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Correction of room impulse response truncation based on a nonlinear decay model

Dejan G. Ćirić*, Marko Janković

Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia

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ABSTRACT

Serious effects of noise present in room impulse responses (RIRs) on evaluation of room acoustical parameters can be compensated by applying different methods. One of the preferred methods is based on the noise subtraction, RIR truncation and correction for truncation. This paper presents a procedure for calculation of the correction term that should be added to the backward integrated truncated RIR. The procedure can be applied in an automated way, and it is based on a nonlinear decay model consisting of an exponential decay plus stationary noise. Unknown parameters of the model are calculated by an optimization procedure where the model is fitted to the measurements. The proposed procedure for correction term calculation is tested on both synthesized and measured RIRs. The effects of the procedure parameters related to the RIR estimation range used for fitting the model to the measurements are analyzed. This procedure is compared with the one often applied in practice as a reference. The comparison shows that the proposed procedure outperforms the reference one. In addition, the impact of changing the correction term on the reverberation time estimation is investigated.

1. Introduction

The acoustics of a room is typically documented by measuring a set of room impulse responses (RIRs) and deriving room acoustical parameters [1,2] from these responses. They are typically measured using the traditional microphone configuration as defined in the relevant standard [3], although there have been approaches to use other measurement configurations, such as a spherical microphone array [4]. RIRs and their processing have been a subject of many studies presented in the literature. Some standards including ISO 3382 [3] and ISO 18233 [5] also deal with RIRs and their processing.

Ideally, a RIR should be measured in absolute silence, but this condition is never met in practice. In an actual environment, (background) noise consisting of ambient noise and equipment noise is always present. It deteriorates the quality of RIR measurements. Moreover, noise has been proclaimed to be one of the major causes of inaccuracy in calculating the room acoustical parameters from a RIR [6–9]. In more recent papers, the importance to respond to the effects caused by noise is emphasized [8–11]. Despite considerable noise immunity of sophisticated instruments and techniques developed over the years (see, e.g. [12–14]), measured RIRs typically contain sufficient noise to distort the derived acoustical parameters [6,8,9]. Without noise compensation, the relative error of the reverberation time can be as large as about 14% [8], that is, about 16% [9] or even larger, while the error of the clarity index can be greater than -5 dB [8].

In the examination of the variations between current implementations of standard room acoustical measures, it has been shown that there are substantial differences in the automated routines analyzed in [7], especially at lower frequencies. For example, the standard deviation of the mean reverberation time of value of 1.93 s is 0.28 s in the octave band at 125 Hz [7]. Another study has found systematic differences introduced in the algorithms for the calculation of room acoustical parameters [15]. The overall standard deviation of the reverberation time, early decay time, definition and center time is about 5% to 10%, while the deviation of the clarity and sound level is approximately 0.5 dB in frequency bands at 1 kHz and 4 kHz [15]. In both studies ([7] and [15]) background noise and handling of the noise are identified as the main sources of variances between the room acoustical parameters calculated by different software packages. One more problem caused by noise is the lack of indication that noise impact is too large [8]. Thus, the reverberation time can be estimated even when the signal-to-noise ratio (SNR) is not sufficient.

A method widely accepted in room acoustics for obtaining the reverberation decay function (curve) and evaluating the reverberation time is based on the integration proposed by Schroeder [16,17]. In this method, an energy decay curve (EDC) also known as backward integrated impulse response or Schroeder's curve [8] is generated by integrating a squared RIR (h_n) in a backward time order from t, that is, t_k

* Corresponding author.
E-mail address: dejan.ciric@elfak.ni.ac.rs (D.G. Ćirić).

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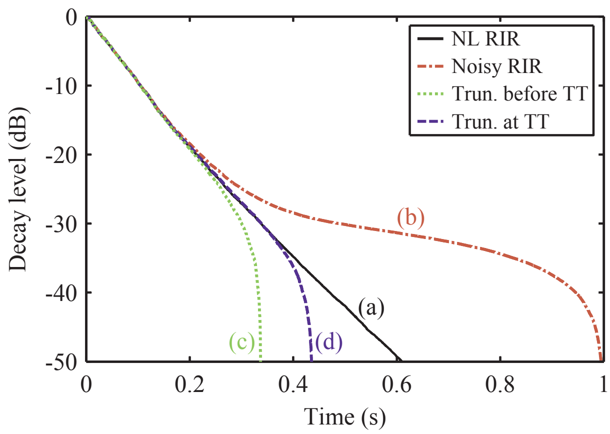

Fig. 1. EDCs of the synthesized RIR without noise (noiseless RIR − "NL RIR") and with noise truncated at various truncation times (TT).

to infinity (the integration starts at infinity and proceeds to the beginning of the squared RIR [3]):

$$d(t) = \int_t^{\infty} h_n(\tau)^2 d\tau, d(t_k) = \sum_{r=t_k}^{t_\infty} h_n(r)^2 = \sum_{r=t_k}^{t_\infty} (h(r)+n(r))^2, \quad (1)$$

where $d(t)$ is the continuous time decay function, $d(t_k)$ is the discrete time decay function (decay function in the digital domain), t_k is a discrete time given as $t_k = k\ \Delta t$, $k = 0, 1, 2, \ldots, \Delta t = 1/f_s$ and f_s is the sampling frequency, h is the noiseless RIR, and n is the noise. It is interesting to note that according to recent study [18] the Schroeder's method increases the bias of the decay rate estimation. This means that the Schroeder's "approach in many cases deteriorates the decay rate estimation performance" [18].

In applying Eq. (1) on a RIR containing both the reverberation decay and noise, there are two distinct problems caused by the noise and infinite upper limit of the integration, that is, finite length of the RIR. The noisy decay curve obtained from a noisy RIR is systematically above the noiseless curve, although the initial decay rate may still be approximately correct, see the curves (a) and (b) in Fig. 1. Nevertheless, there will be a point along the EDC where noise contribution becomes large enough to cause a reduction in the slope steepness, that is, bending of the curve upward [6] shown by the curve (b) in Fig. 1. This bending may potentially lead to errors in the calculation of room acoustical parameters such as reverberation time. Many authors have addressed the curve bending or tail problem, and proposed some solutions on how to reduce the slope biasing [15,19–23].

In order to avoid the bias caused by noise and not to misinterpret the real energy decay in the room, the noise needs to be left out by excluding the tail of the RIR that is corrupted by noise [9]. This is typically done by finding the point where the room decay meets the noise level (truncation time), and truncating the RIR at that point. By the RIR truncation, the upper limit of the backward integration is lowered and made finite instead of infinite, representing a weak point of using a real RIR of finite length in the Schroeder's method. The finite limit causes a characteristic drop of the EDC tail where the amplitude of the curve approaches negative infinity, as presented by the curves (b), (c) and (d) in Fig. 1. Consequently, the available dynamic range of the EDC appears to be infinite allowing the reverberation time to be estimated even if the SNR is insufficient for that purpose. If the integration limit is too close to the RIR start, the impact of the drop is increased pushing the EDC downward, see the curve (c) in Fig. 1.

So, noise and finite upper integration limit bend the decay curve in opposite directions, and their biases can cancel each other to some extent [18]. The canceling can even be complete, but not along the whole EDC [18]. Instead, it can be achieved at a point in time or in a very limited time range.

Although a standard needs to maintain a liberty to deal with a broad range of applications, in several recent papers the attention is paid to the problems of the ISO 3382 standard [3]. Correct truncation of RIRs or interpretation of the integration limit of positive infinity when calculating room acoustical parameters represents one of the major problems [7–10]. If the truncation is not done in a proper way, it may lead to variations in the parameter values larger than the just noticeable difference (JND) [10]. In the case of the reverberation time, depending on the noise level, the error may reach even a value of a few tens of percent [10].

Another problem of the RIR truncation is exclusion of the energy from the truncation time to infinity generating a systematic error. It can be compensated for by calculating this energy called total compensation energy [15] or correction term [8], and by including that term in the RIR backward integration. One more benefit of this compensation is an automatic limitation of the decay curve to its reliable dynamic range according to the actual SNR.

Unfortunately, it is not easy to calculate accurately the correction term since the actual decay after the truncation time is buried in noise, and a measured RIR is always of a finite length. To the best of knowledge of the authors, there are only few references proposing how to calculate the correction term including the ISO 3382 standard [3] and [15]. Lundeby et al. proposed "inventing" a curve based on extrapolation of the regression line [15]. To reduce the errors especially in non-perfectly exponential decays, the regression line should correspond to the late decay near the truncation time. An expression for the assumed (constant) exponential decay can be obtained from the coefficients of the regression line.

It is still not completely clear which range of a RIR exactly to use as a late decay. ISO 3382 recommends that the decay rate of the assumed exponential decay should be the same as the rate of the last 10 dB of the squared RIR decay before the truncation time. However, contribution of noise in this part of the RIR is already significant, since the signal energy should be equal to noise energy at the truncation time [8]. On the other hand, Lundeby et al. have suggested using a decay of 10 dB to 20 dB shifted for a safety margin of 5 dB to 10 dB from the truncation time upward as a late decay [15].

A procedure for the correction term calculation based on the nonlinear decay model from [24] is proposed here and described in Section 3. This represents an original approach for calculation of the correction term. Both synthesized RIRs and measured RIRs are used as tested RIRs, which is described in Section 4 related to methods of investigation. The effects of changing the parameters of the proposed procedure including the late decay segment and noise range (a segment of a RIR contaminated with noise, where noise is dominant) are analyzed in Section 5.1 using the synthesized RIRs. The late decay segment represents the last part of RIR decay before the intersection with the noise floor. This segment and noise range form the RIR estimation range within which the model is fitted to the measurements. The calculation of the correction term using the measured RIRs is presented in Section 5.2. The proposed procedure for correction term calculation is compared with the procedure from [15] widely accepted in practice for that purpose in Section 6. Sensitivity of the estimated reverberation time to the correction term change (i.e. correction term deviation from the true value) that seems to be lacking in literature is analyzed in Section 7.

2. Compensation of negative effects in decay curve

2.1. Compensation of noise effects

A number of studies have been focused on the implications of noise in RIRs, and various compensation methods for reducing the noise intrusion have been proposed [6,18]. A widely accepted method is to truncate the analyzed RIR at the intersection of the RIR decay and the constant noise floor (truncation time) [8,21], as mentioned in Section 1. Different procedures have been suggested and used in practice to