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Prediction of reverberance in rooms with simulated non-single-exponential sound decays

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ABSTRACT

It has been known that the application of diffuse field theory to the sound field with a non-single-exponential sound decay did not comply well with listeners' experience. Recent researches have concentrated on quantifying and controlling the non-single-exponential decay processes in rooms. However, the effect of non-single-exponential sound decay on listeners' reverberance has not been clearly known in spite of its importance. The present work tried to explore the relationship between the non-single-exponential decay of sound in rooms and the listener's reverberance, and further to develop a simple way of predicting subjective reverberance caused by non-single-exponential decay processes. A series of listening experiments were carried out with various computer generated non-single-exponential sound decay patterns using a two alternative forced choice (2AFC) paired comparison method. A simple way of predicting listeners' reverberance for non-single-exponential sound decays was proposed by combining the results of subjective tests and the analysis of Schroeder decay curves using decay rates at multiple fixed intervals and their effects on listeners' reverberance. The correlation analyses suggested that the proposed method could predict listeners' reverberance caused by non-single-exponential sound decays better than conventional parameters within the range of non-single-exponential decay patterns examined in the present work.

1. Introduction

Since the Sabine's pioneering work [1], numerous room acoustics measures have been developed to describe and appreciate various aspects of room acoustics properties. Among those, reverberation time is undeniably the most frequently used parameter. Reverberation time is a perceptually derived measure of physical sound decay process in a diffuse field.

However there have been so many diverse efforts to develop a physical parameter which represents the human auditory perception of reverberation, known as reverberance [2], as there has been a general consensus on that reverberation time is an imperfect measure of reverberance. In particular, Hass's work [3] motivated number of important parameters for reverberance, such as early decay time (EDT) [4] and initial reverberation time ($T160$) [5]. Barron [6] found that T_t (EDT, 5 octaves average over 125 Hz–2 kHz) correlated better than reverberation time at mid frequency (the average of 500, 1000 and 2000 Hz) with reverberance. Soulodre and Bradley [7] showed that EDT_{oct} (average over 125 Hz–4 kHz) significantly outperformed T_{oct} and T_{mid} (the average of 500 and 1000 Hz) in predicting reverberance. Also, T_S (center time averaged over all octaves) correlated very well with slightly higher correlation coefficients than EDT_{oct} did.

On the other hand, it has been quite well known that the application of diffuse field theory to the spaces where the decay of sound did not behave in an exponential way resulted in erroneous outcomes. Numerous efforts have been made in both perception and quantification of non-single-exponential reverberation. In particular, there have been active research reports on non-single-exponential decays and many advanced quantifiers [8–15] have been introduced since early 2000. However little has been known for the relationship between reverberance and those quantifiers. A few researches on reverberance for non-single-exponential decays have been conducted. Atal et al. [5] found that the reverberation time of the non-single-exponential decay calculated on the basis of the first 160 ms or the first 15 dB of the decay ($T160$) corresponded well to reverberance. They also observed that EDT could predict reverberance more accurately than $T160$. Yegnanarayana and Ramakrishna [16] examined the influence of non-single-exponential decay on the intelligibility of speech. They concluded that the perception of decay was mainly due to the initial portion

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of a non-single-exponential decay and the sound near a highly absorbing material in a room sounded less reverberant than at a point away from it. Bradley and Wang [8] investigated the effect of combined changes in volume ratio and aperture opening size on reverberance in a computer simulated coupled space. They found that both greater coupled volume size and aperture size provoked increased reverberance. EDT also tended to increase as volume and aperture size increased. Comparative analysis between EDT values and reverberance seemed to support the result of Atal et al. [5]. Also, reverberance was increased with higher BP_L (the decay level at which the bending point appears) and greater decay ratio (decay time of the second slope evaluated on 60 dB/ decay time of the first slope evaluated on 60 dB). Erman [17] examined whether both experienced and inexperienced music listeners could distinguish a double-sloped decay from a Sabine decay, as well as preference for the double slope. He found that the more a recording diverged from a standard Sabine decay, the more likely the subjects were to identify that recording as having a double slope. He noted that subjects were more likely to correctly identify the difference when the late portion of the impulse responses of the two tracks varied from one another while the early parts of the decays were similar. Frissen et al. [18] performed listening experiments using non-single-exponential IRs by combining two independent exponential decays and brief speech segments. It was found that the sounds were perceived to be different if the RT of the second slope was at least 1.5 times larger than the one corresponding to the exponential decay. Luizard et al. [19] tried to estimate perceptual thresholds for reverberation in coupled volumes as a function of the coupling aperture area connecting two volumes and for different musical excerpts. The obtained perceptual thresholds for reverberation as a function of the coupling area were 10% of variation of a given coupling area.

Other researches took notice of the role of loudness change in perceived reverberance. Hase et al. [20] examined the relationship between reverberance and two orthogonal physical factors subsequent reverberation time (T_{sub}) and sound pressure level (SPL). They found that reverberance was increased by raising SPL and T_{sub} of heard sounds. Their results were confirmed by Lee et al. [21–23]. Sum and Pan [24] proposed a so-called subjective evaluation of reverberation time, which accounts for the 50 ms average response time of the human ear and the 3 dB just-detectable loudness change of ear. They concluded that reverberation times evaluated by the proposed technique correlated better to the subjective test results especially for highly non-single-exponential decays.

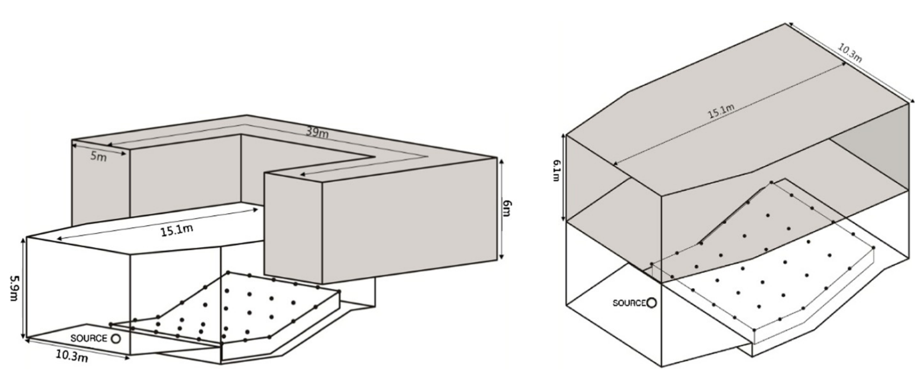
Review of previous works indicated that the decay time of early reverberant energy as well as the loudness change of a decay energy were very important for listeners' reverberance. Also, the late part of a sound decay as well as the early part seemed to play a significant role in identifying non-single-exponential decays. However it is still unclear how the extent of the reverberation with non-single-exponential decays heard by the ear is described and what physical parameters can be used. Further works for developing reliable physical parameters which correspond well with listeners' reverberance for non-single-exponential decays are necessary. The present work investigated the relationship between the non-single-exponential decay of sound in rooms and the listener's reverberance. Listeners' reverberance was measured through a series of listening experiments carried out with various computer generated non-single-exponential sound decay patterns. The decay interval (−5 dB to −35 dB), generally used for calculating T_{30}, was equally divided into a number of fixed intervals considering human perception of loudness [25–30]. A parameter was determined by combining the contribution of a decay rate at each section to reverberance. The validity of the parameter was examined in an additional listening test and its performance was compared with conventional parameters.

2. Experimental arrangements

2.1. Non-single-exponential decay patterns for experiments

Various decay patterns were produced in a computer-simulated small performance hall with a coupled volume system. Main volume was connected to the secondary volume attached either horizontally or vertically (Fig. 1). Many researches [19,31–34] reported that predicted acoustics of coupled spaces using geometrical acoustical prediction software were well accordance with the measurement results. In the present work, impulse responses with various non-single-exponential decay patterns were produced using the acoustical prediction software package CATT-Acoustics v9.0 [35].

Among various control parameters for non-single-exponential decay in coupled spaces, two architectural parameters, the opening ratio and absorption ratio between the two spaces were varied to obtain different decay patterns, while each volume of the main and the secondary space was held constant (Table 1). The architectural parameter value ranges were chosen to obtain a wide range of non-single-exponential decay patterns. The absorption ratio depicted the equivalent absorption area in the coupled volume as a percentage of the equivalent absorption area in the main room. The equivalent absorption area was calculated by multiplying total surface area of each room by its average absorption coefficient. The average absorption coefficient of the main volume was kept con-



(a) Horizontally attached (b) Vertically attached

Fig. 1. Perspective views of computer models used in the present work. Initially, RIRs at 36 receiver points were examined but RIRs obtained at the two positions in the middle of the last row were used in listening experiments, as they showed more diverse decay patterns.