calculation times increase rapidly with frequency.

Our approach executes a frequency domain wave-based calculation as a FE problem using the commercial software COMSOL Multiphysics [14]. Representative room geometry, including a table-top if required, is defined for an interior problem with (non-complex) impedance boundary conditions implemented based on assumed sound absorption coefficients of the construction, utilising the 55 degree rule [15]. Acoustic TV set sources represented as a weighted summation of $N = 2$ multipole (monopole, dipole and quadrupole) sources centred at the TV loudspeaker location. The weights are based on C_{mn} coefficients calculated in the previous section rotated to reflect the required orientation [10, Eqn. 3.3.36-39], and converted to multipoles [10, pp 71-72].

For reconstruction of the RIR by iFFT, a solution is required for each frequency bin. Aretz et al. [16] defines a criterion for frequency bin width $\Delta f = 0.8/T$, where T is the reverberation time, to ensure that the simulated phase can be unwrapped correctly. As an additional criterion he suggests a maximum simulation frequency at least $1/2$ octave above the crossover frequency, whereas Hargreaves et al. [11] recommends a more cautious full octave. Both of these authors apply a frequency domain interpolation operation to reduce the required number of calculations, however Prinn [17]

has more recently warned against this shortcut citing a degradation in the quality of the RIR.

For an expected $\sim$ 2 s reverberation time, and a crossover frequency of 550 Hz, our approach calculates solutions for $\Delta f = 0.5$ Hz up to 1 kHz using the MUMPS (multifrontal massively parallel sparse direct solver) [18] in 20 separate frequency bands of 50 Hz bandwidth. Each frequency band is meshed with quadratic tetrahedral finite elements with a mesh resolution of 1/6 wavelength of the maximum frequency in the band. As a step taken to reduce the excessive calculation times for the higher frequency bands [1], we forgo the frequency-based refinement of the FE mesh for the bands above the crossover frequency using a similar approach as Hargreaves et al. [11].

8 Diffuse field simulation (FE)

Whist the modal field model is a valid formulation for all frequencies, the high density of modes in a room at short wavelengths make their accurate representation practically unworkable, and of limited benefit since individually, they are unable to be identified from one another. As such, and borrowing from optics, the acoustic ray model is often employed, applying the limiting case whereby the acoustic wavelength is vanishingly small. The GA paradigm is based on this simplification.

In this investigation a GA simulation approach is taken using the MCRoomSim program [19]. The program employs a hybrid ISM/STR approach to simulation. ISM as a means for representative specular reflections and SRT as an efficient means for approximating diffuse reverberation. Each is applied in separate steps, generating individual RIRs to be combined by summation.

The geometry is limited to 'shoebox' shapes for this tool. Room dimensions are set, as are absorption and scattering coefficients on a per-wall basis. Custom directional sources can be defined based on a table of sampled free-field source impulse responses at various directions but limited to 256 samples. For our implementation, we initially defined a custom simulated source based on the set of fully anechoic measurements of section 5. A corrective step was applied order to align the centre of directional reference with the acoustic centre (i.e. position of loudspeaker slot) and

[1] Approximately 9 hours for the 500-550 Hz band, solved on an Intel Xeon 3.60 GHz quad-core workstation

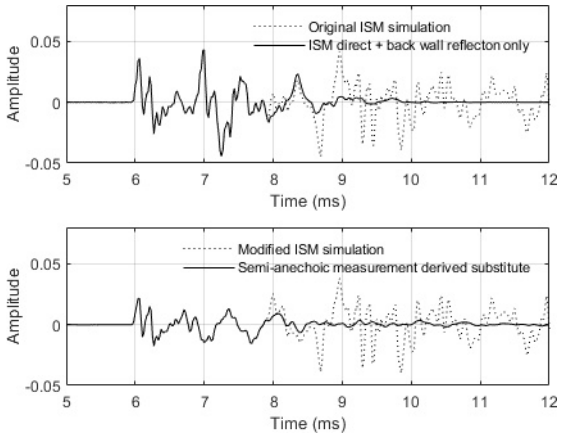

Fig. 5: ISM modification concept. Early part of ISM simulated RIR, including direct and back wall reflection (top). Semi-anechoic measurement derived substitution (bottom)

achieved by adjusting gains and arrival times of impulse responses based on the difference in distance between the measurement and acoustic centre. In the simulation, the adjusted source was assigned to the location of the acoustic centre. This approach can be valid for frequencies in the far-field when measured. These impulse responses were truncated to 256 samples with an Adrienne window [20]. The windowing occurred with synchronicity, i.e., the relative times of initial peaks between different directions were maintained, with the initial peak of the earliest arrival aligned with the beginning of the flat part of the window. The same windowing process was applied to the impulse responses of the Genelec loudspeaker, and a custom source for its simulation constructed appropriately.

As discussed in section 3, to mitigate some of the problems of TV set simulation we employ a counter strategy. As a post-processing step for the ISM part of the simulation, before combining with the STR, we manually identify, and remove, the direct and back wall reflection, and replace it with a full semi-anechoic impulse of appropriate direction, with an adjusted gain and time delay according to the propagation from source. This concept is illustrated in Figure 5. The identification and extraction process is practically achieved by carrying out a second ISM simulation of identical condition to the first except the absorption condition of all walls except the back wall are set to 1, and subtracting the result of the second simulation from the first.

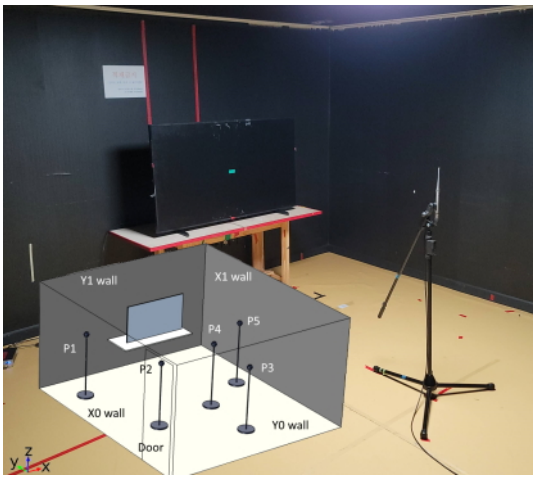

Fig. 6: Measurement set up of room utilized for verification with receiver positions P1-5, with origin (0,0,0) in intersection point of X0, Y0 walls and floor

9 Combination of FE and GA simulation

The FE and GA simulations are combined in the frequency domain by means of a loudspeaker type 8th order Linkwitz-Riley crossover. The GA simulated RIR is initially converted to a frequency domain RTF by applying a FFT. The crossover frequency chosen as the simulated room's expected Schroeder frequency, calculated as 550 Hz, a natural choice since it can represent the (soft) boundary between the modal and diffuse regime. A full bandwidth RIR is achieved by iFFT of the combined high-pass filtered GA simulated RTF and low-pass filtered FE simulation with assumed zero receiver pressures above the maximum simulated frequency.

10 Room measurement and analysis

The room by which the simulation techniques are evaluated is shown in Figure 6. It is shoebox shaped, relatively small at 3.66 x 4.10 x 2.08 m, and windowless with one door. Each wall is of light construction, seemingly wooden, as is the ceiling. The floor is relatively hard and covered with linoleum tiles.

The TV source was installed on the Y1 wall at 2.23 m from the X0 wall (as identified in Figure 6) in wall-mount condition with -Y orientation at 11.5 cm distance from the back wall with a distance of 19 cm between the top of the TV set and the ceiling. and in tabletop condition at 40 cm from the back wall on a 150 x 59 cm table surface at height of 61.5 cm. Additionally a second loudspeaker source (Genelec 8020), located at (1.44, 2.80, 0.64) m, also in -Y orientation was utilised as a reference. RIR measurements were taken using a 1/4 inch measurement microphone at five locations. Reverberation time was calculated for third octave bands to the T_{20} standard and shown in Figure 7 with 1.5 s as a 250 Hz – 4 kHz mean value.

For accurate room simulation it is essential to have a reliable characterisation of the boundaries. Measurement of surface impedance or absorption coefficient in the laboratory using material samples, and techniques described in e.g. [15] is an ideal approach, but typically unavailable. There exists a few methods to measure surface impedance in situ as summarised in [21], however with limited time for this study there was no opportunity to carry this out. Our investigation characterises the room by utilising previously published absorption coefficient data selected based on the assumed room construction. Inevitably, this approach can be a significant source of error. In order to reduce this error we follow an approach described by Aspöck [21] in which fitted absorption coefficients are derived by introducing a frequency dependent correction factor $k(f)$ uniformly applied to the initial absorption coefficients α', which matches a predicted reverberation time based on Eyring's formula, with measured reverberation time $T(f)$. Ignoring air absorption, this is expressed in Equation 3, with $\bar{\alpha}' = 1/S \cdot \Sigma_i S_i \alpha'_i$, the mean absorption, S the room surface area, and V the room volume.

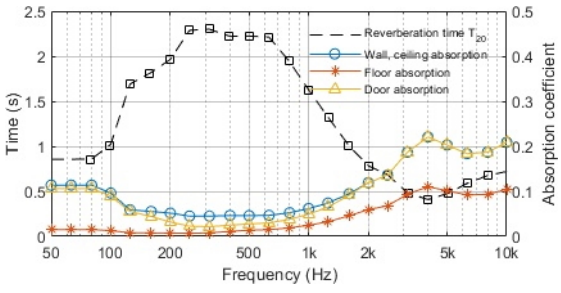

Fig. 7: Plot of measured reverberation time and fitted absorption coefficient data based on seed values in Table 3 and application of Eqn. 3

Table 1: Initial absorption coefficients taken from published data. Floor = "Linoleum or vinyl stuck to concrete" #600 from [22]; Walls, Ceiling = "Wood boards on joists or battens" from [23, p731]; Door = "Solid wooden door" #396 from [22]

	Frequency (Hz)					
Surface	125	250	500	1k	2k	4k
Floor	0.02	0.03	0.03	0.04	0.05	0.05
Walls	0.15	0.20	0.10	0.10	0.10	0.10
Ceiling	0.15	0.20	0.10	0.10	0.10	0.10
Door	0.14	0.10	0.06	0.08	0.10	0.10

$$k(f) = 1/\bar{\alpha}'(1 - e^{0.161V/ST(f)}) \tag{3}$$

The initial absorption coefficients used in this investigation are shown in Table 1. Figure 7 shows the measured reverberation time at 1/3 octave bands and the fitted absorption data for each surface type. These absorption coefficients were applied directly in the GA simulation, except for the X0 wall in which the average of the door and wall absorption was applied based on their relative size. For the FE simulation the absorption coefficients were converted to surface impedance. Since the room was relatively bare, we assume minimal scattering from the room surfaces, thus in the GA simulation the scattering coefficients were set to respectively 0.1 and 0.15 for 1/3 octave bands below and above 1 kHz, uniformly for all surfaces.

11 Results and Discussion

The results of simulation of the room for the loudspeaker and TV sources in wall-mount and table-top installation condition based on the techniques and characterisations described, and are shown in Figures 8 and 9. Figure 8 shows the magnitude of the RTF at receiver position 4. Figure 9 shows simulated and measured RIR for position 4 in full bandwidth in dB and as separated low and high frequency reconstructions compared with the filtered measured RIR.

For the RTF in Figure 8, the spectral amplitude characteristics are each, at least, reasonably well reproduced. The loudspeaker simulation was mostly successful but the TV simulations showed some deviations, in the low-mid frequencies (200 - 500 Hz). In this region some of the expected differences between the two TV cases were predicted, albeit not reproduced with accuracy. Some of these deviations could be due to the reduced order source representation, as directivity becomes significant with increasing frequency; or as the as secondary reflections of the TV structure become more significant, and diffraction plays less of a part, since the TV structure is not modelled in this region. In the middle frequencies, between 500 Hz and 1 kHz, all simulated cases showed deviations which can reasonably attributed to the limited frequency resolution (256 sample window) of the of the source definition in the GA simulation. In fact, the prominent peak seen at 800 Hz was successfully reproduced in the FE simulation (not shown) before being filtered out. Unfortunately, the spectral differences between the two TV cases in the 5 kHz region perhaps related with the expectedly more 'bright' sound perception of the table-top case are not well reproduced

For the RIR in Figure 9 we can see differences in the fine detail of the response between measured and simulated data, which is expected since the SRT algorithm is based on random processes. However, we can also see that the decay characteristics are similar. In each case the FE simulation reproduces the early part of the impulse response to a reasonably good standard. For the GA simulations, we notice that the loudspeaker simulation reproduces the early part of the impulse response relatively well. For the wall-mount case the first ~ 15 ms are predicted more accurately than the later parts, for the table-top case this is reduced to the first ~ 8 ms. It may be interesting to extend the applied technique of replacing the (0,0,0) (direct) and (0,1,0) [2] specular reflections with a semi-anechoic derived substitute, to other early reflection pairs (1,0,0)+(1,1,0), (-1,0,0)+(-1,1,0), (0,0,1)+(0,1,1) and (0,0,-1)+(0,1,-1) as a means to improve the accuracy of the important early specular reflections. However, it should be acknowledged that the approach of interpolating and extrapolating and the measured semi-anechoic data as described, as a defacto ISM acoustic source is essentially flawed since far-field measurement conditions are not achieved. Additionally, for each TV source characterisation, spatial aliasing is a potential source of error for which no counter strategy was applied. We also acknowledge the likely error introduced as a result of the method used

[2] Applying a vector integer notation (i_X, i_Y, i_Z) to represent image sources, as identified by their order and directional origin with respect to the receiver

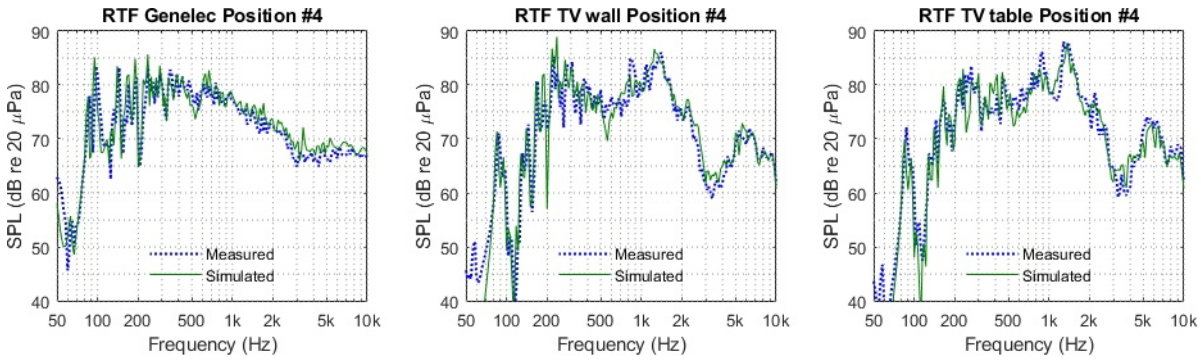

Fig. 8: Measured and simulated RTF magnitude for position 4 (2.23,1.90, 1.20) m, 1/24th oct smoothing

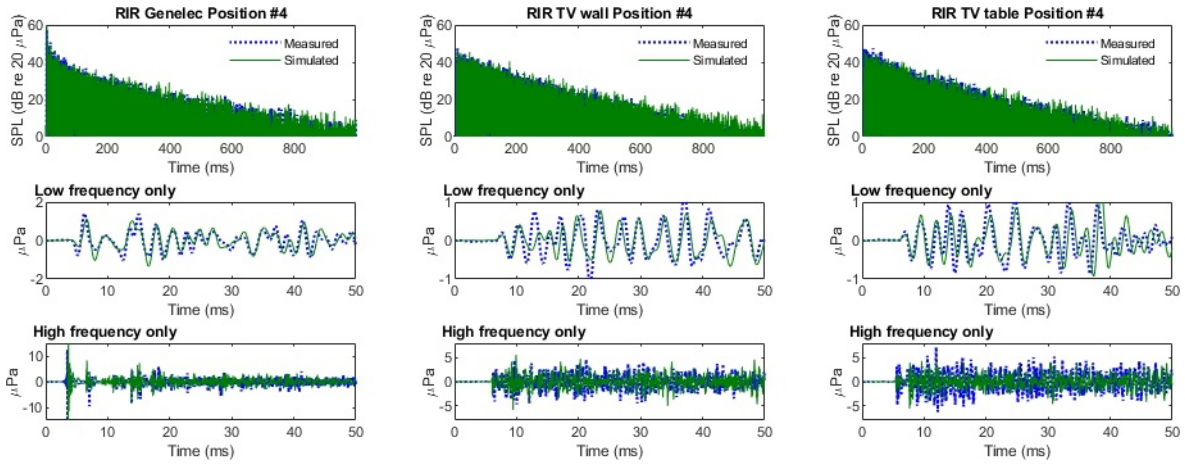

Fig. 9: Measured and simulated RIR for position 4, full reconstruction (dB, top), components (middle, bottom)

for the characterisation of the room boundaries.

12 Conclusion

In this investigation we demonstrated a method for an in room prediction of the acoustic response of a TV set in typical installation conditions. The approach was moderately successful although there are areas for improvement which can become a focus for our on-going research and development on this topic.

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