Analysis of Wavelet Usage in De-noising of Room Impulse Responses

Đorđe Damnjanović and Dejan Ćirić

***Abstract*—After decades of research, Fourier transform can be easily replaced with wavelet transform in some applications, especially when frequency resolution problems need to be solved. Wavelet usage nowadays is widespread and it includes signal de-noising, which is the main focus of this research. This paper presents analysis of the wavelet de-noising process implementing different wavelet families and parameters on room impulse responses (RIRs) contaminated with different synthetic white and pink noises. All RIRs used in this process are also filtered in third-octave and octave bands. Special attention is paid to the wavelet parameters that have a major role in the de-noising process. The results show that usage of adequate wavelets and their parameters can provide significant reduction of noise effects, or more specifically improvement of the dynamic range of a RIR and corresponding decay curve.**

***Index Terms*—Wavelet; De-noising; Room impulse response; Third-octave bands; Octave bands.**

I. INTRODUCTION

One of serious problems appearing in many scientific areas including telecommunications, biomedical engineering, signals and systems is contamination of the signal with noise. Various sources can produce an already contaminated signal, and cases where the signal contains only the useful information are rare. De-noising techniques are very common nowadays, but the nature of signals and noises can cause certain difficulties when noise removal is in the focus. Actually, in most practical cases, noise will still have some influence on the signal even after de-noising, but the result can be satisfactory at the end.

There are a number of different de-noising techniques including various filtering methods (optimal, adaptive, notch, Wiener, Kalman, etc) [1-3]. Adaptive filtering is wide spread in the biomedical and speech engineering, while optimal filtering, like Wiener filter can often be used in the image processing [4]. Although some algorithms are not so useful in de-noising, they can provide an acceptable solution in combination with other algorithms. Illustrative examples are related to usage of IIR and FIR filters. Besides in de-noising, all these techniques have found their place in some other applications, such as unknown system detection, echo cancelation, noise control, etc.

The main focus of this research is de-noising using the wavelets. At the beginning, wavelets were used as an improvement for the Fourier transform [5], but very quickly they found their place in signal de-noising [6]. There are lots of wavelet families and parameters that need to be considered. For achieving a better performance in de-noising, it is necessary to adjust the setup parameters, like hard or soft thresholding as well as decomposition level. These parameters often depend on the nature of signal and noise.

When the room impulse responses (RIRs) are in focus, noise also makes a negative impact. This is reflected in the decay curve (Schroeder's decay curve - also known as the energy decay curve - EDC) where the slope of the obtained curve is changed in comparison to the curve of noiseless RIR.

The authors of this paper have already investigated some aspects of usage of wavelets and effects of changing the wavelet parameters in the RIR de-noising [6-8]. This is an interesting approach, since in spite of the widespread application of wavelets, for example in de-noising of speech, the usage of wavelets for de-noising of RIRs can hardly been found in literature. In order to shed light from another perspective on this topic, special attention is paid here to the effects of different noises as well as to the de-noising of RIRs filtered in third-octave and octave bands.

II. BACKGROUND ON WAVELETS AND ITS USAGE IN SIGNAL DE-NOISING

Although the Fourier transform is a common algorithm for signal processing and analysis, during the years wavelets have also found their place in the same field. A main reason for developing such an alternative approach was to solve time and frequency resolution problems of the short time Fourier transform (STFT) [9]. Despite the fact that the wavelet transform is done in a similar way as the STFT – a signal is multiplied by the window function and by the wavelet function in the STFT and wavelets, respectively, the wavelets differ from the STFT in many aspects. One of the most important aspects is that the width of the window is changed as the transform is computed for every single spectral component [9].

All data functions in the wavelet transform are decomposed into various frequency components during the whole process, where each component is analyzed at the resolution best fit for its scale. A starting transform in most cases where wavelet algorithms are used is the continuous wavelet transform (CWT), and it is defined by the inner product of the function

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Đorđe Damnjanović is with the Faculty of Technical Sciences Čačak, University of Kragujevac, Svetog Save St. 65, 32000 Čačak, Serbia (e-mail: djordje.damnjanovic@ftn.kg.ac.rs).

Dejan Ćirić is with the Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia (e-mail: dejan.ciric@elfak.ni.ac.rs)

(*f*) and the basis wavelet (so called "mother" wavelet $\psi_{a,b}(x)$) [9]:

$$CWT_f(a,b) = (f, \psi_{a,b}) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(x) \psi^* \left(\frac{x-b}{a} \right) dx, \qquad (1)$$

where a is the scaling parameter and b is the translation parameter.

III. METHODS OF ANALYSIS

For the purpose of analysis, two types of the synthetized RIRs are used (the first type is generated by the image source model and the second type has truly exponential decay as in diffuse sound fields). Five RIRs of each of these types are selected for further processing. All synthetized RIRs are sampled at 44100 Hz and contaminated with two types of noise: the Gaussian white noise and pink noise. In the synthesized RIRs scenario, the RIRs with noise obtained after the wavelet de-noising are compared to their noiseless counterparts, but also to the same RIRs before the wavelet de-noising. Measured RIRs lead to similar results, and they are used in some other papers of the authors, see, e.g. [7].

Different wavelet families are used in the investigation for de-noising: Haar, Daubechies, Coiflets, Symlet, biorthogonal, reverse biorthogonal and Mayer. Besides the wavelet function itself, other wavelet parameters need to be considered too: thresholding, selection rule, rescaling and decomposition level. It is an objective of this research to try to find out an optimal set of the parameters leading to the best results of de-noising. This means the greatest improvement of the dynamic range of the EDC related to the greatest noise floor reduction that causes as little as possible disturbance (degradation) of the useful signal (reverberation decay in this case). The dynamic range improvement represents a difference between the dynamic ranges after and before the wavelet application, see Fig. 1. In that regard, the dynamic range for both cases is calculated as a decay range difference between the initial maximum of the EDC (0 dB) and decay level of the point where the tested EDC goes away from the reference EDC for more than the pre-defined threshold (0.2 dB). Besides the dynamic range improvement, noise floor reduction due to the wavelet de-noising is also used as a control measure.

The wavelets are applied by the Matlab function *wden* [10], where the following parameters can be set: thresholding selection rule – *rigrsure* (uses the principle of Stein's unbiased risk), *minimaxi* (minimax thresholding), *sqtwolog* (universal thresholding), and *heursure* (heuristic variant of the *rigrsure* option); thresholding – *hard* (cruder thresholding) and *soft* (wavelet shrinkage); multiplicative threshold rescaling – *one* (without rescaling), *sln* (rescaling using a single estimation of level noise based on first-level coefficients), *mln* (rescaling using level-dependent estimation of level noise); various wavelet decomposition levels as well as wavelet functions.

The focus of the research presented here is on the investigation of effects of changing the noise characteristics. They include the noise type, level and time distribution of noise amplitudes (noise shape in the time domain randomly generated from trial to trial). The focus is also on de-noising of RIRs filtered in third-octave and octave bands. For that purpose, the RIRs are filtered by third-octave band and octave band Butterworth filters that are in accordance with the IEC 61260 [11]. Central frequencies of these bands ranges from 100 Hz to 5 kHz.

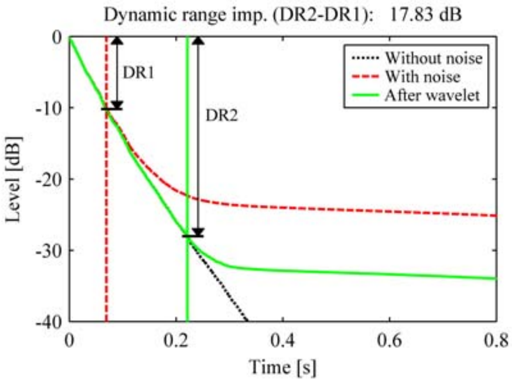

Fig. 1. Dynamic range improvement as a difference between the dynamic ranges of the EDCs of a noisy RIR after (DR2) and before the wavelet de-noising (DR1)

IV. RESULTS

Since it is noticed that the optimal values of some wavelet parameters such as decomposition level depend on type of noise, level of noise and used RIR [8], the effects of these factors are first analyzed.

A. Influence of Noise Level and Type

Illustration of effects of the wavelet de-noising using the optimal set of the wavelet parameters (*minimaxi* selection rule, *hard* thresholding and *mln* rescaling) where synthetic white noise of level of -50 dB is added to the broadband synthesized RIR are shown in Fig. 2.

It can be seen that a significant dynamic range improvement and noise floor reduction can be achieved. In the broadband RIRs contaminated by white noise, the noise is typically reduced only above 1 kHz when the optimal decomposition level of 3 is applied. The noise can be reduced at lower frequencies too, but using a higher decomposition level. However, this leads to degradation of the reverberation decay that is an unacceptable option.

The effects of using the optimal set of the parameters and changing the wavelet function and noise level are summarized in Table I, where the average dynamic range improvement after 10 trials is given. In each new trial, the noise of the same type and level is added to the tested RIR. These noises have different time distributions of noise amplitudes – they actually represent different noises of the same type and level. Regarding the decomposition level, it takes the value of 3 for the noise levels of -60 dB and -50 dB, while it takes the value of 4 for the noise level of -40 dB.

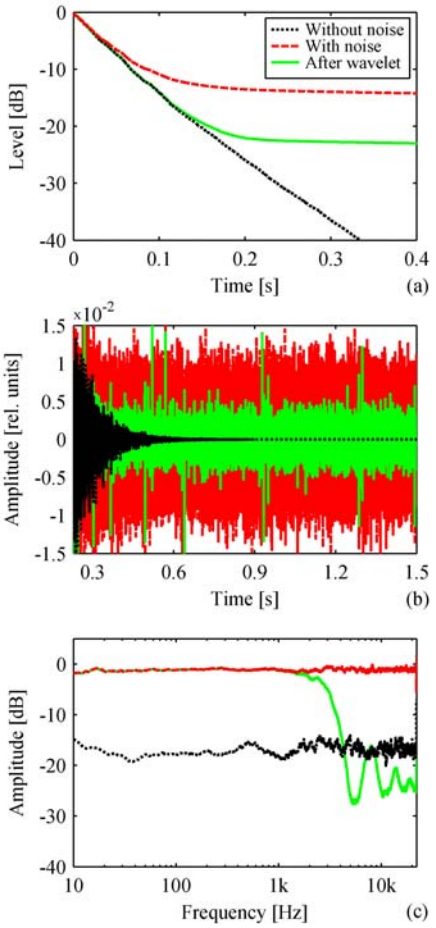

Fig. 2. Wavelet de-noising of the RIR synthesized by the ISM contaminated with the synthetic white noise of level of -50 dB using *minimaxi* selection rule, *hard* thresholding, *mln* rescaling and Daubechies 2 wavelet with decomposition level of 3: (a) EDCs, (b) RIRs after the knee where the main decay of a RIR intersects the noise floor and (c) spectra of the RIRs after the knee

The same procedure is repeated for calculation of the noise floor reduction and the results are given in Table II. This control measure is less sensitive to a change of the time distribution of noise amplitude (the differences from iteration to iteration are typically within 0.5 dB). The effect of changing the wavelet function is almost negligible. A larger influence is caused by changing the decomposition level. It is actually interesting to note that the noise floor is reduced for about 3 dB using the decomposition level of 1, and the noise floor reduction increases for about 3 dB for every increase of the decomposition level by 1.

The obtained results show that the dynamic range improvement can go up to almost 19 dB, and noise floor can be reduced by 9 dB or 12 dB depending on the used decomposition level. Some wavelets give slightly better results regarding these two control measures as presented in the previous two tables.

The second case scenario is related to contamination of the synthesized RIR with pink noise of levels from -70 dB to -50 dB. It is worthwhile to note that de-noising of a RIR with pink noise is more complicated than de-noising of a RIR with white noise. Due to larger noise amplitudes at lower frequencies in pink noise, it is necessary to use a higher decomposition level. This causes a larger degradation of the reverberation decay in some cases, or in other words, less stable and consistent results.

TABLE I

MEAN VALUES OF DYNAMIC RANGE IMPROVEMENT OF THE EDC AFTER APPLYING VARIOUS WAVELETS ON THE SYNTHESIZED RIR WITH WHITE NOISE OF LEVELS OF -60, -50 AND -40 DB

Wavelet	Noise level		
	-60 dB	-50 dB	-40 dB
Haar	18.3	13.5	11.02
Daubechies 2	18.16	13.51	10.94
Symlet 2	18.33	13.24	10.45
Coiflet 3	18.31	13.22	10.81
Biorthogonal 2.2	15.65	10.83	8.9
Reverse bior. 1.1	18.32	13.25	11.16
Meyer	18.53	13.8	11.31

TABLE II

MEAN VALUES OF REDUCTION OF NOISE FLOOR OF THE RIR AFTER APPLYING VARIOUS WAVELETS ON THE SYNTHESIZED RIR WITH WHITE NOISE OF LEVELS OF -60, -50 AND -40 DB

Wavelet	Noise level		
	-60 dB	-50 dB	-40 dB
Haar	7.04	8.78	11.99
Daubechies 2	7.18	8.98	12.13
Symlet 2	7.17	8.97	12.14
Coiflet 3	7.03	8.87	12
Biorthogonal 2.2	6.81	8.47	11.49
Reverse bior. 1.1	7.04	8.8	11.95
Meyer	7.01	8.79	11.95

The wavelet parameters are the same as in the case of white noise, but the decomposition level is now 15. The illustration of large noise floor reduction by the wavelet de-noising of a RIR with pink noise is shown in Fig. 3 as one of the possible cases. The impact of de-noising is visible in a wider frequency range, since the decomposition level of 15 is applied. The dynamic range improvement and noise floor reduction are now smaller comparing to the results obtained with white noise (see Table III and IV). Nevertheless, even in these cases significant improvements of the results are achieved.

B. *Third-Octave and Octave Filtering Before Wavelets*

Common situation in room and architectural acoustics is to estimate the acoustical parameters in third-octave or octave bands. To perform such a band-pass analysis, the measured RIR is first filtered by the third-octave or octave band filters. This is why the effects of wavelet de-noising on the RIRs filtered in these bands are also investigated.

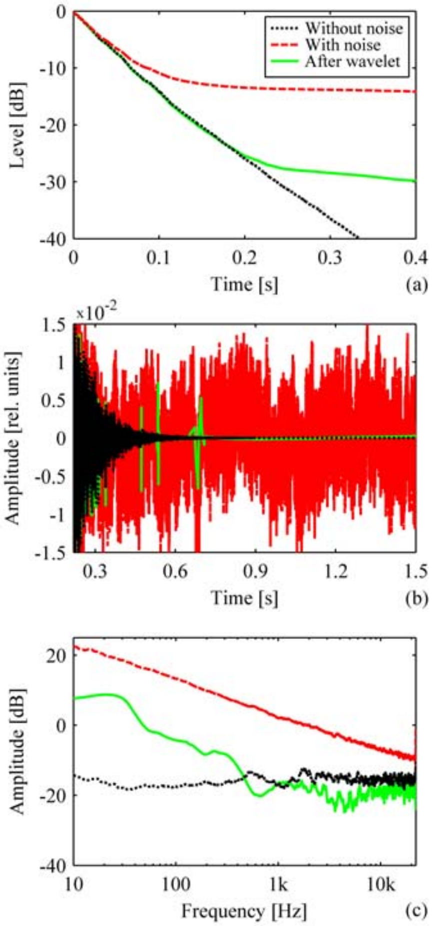

Fig. 3. Wavelet de-noising of the RIR synthesized by the ISM contaminated with the synthetic pink noise of level of -50 dB using *minimaxi* selection rule, *hard* thresholding, *mln* rescaling and Daubechies 2 wavelet with decomposition levels of 15: (a) EDCs, (b) RIRs after the knee and (c) spectra of the RIRs after the knee

TABLE III
MEAN VALUES OF DYNAMIC RANGE IMPROVEMENT OF THE EDC AFTER APPLYING VARIOUS WAVELETS ON THE SYNTHESIZED RIR WITH PINK NOISE OF LEVELS OF -70, -60 AND -50 DB

Wavelet	Noise level		
	-70 dB	-60 dB	-50 dB
Haar	11.41	13.49	15.15
Daubechies 2	14.61	14.73	12.1
Symlet 2	13.53	13.82	14.2
Coiflet 3	1.9	5.38	6.64
Biorthogonal 2.2	13.72	13.35	9.76
Reverse bior. 1.1	12.02	14.33	12.71
Meyer	8.42	6.35	3.12

It is noticed that the results related to the wavelet parameters and decomposition level are now more stable and consistent than in the case of broadband RIRs. The optimal set of the wavelet parameters leading to the best results also contains the parameters *minimaxi*, *hard*, and *mln* as well as *Haar* wavelet. The optimal decomposition level depends on the central frequency of particular third-octave or octave band. The mean values of optimal decomposition level obtained using 10 different random time distributions of noise amplitudes (in 10 iterations), 10 different synthesized RIRs (5 of them are synthesized by the image source model, and 5 of them have an ideal exponential decay) and both white and pink noise of different levels ranges from 8 for the lowest third-octave frequency band at 100 Hz to 2 for the highest frequency band at 5 kHz, see Fig. 4. Similar situation exists in the RIRs filtered by the octave band, as shown in Fig. 5.

TABLE IV
MEAN VALUES OF REDUCTION OF NOISE FLOOR OF THE RIR AFTER APPLYING VARIOUS WAVELETS ON THE SYNTHESIZED RIR WITH PINK NOISE OF LEVELS OF -70, -60 AND -50 DB

Wavelet	Noise level		
	-70 dB	-60 dB	-50 dB
Haar	5.36	8.06	12.91
Daubechies 2	4.22	8.42	11.46
Symlet 2	4.62	9.84	12.54
Coiflet 3	0.32	3.11	7.05
Biorthogonal 2.2	4.09	7.41	9.9
Reverse bior. 1.1	5.17	9.24	12.87
Meyer	2.65	4.08	3.99

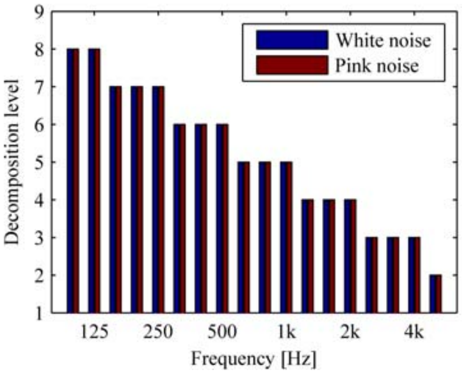

Fig. 4. Optimal decomposition level for the RIRs filtered in third-octave frequency bands obtained using 10 different random time distributions of noise amplitudes, 10 different synthesized RIRs as well as white and pink noise of two levels (-60 dB and -50 dB); Haar wavelet is applied

All the results from Figs. 4 and 5 are given in Table V and VI, where the impact of changing the decomposition level on the dynamic range improvement and noise floor reduction can directly be observed. The mean values of the dynamic range improvements and noise floor reduction also obtained using 10 different random time distributions of noise amplitudes, 10 different synthesized RIRs as well as white and pink noise of two levels (-60 dB and -50 dB) are shown in Figs. 6 to 9. The structures of the dynamic range improvement and noise floor reduction from Figs. 6 and 8 are periodic as a consequence of keeping the same decomposition level for a few third-octave bands, and changing the level afterwards.

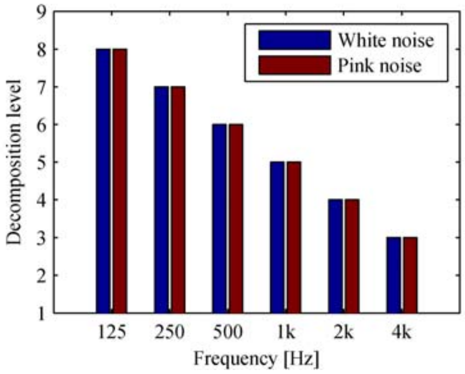

Fig. 5. Optimal decomposition level for the RIRs filtered in octave frequency bands obtained using 10 different random time distributions of noise amplitudes, 10 different synthesized RIRs as well as white and pink noise of two levels (-60 dB and -50 dB); Haar wavelet is applied

TABLE V

OPTIMAL DECOMPOSITION LEVELS AND MEAN VALUES OF DYNAMIC RANGE IMPROVEMENT AND NOISE FLOOR REDUCTION FOR THE RIRS FILTERED IN THIRD-OCTAVE FREQUENCY BANDS OBTAINED USING 10 DIFFERENT RANDOM TIME DISTRIBUTIONS OF NOISE AMPLITUDES, 10 DIFFERENT SYNTHESIZED RIRS AS WELL AS WHITE NOISE OF TWO LEVELS (-60 DB AND -50 DB); HAAR WAVELET IS APPLIED

f_c [Hz]	100	125	160	200	250	315
Dec. level	8	8	7	7	7	6
Dyn. range impr. [dB]	3.64	4.03	3.84	4.27	5.76	3.49
Noise floor diff. [dB]	4.47	6.81	3.50	4.37	6.70	3.14

f_c [Hz]	400	500	630	800	1000	1250
Dec. level	6	6	5	5	5	4
Dyn. range impr. [dB]	5.30	6.54	4.13	5.89	7.37	4.29
Noise floor diff. [dB]	5.34	7.38	3.85	4.81	7.44	3.06

f_c [Hz]	1600	2000	2500	3150	4000	5000
Dec. level	4	4	3	3	2	2
Dyn. range impr. [dB]	6.56	9.53	4.29	6.70	11.10	4.61
Noise floor diff. [dB]	4.66	7.37	2.98	4.59	7.053	3.18

TABLE VI

OPTIMAL DECOMPOSITION LEVEL AND MEAN VALUES OF DYNAMIC RANGE IMPROVEMENT AND NOISE FLOOR REDUCTION FOR THE RIRS FILTERED IN THIRD-OCTAVE FREQUENCY BANDS OBTAINED USING 10 DIFFERENT RANDOM TIME DISTRIBUTIONS OF NOISE AMPLITUDES, 10 DIFFERENT SYNTHESIZED RIRS AS WELL AS PINK NOISE OF TWO LEVELS (-60 DB AND -50 DB); HAAR WAVELET IS APPLIED

f_c [Hz]	100	125	160	200	250	315
Dec. level	8	8	7	7	7	6
Dyn. range impr. [dB]	3.61	2.83	2.48	3.84	4.72	2.63
Noise floor diff. [dB]	7.189	8.253	4.116	5.122	8.089	2.98

f_c [Hz]	400	500	630	800	1000	1250
Dec. level	6	6	5	5	5	4
Dyn. range impr. [dB]	4.48	5.67	3.10	5.41	8.05	3.99
Noise floor diff. [dB]	4.88	8.04	2.89	4.97	7.42	3.47

f_c [Hz]	1600	2000	2500	3150	4000	5000
Dec. level	4	4	3	3	3	2
Dyn. range impr. [dB]	6.95	9.48	4.57	7.09	11.18	4.17
Noise floor diff. [dB]	4.54	6.99	2.65	3.93	6.43	2.17

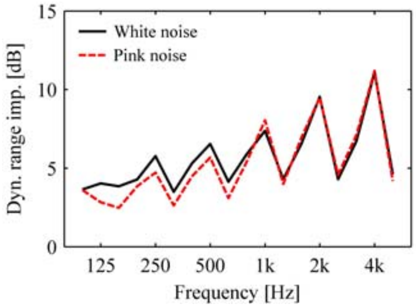

Fig. 6. Mean values of dynamic range improvement for the RIRs filtered in third-octave frequency bands obtained using 10 different random time distributions of noise amplitudes, 10 different synthesized RIRs as well as white and pink noise of two levels (-60 dB and -50 dB); Haar wavelet is applied

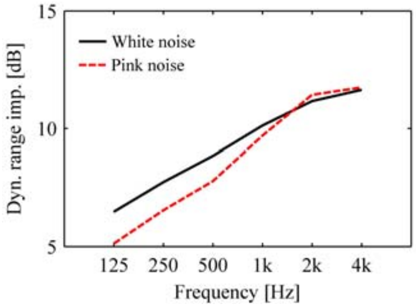

Fig. 7. Mean values of dynamic range improvement for the RIRs filtered in octave frequency bands obtained using 10 different random time distributions of noise amplitudes, 10 different synthesized RIRs as well as white and pink noise of two levels (-60 dB and -50 dB); Haar wavelet is applied

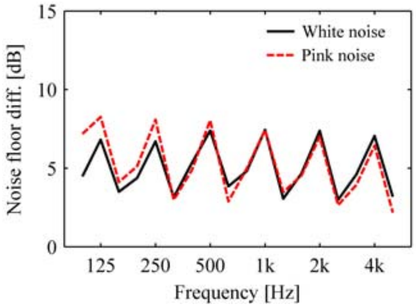

Fig. 8. Mean values of noise floor reduction for the RIRs filtered in third-octave frequency bands obtained using 10 different random time distributions of noise amplitudes, 10 different synthesized RIRs as well as white and pink noise of two levels (-60 dB and -50 dB); Haar wavelet is applied

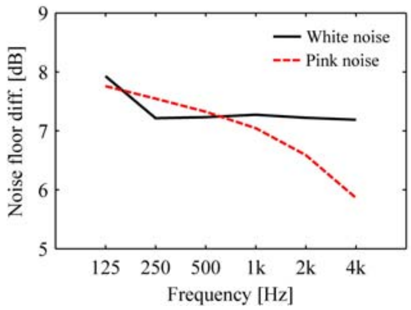

Fig. 9. Mean values of noise floor reduction for the RIRs filtered in octave frequency bands obtained using 10 different random time distributions of noise amplitudes, 10 different synthesized RIRs as well as white and pink noise of two levels (-60 dB and -50 dB); Haar wavelet is applied

The optimal decomposition level, the mean values of the dynamic range improvements and noise floor reduction obtained using 10 different random time distributions of noise amplitudes, 10 different synthesized RIRs as well as white and pink noise of two levels (-60 dB and -50 dB) are given in Tables VII and VIII.

TABLE VII

Optimal decomposition levels and mean values of dynamic range improvement and noise floor reduction for the RIRs filtered in octave frequency bands obtained using 10 different random time distributions of noise amplitudes, 10 different synthesized RIRs as well as white noise of two levels (-60 dB and -50 dB); Haar wavelet is applied

f_c [Hz]	125	250	500	1000	2000	4000
Dec. level	8	7	6	5	4	3
Dyn. range impr. [dB]	6.48	7.73	8.85	10.12	11.16	11.64
Noise floor diff. [dB]	7.92	7.21	7.23	7.27	7.22	7.18

TABLE VIII

Optimal decomposition levels and mean values of dynamic range improvement and noise floor reduction for the RIRs filtered in octave frequency bands obtained using 10 different random time distributions of noise amplitudes, 10 different synthesized RIRs as well as pink noise of two levels (-60 dB and -50 dB); Haar wavelet is applied

f_c [Hz]	125	250	500	1000	2000	4000
Dec. level	8	7	6	5	4	3
Dyn. range impr. [dB]	5.12	6.54	7.78	9.70	11.43	11.74
Noise floor diff. [dB]	7.76	7.54	7.32	7.04	6.58	5.86

V. Conclusion

Wavelets have widely been applied for de-noising of speech, audio and some other signals, but they have barely been applied for de-noising of room impulse responses. This was very interesting for authors who decided to investigate the potentials of RIRs de-noising by the wavelets.

When de-noising of broadband RIRs is considered, the optimal set of the wavelet parameters leading to the best results can consist of the same parameters (*minimaxi*, *hard* and *mln*) for both white and pink noise. The only difference is in the decomposition level, which is typically equal to 3 or 4 for white noise, and equal to a value between 13 and 15 for pink noise. With the optimal parameter set and the mentioned decomposition levels, it is possible to achieve a significant improvement of the dynamic range of the EDC as large as 18 dB or even 20 dB. It is worthwhile to note that the values of the performance measures (dynamic range improvement and noise floor reduction) depend to a certain extent on the noise and RIR characteristics.

Wavelet de-noising of the RIRs filtered in third-octave or octave bands leads to more consistent and stable results in comparison to de-noising of broadband RIRs. The optimal set of the wavelet parameters also consists of *minimaxi*, *hard*, *mln* and Haar wavelet function, while the decomposition level depends on the central frequency of third-octave or octave band of interest. It reduces from the value of 8 at about 100 Hz to the value of 2 at about 5 kHz.

The results presented in this research show that wavelets can be applied for reducing the noise floor in a RIR. Unfortunately, it causes a certain degradation of the reverberation decay. The larger the noise floor reduction, the larger the degradation. This is why it is necessary to choose the optimal set of the wavelet parameters that leads to the largest dynamic range improvement before a significant degradation of the reverberation decay occurs.

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