COMPENSATING THE ACOUSTICAL LOADING OF SMALL LOUDSPEAKERS MOUNTED NEAR DESKTOPS

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1 INTRODUCTION

Studies into the effects of acoustical loading on the in-situ response of loudspeakers generally consider the effects of room boundaries[1–5] and room modes[6–7]. Small two-way loudspeakers in control rooms and studios are positioned close to the listener in order to reduce room effects. These so-called "near-field monitors" are frequently positioned on the meter bridge of large format consoles, on some construction around medium format consoles, or simply on the desktop of a workstation control surface. Sometimes loudspeakers are mounted onto a stand in order to avoid mechanical coupling and reduce the level of the reflection off a surface. In all of these cases, acoustical loading of the surface reflection affects the in-situ magnitude response. Assuming that the surface is acoustically solid, the desktop acoustical loading can be predicted and is a function of the surface area. A typical 1–3 m^2 surface causes an upward deviation in the in-situ magnitude response between 100–250 Hz as well as comb filter in the mid-to-high frequencies.
The effects of a desktop (2.1 m x 1.2 m = 2.52 m^2) on the impulse response of a loudspeaker in anechoic conditions are shown in Figures 1 and 2. A reflection is visible about 1 ms after the direct impulse. In the frequency domain, the reflection causes strong comb filtering starting at 1 kHz as well as an acoustical loading related increase in level over the range 100 – 500 Hz.

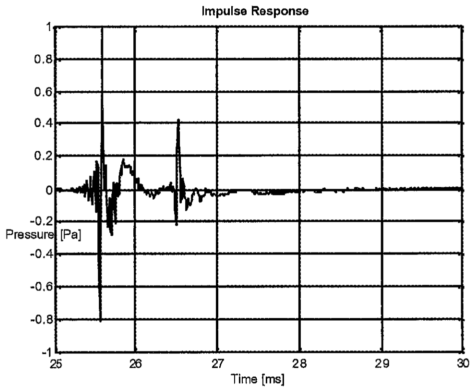

Figure 1. Impulse response of a loudspeaker mounted near a desktop in anechoic conditions. A reflection is clearly visible.

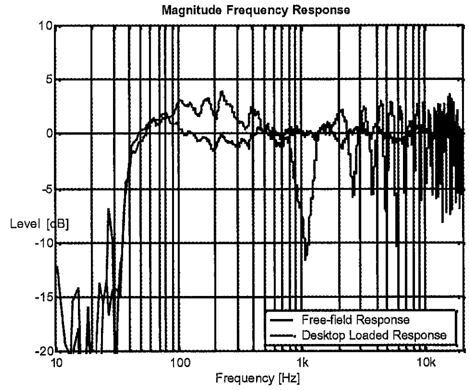

Figure 2. Unsmoothed anechoic magnitude response of a loudspeaker mounted near a desktop. Loading and comb filtering are visible.

In non-anechoic conditions the in-situ response is often affected by reflections off other nearby boundaries. A typical example of a notch filter being required to compensate for the acoustical loading of a mixing console is shown in Figure 3. Other features often seen in the low frequencies are associated with cancellations due to reflections off nearby large acoustically solid surfaces such as the walls, floor or ceiling. An example of 50 and 100 Hz cancellations caused by these reflections can be seen in Figure 4. Other cancellations can also be seen at higher frequencies. In the range 300–700 Hz there is often a broad dip in the magnitude response due to coincidence of higher frequency notches caused by comb filtering due to reflections. An example of this can be seen in

Figure 5. Also visible in this figure is comb filtering in the range 0.5–5 kHz due to a reflection off the desktop surface.

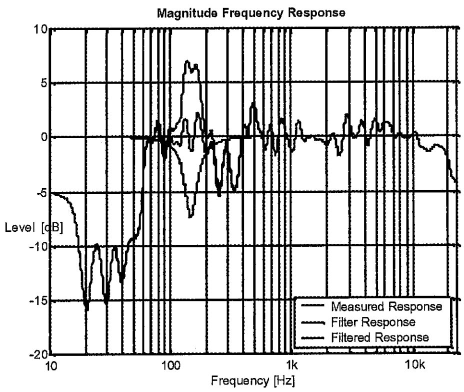

Figure 3. A typical example of the effect of acoustical loading on the magnitude response of a loudspeaker and the compensation filter required to correct for it.

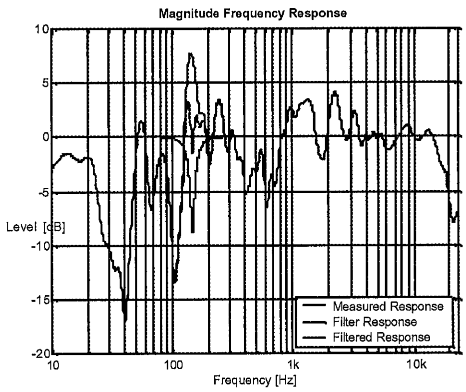

Figure 5. In addition to the effects shown in Figure 2, constructive interference at 150 Hz increases the effect of acoustical loading. Desktop comb filtering is also visible in the range 500–5000 Hz.

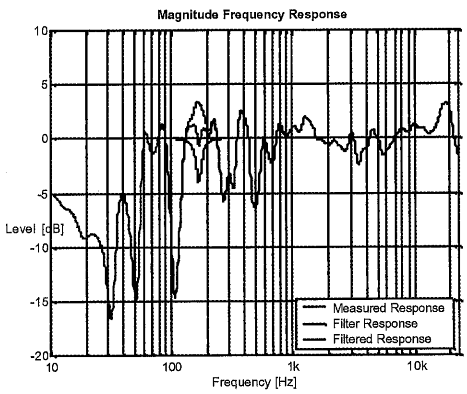

Figure 4. A notch at 100Hz caused by a reflection reduces the effect of acoustical loading. Other cancellations are also apparent.

The purpose of this paper is to investigate the effect of this acoustical loading within the frequency band of 100–250 Hz on 89 in-situ magnitude responses *after* having already equalised the loudspeakers using the existing set of Room Response Controls[8–13]. Secondly, the parameters are determined for a single compensating notch filter design to equalise this upward deviation. Finally, a statistical evaluation is conducted to determine the benefit of applying such a "one-size-fits-all" filter individually to each of the responses. An optimisation algorithm is used to define notch filter parameters.

2 IN-SITU EQUALISATION AND ROOM RESPONSE CONTROLS

A notch filter[14] was constructed using a bi-quadratic transfer function of the form,

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \qquad (1)$$

where the scaling of the transfer function is given by the coefficients,

$$a_0 = 1 + \frac{\sin(2\pi f_0/f_S)}{2QA}$$
$$A = \sqrt{10^{G/20}} \tag{2}$$

with the centre frequency f_0, sampling frequency f_S, gain of the resonance A, calculated from the dB-gain value G, and the Q-value Q. The transfer function coefficients are then defined as,

$$b_0 = \frac{\left(1 + A\frac{\sin(2\pi f_0/f_S)}{2Q}\right)}{a_0}$$
$$b_1 = \frac{-2\cos(2\pi f_0/f_S)}{a_0}$$
$$b_2 = \frac{\left(1 - A\frac{\sin(2\pi f_0/f_S)}{2Q}\right)}{a_0} \tag{3}$$
$$a_1 = \frac{-2\cos(2\pi f_0/f_S)}{a_0}$$
$$a_2 = \frac{\left(1 - \frac{\sin(2\pi f_0/f_S)}{2QA}\right)}{a_0}$$

3 OPTIMISATION OF THE EQUALISATION

Boundaries are defined for the gain G (0 to –20 dB), centre frequency f_0 (100–250 Hz) and Q-value Q (0.5 to 20). Initial values were set to $G = 0$ dB, $f_0 = 150$ Hz and $Q = 4.33$ (third-octave). A least squares method, Matlab's "lsqnonlin" function[15], minimises the objective function,

$$\min_m E = \sum_{f=f_1}^{f_2} \left| \frac{a_m(f)\; x(f)}{x_0(f)} \right|^2 df \tag{4}$$

where $x(f)$ is the third-octave smoothed[16] magnitude of the loudspeaker's in-situ frequency response, $a_m(f)$ is the notch filter magnitude response, $x_0(f)$ is the target response (a flat response at 0dB) and the frequencies f_1 and f_2 define the optimisation band frequency range (100–250 Hz).
Visual inspection of the loudspeaker magnitude responses after equalisation shows that the algorithm is robust in finding the global minimum.

4 LOUDSPEAKER MEASUREMENTS

The 89 active loudspeakers analysed in this study were Genelec 1030A (15 units), 1031A (52 units) and 1032A (22 units). The loudspeaker measurements were supplied by one of the authors (62 measurements) and by a calibration engineer (27 measurements). The measurements were selected on the basis that the loudspeaker cabinets were known to be positioned near a large reflecting surface such as a desktop or mixing console. All loudspeakers were equalised using the existing set of Room Response Controls (Bass Roll-off, Bass Tilt and Treble Tilt). Two acoustic measurement systems were used to acquire the impulse responses (Table 1).

The RMS deviation within the optimisation range 100–250 Hz was recorded for each magnitude response before and after applying a notch filter designed individually to compensate any upwards deviation in the magnitude response. This statistic was used to study how the objective response quality had changed due to individualised notch filtering.

Table 1. Settings in the measurement systems.

Measurement System	MLSSA[17]	WinMLS 2000[18]
Neutrik 3382 Microphone[19]	OM2099	RG2455
Sample rate, f_S	75.5 kHz	48 kHz
MLS sequence order	14	14
Averages	1	1
Impulse response length	0.217 s	0.341 s
Time window	Half-cosine	Half-cosine
FFT size	16384	16384
Frequency resolution	4.61 Hz	2.93 Hz

5 RESULTS

Summary statistics of the upward deviations found in the frequency range 100–250 Hz for the 89 loudspeaker magnitude responses are shown in Table 2.

Table 2. Summary statistics for the upward deviations in loudspeaker measurements within the frequency range 100–250 Hz.

	Median	Standard Deviation
Peak Frequency	141 Hz	31.1 Hz
Peak Deviation from Baseline	5.00 dB	1.52 dB
RMS Deviation	3.38 dB	0.98 dB

5.1 Individually Designed Notch Filters

Third-octave smoothed magnitude responses were calculated for each loudspeaker measurement and a microphone correction applied. The pressure response of each loudspeaker measurement was normalised to the median value of the range 400 Hz to 15 kHz. The least squares optimiser (Equation 4) was used to find the parameters for a notch filter (Equations 1-3) to correct upward deviations in the magnitude response in the range 100–250 Hz individually for each loudspeaker measurement.

Despite the positioning of the loudspeakers near a desktop, 20 (22%) of the 89 loudspeaker measurements did not require notch filter equalisation to minimise the RMS deviation in the range 100–250 Hz. These loudspeakers were therefore excluded from the rest of the analysis.

The maximum height of the deviation and attenuation of the notch filter for each loudspeaker measurement are shown in Figure 6. Figure 7 shows the same data as a scatter plot that indicates good correlation between the peak gain in the loudspeaker measurement and the notch filter gain. The frequency of the highest deviation and the centre frequency of the notch filter for each loudspeaker measurement are shown in Figure 8. Figure 9 shows the same data as a scatter plot and again there is good correlation between the loudspeaker measurement and the notch filter. The notch filter Q-value for each loudspeaker measurement is shown in Figure 10. The RMS deviation in the range 100–250 Hz before and after applying a notch filter and the change in the RMS are shown in Figure 11. Figure 20 in Appendix A shows box plots and histograms of the RMS deviation in the range 100–250 Hz before and after applying a notch filter. Also shown is the change due to equalisation. Summary statistics for the individually optimised notch filters are shown in Table 3. In all cases the RMS deviation has been reduced (improved) after the individually optimised notch filter has been applied to each magnitude response.

Scatter plots (Figures 12–14) of the optimised filter parameters show that there is no correlation between each of the parameter combinations, for example, a low Q factor does not correspond to a low gain or a low centre frequency. The centre frequencies of individually designed notch filters do not in all cases coincide with the upward deviation peak values, creating the outliers seen in Figure 9. These outliers result from the fact that the notch flter design considers the range 100-250 Hz, whereas the upward deviation frequency is taken to be the highest value in the upward deviation. The highest value does not measure central tendency of the upward deviation, whereas the notch filter centre frequency will tend towards this value because of the design method, creating a possibility for discrepancy between the two.

Table 3. Individual notch filter summary statistics.

	Median	Standard Deviation
Notch Centre Freq, f_0	147 Hz	27.5 Hz
Notch Gain, G	–5.69 dB	2.12 dB
Notch Q-value, Q	5.36	4.91
RMS Deviation After	2.31 dB	1.13 dB
RMS Deviation Change	–0.79 dB	0.73 dB

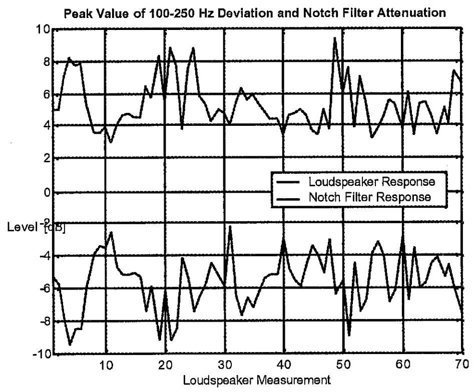

Figure 6. Peak value of the upward deviation and individually optimised notch filter attenuation for each loudspeaker measurement.

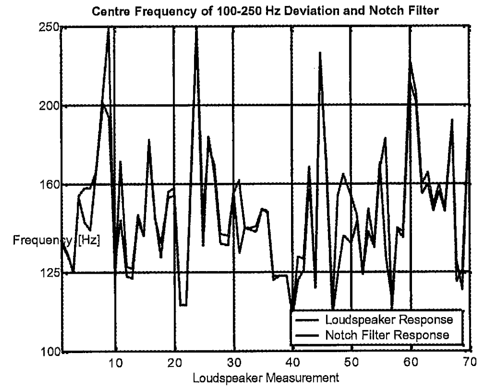

Figure 8. Frequency of the upward deviation and individually optimised notch filter centre frequency for each loudspeaker measurement.

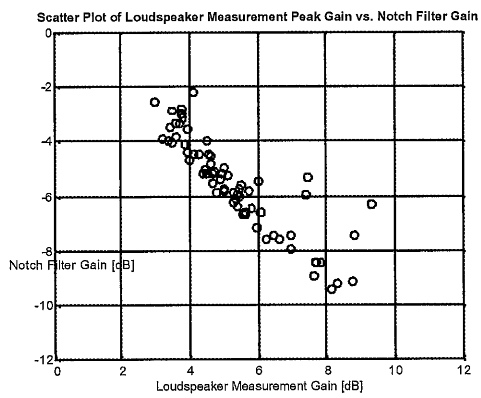

Figure 7. Peak value of the upward deviation and individually optimised notch filter attenuation for each loudspeaker measurement.

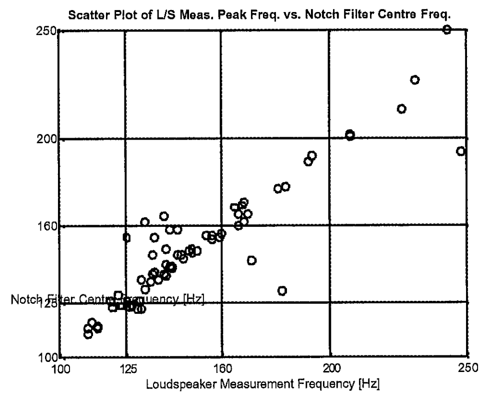

Figure 9. Frequency of upward deviation and individually optimised notch filter centre frequency for each loudspeaker measurement.

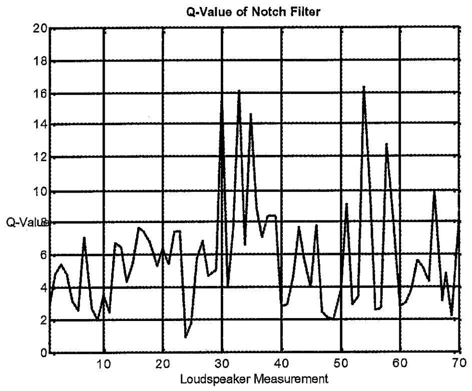

Figure 10. Individually optimised notch filter Q-value for each loudspeaker measurement.

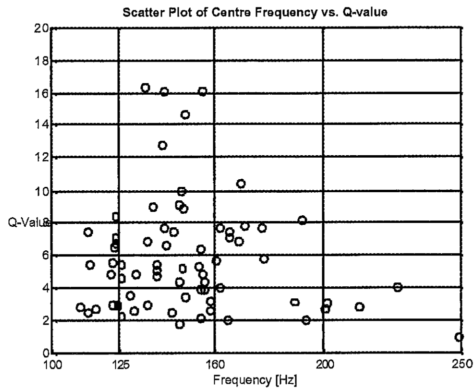

Figure 13. Scatter plot of centre frequency vs. Q-value.

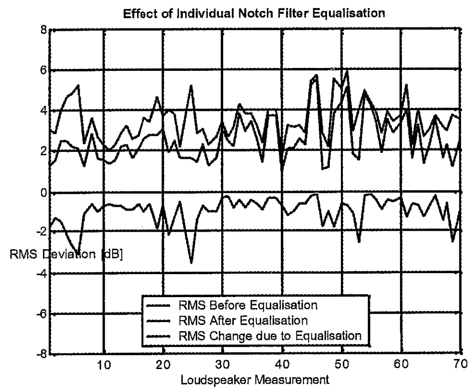

Figure 11. RMS deviation in the range 100–250 Hz before and after equalisation, and the RMS deviation difference after applying individually optimised notch filters.

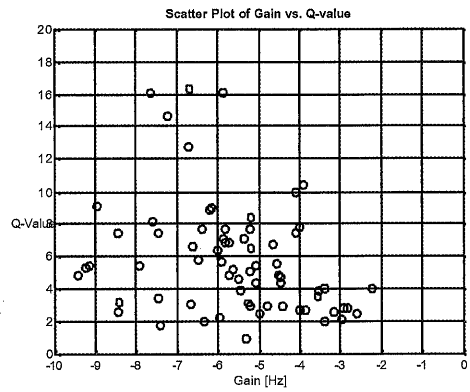

Figure 14. Scatter plot of gain vs. Q-value.

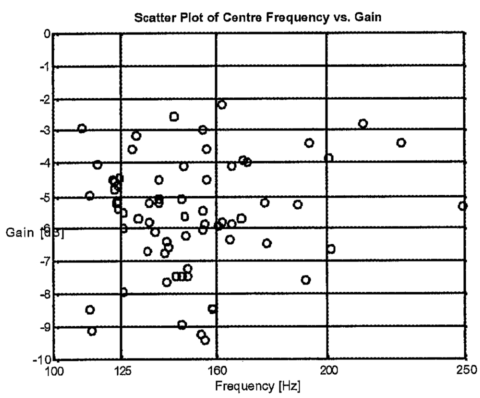

Figure 12. Scatter plot of centre frequency vs. gain.

5.2 Fixed Notch Filter Based on the Median of the Magnitude Responses

A notch filter was designed to compensate the upward deviation in the median of the responses, and then applied to each individual magnitude response to evaluate the benefit of a fixed filter design.

Third-octave smoothed magnitude responses were calculated for each loudspeaker measurement and a microphone correction applied. The pressure response of each loudspeaker measurement was normalised to the median value of the range 400 Hz to 15 kHz. The median of the 69 magnitude responses that remain in the study was calculated. A least squares optimiser was used to find the parameters for a single notch filter to correct the upward deviation within 100–250 Hz range.

This median of the responses is shown in Figure 15. Also shown are the upper and lower quartiles and the 10% and 90% percentiles. A systematic low frequency upward deviation can be seen in all the percentile curves. Figure 16 shows the median of the magnitude responses, the notch filter to correct the upward deviation, and the equalised median of the magnitude responses.

The RMS deviations for all the responses in the range 100–250 Hz before and after applying this notch filter, and the change in the RMS deviation due to equalisation, are shown in Figure 17. Summary statistics for the single optimised notch filter are shown in Table 4. Figure 21 in Appendix A shows box plots and histograms of RMS deviations in the range 100–250 Hz before and after equalisation. Also shown is the change due to equalisation. In the majority of cases the RMS deviation has been improved, but 19 of the measurements show no change or are made worse by filtering.

Table 4. Fixed notch filter design based on the median of the magnitude responses, and the resulting statistics.

	Median	Standard Deviation
Notch Centre Freq, f_0	146 Hz	–
Notch Gain, G	–3.48 dB	–
Notch Q-value, Q	3.23	–
RMS Deviation After	2.99 dB	1.09 dB
RMS Deviation Change	–0.46 dB	0.51 dB

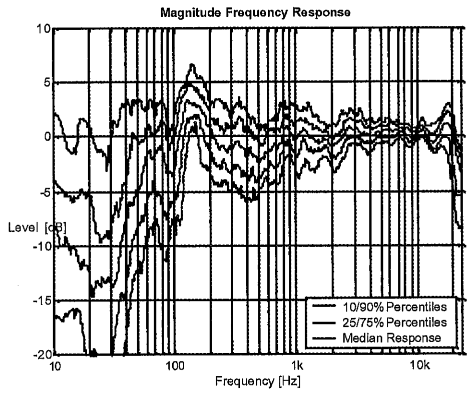

Figure 15. Median and percentiles of the magnitude responses for 69 loudspeakers.

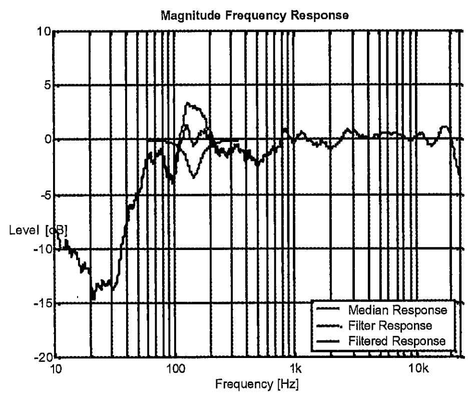

Figure 16. Median of the magnitude responses before and after equalisation.

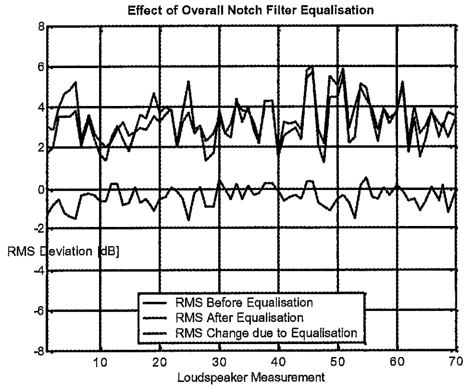

Figure 17. RMS deviation in the range 100–250 Hz before and after equalisation, and difference in the RMS deviation, for each loudspeaker measurement equalised with a fixed notch filter.

5.3 Room Response Control Optimisation Algorithm

The fixed notch filter based on the median of the magnitude responses has been incorporated into the automated in-situ optimiser (DIPtimiser), previously described in[9–12], as a Desktop LF Control. An example loudspeaker measurement, taken from Figure 3, is shown in Figures 18 and 19. As a result of applying the new Room Response Control, the reported *broadband* RMS deviation has been improved from 2.41 dB to 2.01 dB.

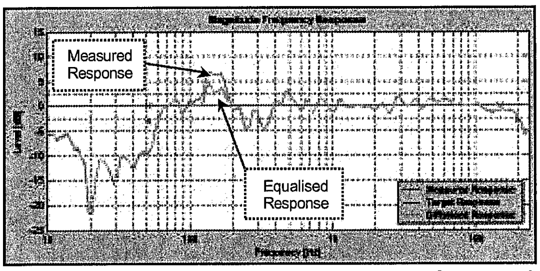

Figure 18. Magnitude responses before and after equalisation for the loudspeaker measurement shown in Figure 3.

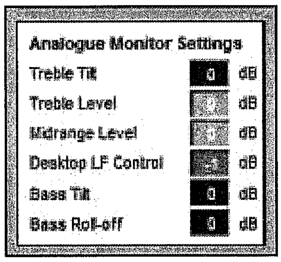

Figure 19. Output section shows that only the Desktop LF Control is required on the previously equalised loudspeaker.

6 DISCUSSION

The existing Room Response Controls in the active loudspeakers (Bass Roll-off, Bass Tilt and Treble Tilt) achieve a good broadband balance but fine detail is not corrected. Also uncorrected is a systematic effect due to the loading from a desktop positioned near the loudspeaker cabinet. An upward deviation of peak value 5.00 dB ± 1.52 dB centred on 141 Hz ± 31.0 Hz is observable in approximately 80% of the 69 analysed cases in this study requiring additional equalisation. This effect would be expected in any conventional direct radiating two-way design mounted in such a way, as it occurs below 250 Hz where loudspeakers of this size are relatively omni-directional.

Correcting fine detail at high frequencies may not be as significant as correcting for the broadband frequency response balance, because the human hearing system is more sensitive at detecting wideband imbalances than small narrow band deviations in the magnitude response[20,21]. The desktop loading at low frequencies (100–250 Hz) becomes subjectively important, creating a "boomy" sound quality, because the critical bandwidth decreases towards low frequencies. The acoustical loading due to a large surface or a tabletop positioned in front of a loudspeaker is independent of the listening position and the upward deviation was seen in varying amounts across all percentiles of the magnitude responses. This can be corrected using a single notch filter.

When a notch filter is optimised for each loudspeaker measurement individually, the median improvement in the RMS deviation in the range 100–250 Hz is 0.81 dB. The magnitude response is improved in all cases but a spread is found in the individual notch filter parameters.

When a single notch filter (fixed filter design) is designed based on the median of the magnitude response all the loudspeakers pooled together, and this single filter is applied to all the magnitude responses, the median improvement in the RMS deviation in the range 100–250 Hz is 0.46 dB. The fixed notch filter achieves 57% of the improvement achieved by notch filters optimised individually for each loudspeaker. 19 measurements show no change or degradation in terms of the RMS deviation, so the magnitude response is improved in 72% of cases. Accounting for the other 20 cases where no equalisation was required, establishes that 56% of loudspeakers placed near a desktop benefit from applying a fixed notch filter.

Median parameter values for notch filters optimised individually for each loudspeaker are f_0 = 147 Hz, G = –5.43 dB and Q = 5.29. The parameters of the fixed notch filter design are f_0 = 146 Hz, G = –3.48 dB and Q = 3.23. The centre frequency shows good agreement but the gain is shallower and Q-value lower for the fixed design. This reflects the effect of filtering individual loudspeaker measurements before pooling rather than pooling the loudspeaker measurements before optimising the filter.

In the case of the fixed filter design, it is interesting to note that a graphic equaliser cannot be used to simulate this notch filter, although the Q-value is similar to that of a graphical analyser and the gain of a graphical equaliser band can be freely adjusted, as the optimum notch filter centre frequency lies between two standard centre frequencies 125 Hz and 160 Hz[22,23].

The proposed desktop loading compensation filter is now available in active loudspeakers[13] and has been successfully added to the automated optimisation algorithm for use in automated in-situ calibrations (DIPtimiser)[9–12].

7 CONCLUSIONS

The objective of this paper was to find a notch filter that can compensate for the effects of acoustical loading when two-way loudspeakers are mounted near desktops.

To define the shape of the most useful fixed compensating filter, a study was performed of 89 in-situ equalised responses of loudspeakers positioned near large reflecting surfaces. The magnitude responses were normalised and pooled to visualise any systematic effects. After equalisation using the current set of Room Response Controls, the remaining major feature in the magnitude response was attributable to the desktop acoustical loading. The typical loading can be described as an approximately third-octave wide 5 dB high upward deviation centred at 141 Hz.

The median of the magnitude responses was used to design the correcting notch filter. The optimal parameters were found to be f_0 = 146 Hz, G = –3.48 dB and Q = 3.23. A graphic equaliser cannot be used to simulate this notch as the centre frequencies do not match. Applying the correcting filter improved the RMS deviation in the range 100–250 Hz from 3.38 dB to 2.99 dB. An improvement was seen in over 50% of the magnitude responses. When a loudspeaker is mounted near a desktop, the proposed filter can improve the magnitude response in more that one in two cases.

Given that the acoustical loading effect caused by a nearby reflecting surface is relatively common in two-way near-field installations, an additional control has been added to the standard Room Response Control set built in loudspeakers. This "Desktop Low Frequency Control" is an active notch filter added in the bass channel of an active loudspeaker. The new control has also been added to the automated optimisation algorithm for use in in-situ calibrations.

8 ACKNOWLEDGEMENTS

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APPENDIX A – BOX PLOTS AND HISTOGRAMS

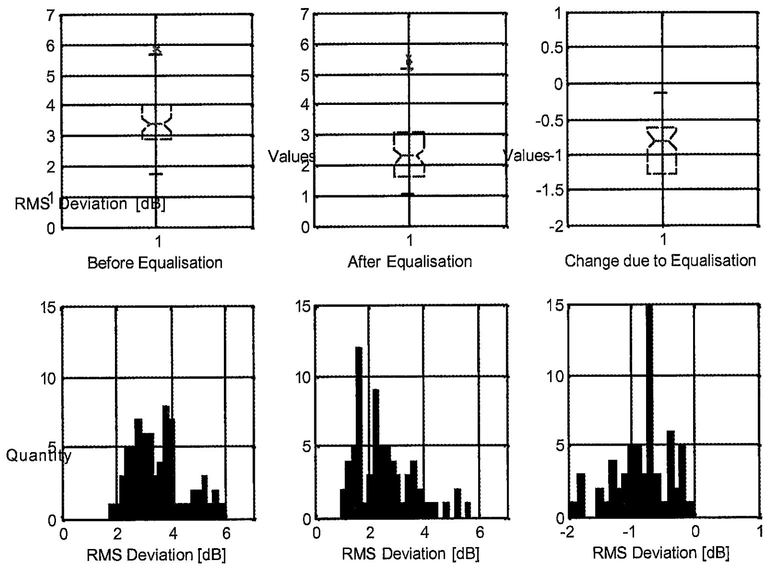

Figure 20. Responses equalised using individually designed notch flter designs. RMS deviation in the range 100–250 Hz before applying the filters (left plots) and after applying the individually optimised notch filters (centre plots) equalisation. Change due to equalisation (right plots).

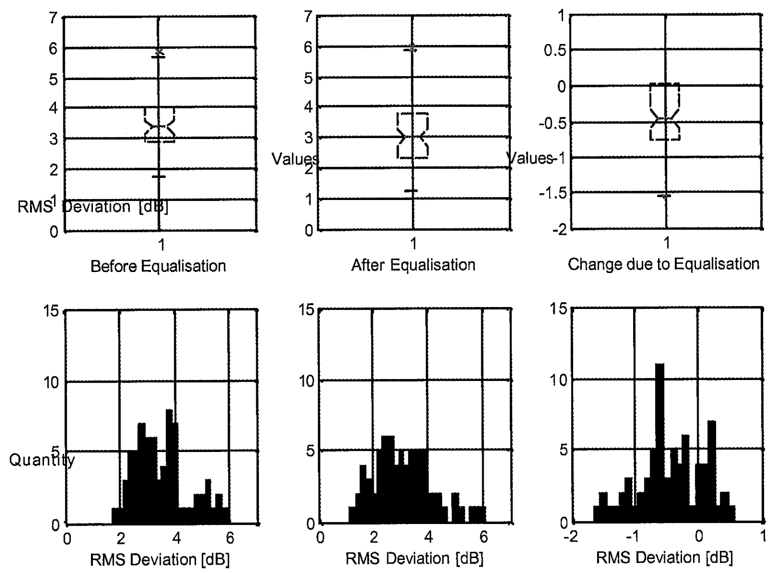

Figure 21. Responses equalised using a fixed filter design. RMS deviation in the range 100–250 Hz before applying the notch filter (left plots) and after applying the fixed notch filter design to all responses (centre plots). Change due to applying the fixed notch filter design (right plots).