MULTI-EXPONENTIAL DECAY CURVES IN AUDITORIUMS

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1 INTRODUCTION

The acoustic design process for auditoria is usually based on specifying a reverberation time (RT) depending on the application of the hall. To meet the desired RT, the volume and the acoustic properties of the surfaces are determined by Sabine's equation or room acoustic simulation techniques. RT is one of the most common parameters for designing and describing concert hall acoustics. How the objective measure RT is related to the perceived reverberance is still not completely clear but the early decay time (EDT) is considered to relate more closely to perceived reverberance than RT[1]. In most cases the values for EDT are slightly shorter than for RT. Barron[2] presented measurements from 17 concert spaces with a trend for shorter EDT than RT, indicating that the decay process is not linear.

Since Schroeder's method of backwards integrating the impulse response[3], RT measurements can be carried out very efficiently. Schroeder pointed out severel advantages, one of them being able to detect multiple sloped energy decays. He showed measurements from the Boston Symphony Hall where the energy decay exhibits a double decay. But as already mentioned, the Boston Symphony Hall is not the only auditorium whose decay process is multiple sloped[2]. Although there is much evidence that in many cases curved decays are present, the conventional method to determine the slope for calculating parameters like EDT and RT (T_{20} or T_{30}) is based on linear regression with fixed evaluation ranges. This is due to the reason that in most cases a linear decay is expected. But applying linear regression to a non-linear data set seems highly questionable to obtain representative parameters.

In coupled systems like the Culture and Congress Centern in Lucerne (KKL), where energy is fed back from a reverberant auxilary space to the main hall, curved decays are very common and have been investigated in the past[4]. In those cases a curvature in the decay process is caused by costly constructional measures. If curved decays are well perceived in coupled spaces, the question is if this behaviour is also desired in concert halls without coupled systems. In this paper, measurements from a multi-purpose auditorium are presented with different room configurations based on a recently finished project, focusing on the shape of energy decays. Common parameters like EDT, T_{20}, and T_{30} are calculated with conventional methods and compared to decay parameters obtained by fitting a sum of exponential decaying functions to the data obtaining decay values independet from the evaluation range. It will be discussed if this method provides an option to linear regression. Additionally, the auditorium is described in detail due to the installation of an active acoustic system.

By using an active acoustic system it is possible to shape and enhance the acoustics of a room in various ways. Several different acoustic presets allow for modifying room acoustic parameters like EDT and RT, or even modify early and late reflections from different directions. This makes active acoustics also the ideal tool when investigating the behaviour of energy decay curves.

The paper is organized as follows: In sec. 2 a short theoretical background about curved energy decays will be given explaining why the curvature occurs. In sec. 3 the auditorium is presented, where measurements have been carried out to investigate if curved decays are present. The room acoustic design as well as the active acoustic system are described in detail, discussing the difficulties between the demands for RT due to the active sound system and the general requirements for RT according to national standards for speech and music application. The measurement results are discussed in sec. 4. The paper concludes with a short outlook in sec. 5.

2 THEORY

2.1 Multi-exponential decay curves

The causes for multiple sloped energy decays are diverse. Barron[2] discussed three different types of energy decay curves: the cliff-type decay, the plateau-type decay and the sagging decay. Those effects could be related to certain types of geometries or measurement positions within a concert hall: fan-shape in plan, poor diffusion and strong overhead reflection from orchestral reflectors, balcony overhangs, directed reflection design, and low ceiling above balcony seating.

Another reason for the curvature was derived by Kuttruff[9]. He showed that the initial part of the decay contains the mean of all exited modes. When looking at third octave or octave bands, it is always a sum of decaying modes, if the decay times within a band vary then the resulting decay will be curved. Hunt et al.[10] showed that sometimes it is necassary to describe a decay process with up to five or seven decay parameters, especially when the space exhibits uneven distribution of absorption. Because axial, tangential and oblique modes have different decay constants[11], the low frequency band will be curved in particular, since those bands are dominated by tangential modes which die out slightly slower than oblique modes.

Nillson[12,13] investigated double slopes in spaces with uneven distribution of absortion with statistical energy analysis models. In classrooms with highly absorbing ceilings the decay is curved because the vertical soundfield will decay faster than the horizontal soundfield.

Energy decays with double slopes are also a common phenomena in coupled spaces. Concert halls like the KKL in Lucern have a reverberation chamber attached to the main space to adapt the late reverberance in the auditory space. The resulting energy decay has a double slope because late energy is fed back to the auditory space from the much more reverberant auxilary space. Eyring thoroughly investigated coupled rooms[5] pointing out that the sound decay may not be straight in coupled or single rooms with uneven distribution of absorption. He pointed out that although he ommited the first few dB of the decay in his analysis because the reverberation meter was not able to record that portion accurately, it did not mean that it had no significance. Strong early reflections produce steps in the integrated impulse response, this is cited as one of the most common reasons for omitting the first 5 dB when evaluating the energy decay curve for calculating T_{20} or T_{30}. By calculating EDT it is possible to estimate a parameter that is important for the perceived reverberance, in those cases the first 5 dB are not omitted. Jordan[6] proposed in 1970 that the first 10 dB drop of the decay matched most closly the subjective reverberation. Before him it was Schroeder[7] who defined the initial reverberation time as the RT corresponding to the first 15 dB or 160 ms of the decay. According to ISO 3382[8] EDT is obtained by using linear regression within the first 10 dB drop of the decay multiplied by six. But due to the fixed evaluation range, the obtained parameter can be questionable in case of multiple sloped data. Examples are given in fig. 1. and fig. 2., where the energy decay curve (EDC) was constructed with the underlying model H for multiexponential decays:

$$EDC(A,T,t) = \sum_{i=1}^{n} A_i \cdot e^{\frac{-13.8 \cdot t}{T_i}}$$

where A_i is the starting point of the decay process, T_i is the corresponding reverberation time and n is the number of decay terms. In fig. 1 the model was constructed with two exponential decays with following starting points and reverberation times: A_1 = 0 dB, T_1 = 0.5 s and A_2 = -5 dB, T_2 = 2.5 s (depicted as EDC in fig. 1 and fig. 2). Calculating room acoustic paramters like EDT in that case results in EDT = 1.22 s, which is not accurate. Reverbertion times T_{20} and T_{30} were obtained by fitting a linear regression between -5 dB and -25 dB and -35 dB respectivly. Those values are close to the second decay time T_2 but are slightly underestimated. If the starting point of the second decay is shifted to A_2 = -10 dB like in fig. 2., the early decay time is slightly overestimated and RT values are underestimated.

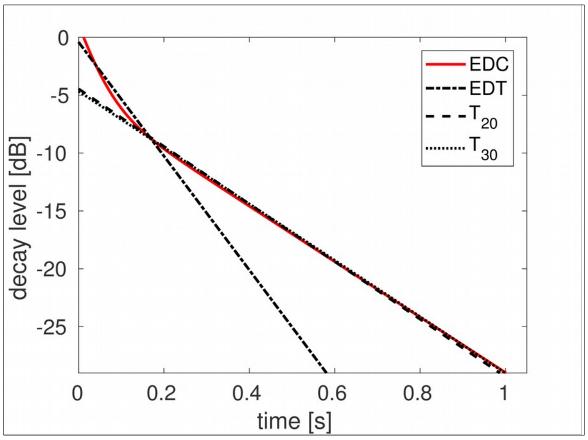

Figure 1: Energy decay curve EDC and room acoustic parameters EDT = 1.22 s, T_{20} = 2.41 s, T_{30} = 2.46 s. EDC model constructed with A_1 = 0 dB, T_1 = 0.5 s and A_2 = -5 dB, T_2 = 2.5 s.

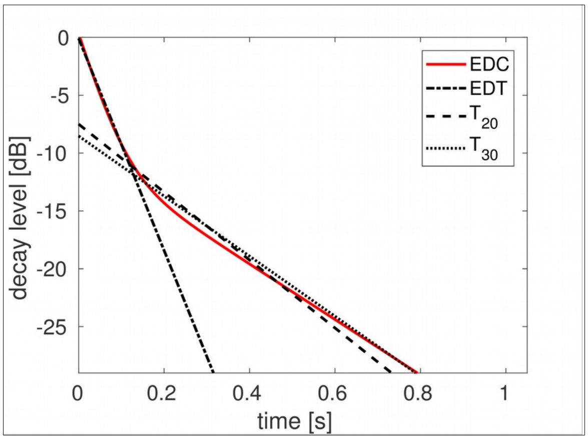

Figure 2: Energy decay curve EDC and room acoustic parameters EDT = 0.65 s, T_{20} = 2.03 s, T_{30} = 2.31 s. EDC model constructed with A_1 = 0 dB, T_1 = 0.5 s and A_2 = -10 dB, T_2 = 2.5 s.

It can be concluded that in many cases a curved decay is present. To be able to calculate multiple decay parameters, Xiang et al.[14] developed a Bayesian framework to investigate energy decays in coupled spaces. He showed with his framework that up to three decay terms can be estimated. The desired effect of curved decays in coupled spaces has been investigated thoroughly[15], but the question remains why in single auditoriums a straight decay is expected and even favoured? As Barron mentioned, a shorter EDT value than RT value 'are not in itself undesirable'[1]. Furthermore, it does not necessarily mean that there is a lack of diffusion in the hall. In the following sections we present the auditorium with different room configurations (A,B,C,D) where measurements were carried out.

3 AUDITORIUM

The auditorium in the Congress Center Alpbach (CCA) is used for lectures and conference sessions as well as for acoustic and amplified concerts. Therefore an active acoustic system was installed to vary the reflections and reverberance of the space. Without the active acoustic system the hall should exhibit a suitable reverberation time for adequate speech inteligibility.

The auditorium (see fig. 3) has a total volume of V = 3800 m^3 (configuration A) with a rectangular ground floor (23.5 x 28.9 m) and varying heights between h = 4 - 6 m. It can be subdivided into four halls if desired. The rear third of the hall can be separated from the main hall resulting in one elongated auditorium (23.5 x 11.7 x 4 m, V = 1090 m^3, configuration B) or it can be split in three rectangular conference rooms (V = 350-380 m^3 each, configuration C). The remaining volume of the main space is V = 2710 m^3 (configuration D).

The ceiling in the front half of the hall is partly covered by the HVAC system and partly with an acoustic plaster. The entire front wall (gypsum board) serves as a screen, the side walls in the first two third of the hall are covered by a special paneling system containing wood and felt. The back third of the hall has sound hard wooden walls which can be used to split the hall. The back of the auditorium has a glass front, the ceiling in the back third of the hall is a perforated gypsum board filled with glass wool and an air gap.

The challenges in this project were the different requirements concerning the reverberation time. According to national standards[16] a target reverberation time betwwen 1.1 - 1.4 s for adequate speech intelligiblity is required in configuration A + D, whereas target values of 1 - 1.2 s were demanded by the active acoustis system. On the one hand the acoustics should not be too dry, on the other hand too much reverberation reduces the function of the active acoustic system due to feedback issues.

3.1 Active Acoustic System

Active Acoustics is the term comprising several techniques to influence the sound field in rooms in order to achieve goals like speech and acoustic enhancement. This comprises the generation and distribution of early reflections, the generation and shape of late reverberation and the generation and projections of 3D audio scenes.
The idea for such an approach to room acoustic enhancement exists since the 1950's - starting out in the Royal Festival Hall in London – and different variants of such systems are commercially available ever since[17,18].

An Active Acoustics system always consist of microphones, pre-amplifiers, A/D and D/A converters, a signal processing unit, amplifiers and loudspeakers. Fig. 4 shows a schematic drawing of an Active Acoustics system.

Figure 3: Auditorium of the Congress Center Alpbach, V = 3800 m³. © CCA

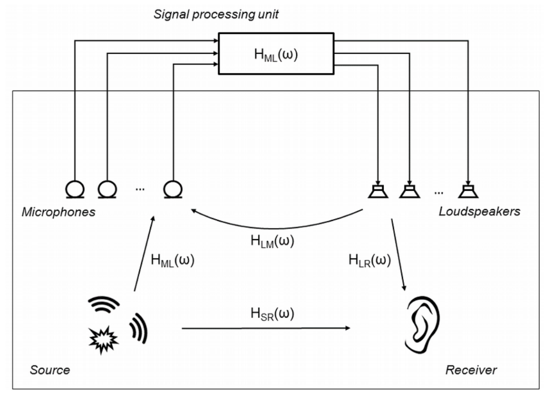

Figure 4: Schematic drawing of an active acoustic system[19].

Basically, there are two different approaches to active acoustics: In-Line and regenerative (or non-in-line). The difference lies mainly in the way feedback is handled – or, more technically spoken, in the way the transfer function $H_{LM}(\omega)$ is handled.
The In-Line approach uses directive microphones positioned rather closely to the sound sources, usually within their critical distance. Reverberance is added to the microphone signals either by algorithms or by convolution of synthesized or measured impulse responses. Typically, 4-8 microphones are placed in the stage area and many loudspeakers are placed in the audience area. Feedback is avoided by the directive characteristic and the spatial separation of microphones and loudspeakers. Hence, the loop gain is inherently low and the focus of system design lies on the reverberation generation.

On the other hand, the regenerative approach uses signal loops in between loudspeakers and microphones to generate reverberation. Microphones are placed outside the critical distance of sound sources and loudspeakers. The basic idea is that the picked-up signals are directly given back via the loudspeakers, however, usually a reverberation stage is added to the signal chain. The loop gain is therefore higher and audible artefacts like ringing tones are likely to occur. In order to increase stability a very high number of microphones and loudspeakers has to be used. A combination of both approaches is typically called a hybrid system (e.g. Amadeus Active Acoustics).

In the Congress Center Alpbach the main requirement for the active acoustic system was the uniform performance across the whole hall. There should be no preferred spots for the stage, performers and musicians can be positioned at any point in the hall. A special feature of this hall is that the rear third of the hall can be separated from the main hall and be split in three small conference rooms. This needed to be considered in the process of developing the system.

The active acoustic system in the Congress Center consists of altogether 44 loudspeakers and 17 microphones. In the front two thirds of the hall a hexagonal grid was used at the ceiling (17 microphones, DPA, 18 loudspeakers + 4 subwoofer, Renkus-Heinz). The microphones had to be hung from the ceiling ranging from h = 4 - 6 m above floor level and following the line of projection. On the walls 22 loudspeakers (Renkus-Heinz) were installed at a height of h = 2 m.

The system was tuned to five different acoustic presets dedicated to different applications like solo concert, chamber music, orchestra or choir music. A special challenge was that every acoustic preset had to be tuned for two cases, the open hall with V = 3800 m³ (configuration A) and the separated hall with V = 2710 m³ (configuration D).
The system can be remotely controlled via a web interface using an iPad or a regular computer. Using the web interface, the technical team is able to turn the system on/off, select presets, get status information about the components, and playback 3D audio-content or select virtual speaker setups for motion picture playback. Fig. 5 shows the reverberation times T_{30} measured in the hall (configuration A, V = 3800 m³) with different acoustic presets, averaged over eight independent microphone-source positions.

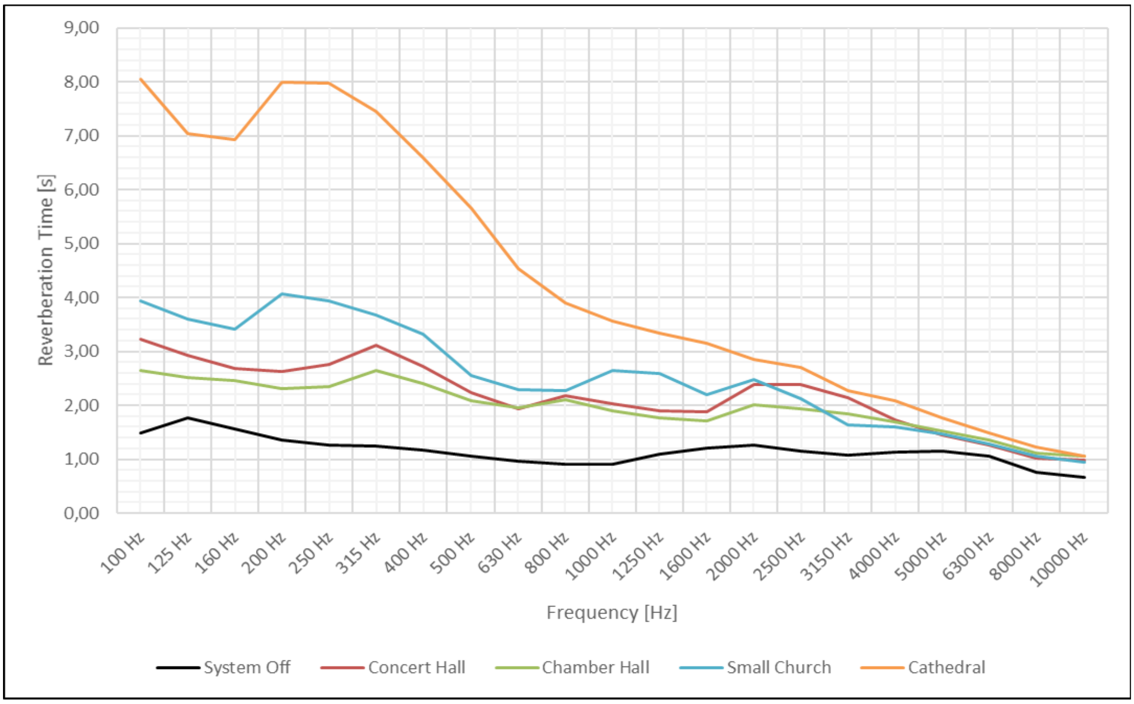

Figure 5: Reverberation time T_{30} of different acoustic presets of the active acoustic system measured in the auditorium of the CCA Alpbach.

3.2 Measurements

Impulse responses measurements were carried out according to ISO 3382-2 without audience at eight independent microphone - source positions with the swept sine method. In configuration A and configuration D the active acoustic system was both turned on and off. The energy decay curve was calculated with the Schroeder backwards integration for every measurement position. Results depicted in fig. 6 - fig. 9 correspond to one measurement position near the center of the auditorium. In fig. 10 and fig. 11 energy decay curves were averaged over four measurement positions due to the different room configurations.

4 RESULTS AND DISCUSSION

Figure 6 shows the EDC for the octave band f = 250 Hz for configuration A (V = 3800 m³). The EDT is shorter than the reverberation times T_{20} and T_{30}, clearly indicating that the decay process is not linear. When a sum of exponential functions is fitted to the data (a modified version of MELT[20] algorithm was used), the resulting decay times are T_1 = 0.70 s and T_2 = 1.53 s. With this method the initial reverberation time T_1 is shorter than the EDT. The late part of the decay curve seems to be underestimated by the reverberation times, since the late decay parameter T_2 is greater than T_{30}.

In the case when the active acoustic system is turned on (see fig. 7), the early as well as the late decay can be altered in various ways. In the following case reverberance was added to both the early and late part. Again the reverberation parameters EDT, T_{20}, and T_{30} differ from each other. In this case the results for the decay times when a sum of exponential functions is fitted to the data are T_1 = 0.76 s, T_2 = 2.31 s, T_3 = 4.16 s. The initial decay time T_1 is much shorter than EDT, indicating that the curvature already effects the evaluation with linear regression.

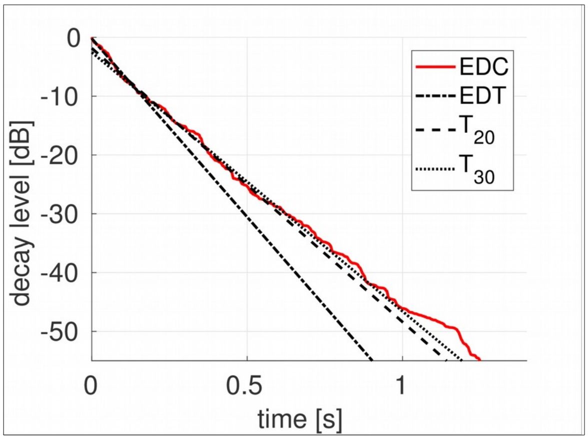

Figure 6: Energy decay curve EDC and room acoustis parameter EDT = 0.99 s, T_{20} = 1.29 s, T_{30} = 1.36 s, f = 250 Hz, measured in conf. A without the active acoustic enhancement system.

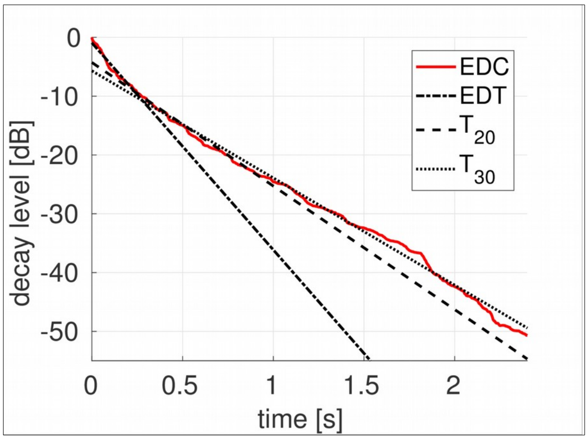

Figure 7: Energy decay curve EDC and room acoustis parameter EDT = 1.70 s, T_{20} = 2.86 s, T_{30} = 3.29 s, f = 250 Hz, measured in conf. A with the active acoustic enhancement system.

The case for the octave band f = 500 Hz is similar to the lower octave band, although the EDC is almost straight over the first 30 dB drop (see fig. 8), the parameters EDT, T_{20}, and T_{30} are almost equal. But it is clear already by visual inspection that the late part of the decay is underestimated also by T_{30}. The results for the fitting procedure are T_1 = 0.96 s, T_2 = 1.61 s. In this case the initial decay time T_1 corresponds well with EDT but the late decay parameter T_2 is greater than T_{20} and T_{30}.

When a sum of exponential function is fitted to the data in the case when the active acoustic system is turned on (see fig. 9), the resulting decay times are T_1 = 0.99 s, T_2 = 2.38 s, T_3 = 3.76 s. In this case the early and the late part of the decay curve is underestimated by EDT, T_{20} and T_{30}.

In fig. 10 the energy decay curve of the seperated hall with a total volume of V = 1090 m³ (config. B) for f = 1 kHz is shown. Because only the ceiling is absorbing and the rest of the surfaces are sound hard, the decay is curved. The reverberation times EDT, T_{20} and T_{30} differ from each other. In fig. 11 the energy decay curve for a single seminar room (config. C) with a total volume of V = 380 m³ for f = 1 kHz is shown. Although the volume is one third of the previous volume, the reverberation parameter stay almost the same. In this case the uneven distribution of absorption is responsible for the curved decay process. In those cases the late part of the decay is highly underestimated.

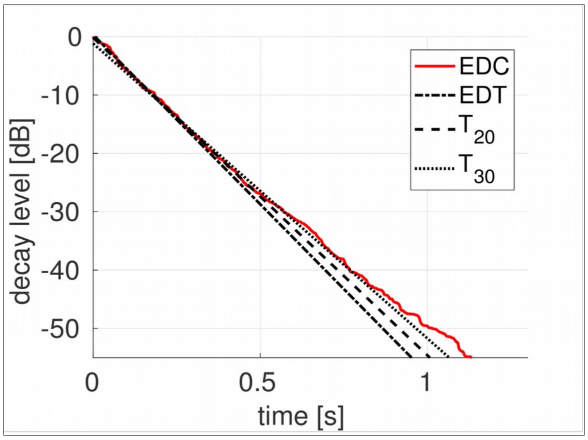

Figure 8: Energy decay curve EDC and room acoustic parameter EDT = 0.95 s,T_{20} = 1.01 s, T_{30} = 1.09 s, f = 500 Hz, measured in conf. A without the active acoustic enhancement system.

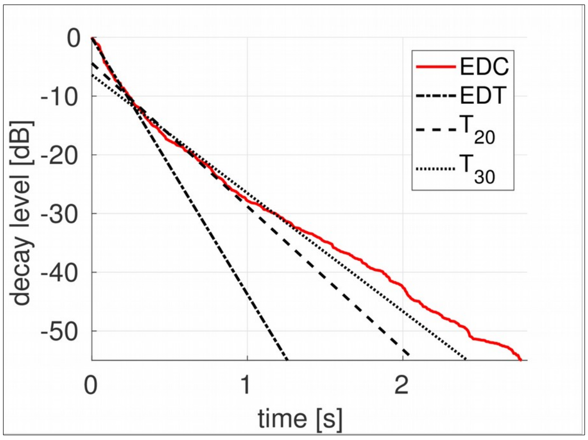

Figure 9: Energy decay curve EDC and room acoustic parameters EDT = 1.22 s, T_{20} = 2.86 s, T_{30} = 3.29 s, f = 500 Hz, measured in conf. A with the active acoustic system.

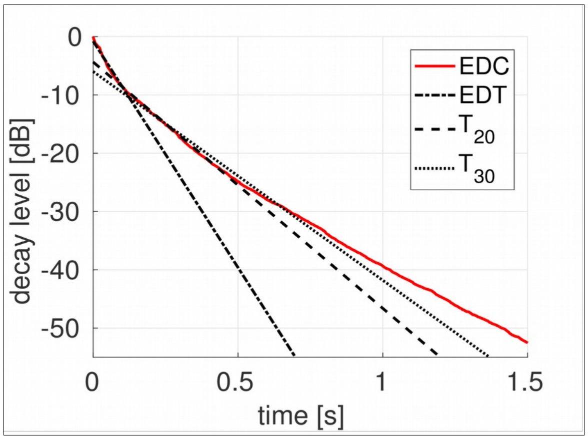

Figure 10: Energy decay curve EDC and room acoustic parameter EDT = 0.77 s, T_{20} = 1.42 s, T_{30} = 1.68 s, f = 1 kHz, measured in conf. B

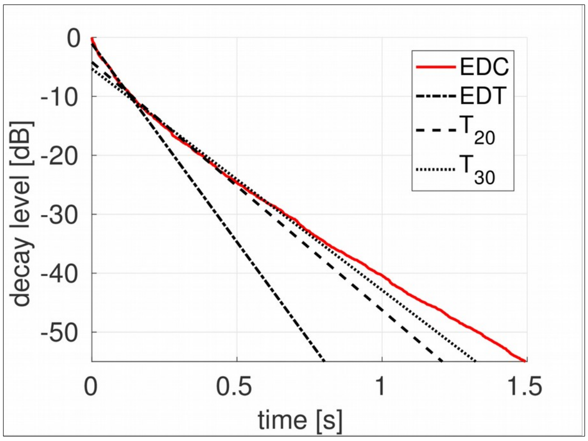

Figure 11: Energy decay curve EDC and room acoustic parameter EDT = 0.89 s, T_{20} = 1.43 s, T_{30} = 1.60 s, f = 1 kHz, measured in conf. C

It can be concluded that in all configurations curved decays are present. The reason for the curvature can be various. At lower and mid frequencies the various decay times of modes within one frequency band can cause a curvature. In fig. 10 and fig. 11 the uneven distribution of absorption causes the non linear decay process. But it is possible also to create curved decays like in coupled volumes with active acoustis systems on purpose. With conventional reverberation parameters it is sometimes not possible to evaluate decay times that correspond to the early or late part of the decay in many cases as shown in this section. The values are either underestimated or overestimated. Therefore the need for a new evaluation method for reverberation time is necessary. Otherwise the room acoustic parameters like EDT, T_{20} and T_{30} will only be an approximation of the decay process in a room. Fitting a linear regression to the data in fig. 6 - fig. 11 only represents certain ranges of the data disregarding the shape of the energy decay.

5 CONCLUSION

In this paper we discussed energy decay curves measured in an auditorium with different room configurations. Decay curves can exhibit multiple slopes due to uneven distribution of absorption, or geometrical reasons, or because of different decay times of modes within one frequency band. In case of curved energy decays the calculation of reverberation parameter with linear regression is questionable. In auditoriums, where it is of utmost importance to determine the accurate early decay time and reverberation time, the methodology of fitting a sum of exponential functions to the data can be an option. If the obtained initial decay parameter correspond better with the perveiced reverberance than the early decay time could be evaluated in the future.

Subjective testing could also be devoted to the low frequency range where a curvature is present in most cases. Also, it could be evaluated if the well-known concert halls like the Musikverein in Vienna or the Sydney Opera Hall exhibit a curved decay and if this is preferred by listeners.

With active acoustic systems it is possible to create a curved energy decay if desired. As well as the early part of the decay and the late part can be modyfied by adding reflections or reverberation to the signal. Acoustics of coupled volumes can be simulated regarding the shape of the energy decay curve.

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