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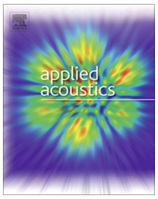

Reverberation time measurements in non-diffuse acoustic field by the modal reverberation time

Andrea Prato [a,*], Federico Casassa [b], Alessandro Schiavi [a]

[a] National Institute of Metrological Research – INRIM, 10135 Torino, Italy
[b] Department of Electronics and Telecommunications, Politecnico di Torino, 10129 Torino, Italy

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ABSTRACT

The increasing presence of low frequency sources and the lack of acoustic standard measurement procedures make the extension of reverberation time measurements to frequencies below 100 Hz necessary. In typical ordinary rooms with volumes between 30 m^3 and 200 m^3 the sound field is non-diffuse at such low frequencies, entailing inhomogeneities in space and frequency domains. Presence of standing waves is also the main cause of bad quality of listening in terms of clarity and rumble effects. Since standard measurements according to ISO 3382 fail to achieve accurate and precise values in third octave bands due to non-linear decays caused by room modes, a new approach based on reverberation time measurements of single resonant frequencies (the modal reverberation time) has been introduced. From background theory, due to the intrinsic relation between modal decays and half bandwidth of resonant frequencies, two measurement methods have been proposed together with proper measurement procedures: a direct method based on interrupted source signal method, and an indirect method based on half bandwidth measurements. With microphones placed at corners of rectangular rooms in order to detect all modes and maximize SNRs, different source signals were tested. Anti-resonant sine waves and sweep signal turned out to be the most suitable for direct and indirect measurement methods respectively. From spatial measurements in an empty rectangular test room, comparison between direct and indirect methods showed good and significant agreements. This is the first experimental validation of the relation between resonant half bandwidth and modal reverberation time. Furthermore, comparisons between means and standard deviations of modal reverberation times and standard reverberation times in third octave bands confirm the inadequacy of standard procedure to get accurate and precise values at low frequencies with respect to the modal approach. Modal reverberation time measurements applied to furnished ordinary rooms confirm previous results in the limit of modal sound field: for highly damped modes due to furniture or acoustic treatment, the indirect method is not applicable due to strong suppression of modes and the consequent deviation of the acoustic field from a non-diffuse condition to a damped modal condition, while standard reverberation times align with direct method values. In the future, further investigations will be necessary in different rooms to improve uncertainty evaluation.

1. Introduction

The growing interest of the international scientific community to extend the conventional architectural and building acoustics measurements to frequencies below 100 Hz [1,2] due to an increase of low frequency sound sources [3,4] requires detailed studies on sound pressure decay and reverberation time in small enclosures and typical ordinary rooms (30–200 m^3). At such frequencies in small rooms, a condition of non-diffuse sound field is reached due to the presence of standing waves, whose wavelengths are comparable to boundary dimensions. The resulting sound field is inhomogeneous in space and frequency domains. Besides, standing waves entail problems on acoustic comfort and quality of listening, especially in recording studios, small concert halls or open-space offices. At resonant frequencies, amplitudes are wider and decays are much longer, causing uneven tonal quality, interference with clarity and rumble effects, and noise in other environments [5–11]. Furthermore, a new method to evaluate speech intelligibility based on reverberation time measurements has been proposed [12]. Therefore, the measurement of reverberation time at low frequency is preparatory and necessary for the acoustic treatment of listening and working rooms.

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[*] Corresponding author.
E-mail address: a.prato@inrim.it (A. Prato).

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Reference measurement standard of reverberation time in ordinary dwellings is ISO 3382-2:2008 [13], which is applied from 100 Hz to 5000 Hz. Such standard reports the procedure for interrupted noise and integrated impulse response methods. For what concerns the interrupted noise method, standard states that the signal provided to the loudspeaker shall be derived from broadband random noise, the source shall be able to produce a sound level sufficient to ensure a decay curve starting at least 25 dB above the background noise in the corresponding frequency band and microphone positions should cover a portion of space sufficient to determine average behaviour of the acoustic diffuse field. No mention to frequencies below 100 Hz is reported, where the diffuse field approach is not suitable. In general there is no frequency distinction and the considered ones are calculated by simple average of decays within a certain bandwidth. At such frequencies sound decay with a broadband analysis (one-third octave bands as stated by ISO standard) is strongly non-linear due to the presence of more resonant frequencies in one band, each one with its own particular decay [14]. Such condition involves high measurement uncertainties (percentage relative standard deviations are in the order of 20–60%) and thus inaccurate values of reverberation time [15–17].

The aim of this work is to determine a new and more suitable measurement method to describe the reverberation time at low frequencies taking into account the involved physical phenomenon and the resulting effects on human perception. Due to the peculiarity of non-diffuse nature of sound field at low frequency in small ordinary rooms, it is convenient to move from a classical approach based on third octave bands measurements, which does not take into account modal peculiarities and entails inaccurate and imprecise values, to a modal approach, based on reverberation time measurements of single resonant frequencies: *the modal reverberation time*. From background theory (see next Section) modal reverberation time can be measured with two different methods: the direct method, based on standard guidelines for interrupted signal method, but with different source/receiving positions and source signals; the indirect method, based on half bandwidth measurement of resonant modes, which is related to the modal damping and, as a consequence, to the modal reverberation time. Both methods were firstly evaluated in an empty test room as described in depth from Section 37, in order to work in a condition of pure modal sound field. At a later stage, modal reverberation times were evaluated in two different ordinary rooms, with different furniture and acoustic treatment. Results are reported in Section 8.

2. Background theory

Reverberation time is defined as the time (in seconds) required for the sound energy density to decrease by 60 dB after the source emission has stopped. In diffuse field conditions (above the Schroeder frequency), the behaviour of sound field is statistical, and the frequency response of the room is linear. This is due to the fact that the room modes are not spaced, and the peaks corresponding to the resonant frequencies are so close to be indistinguishable. In this case measurement of the reverberation time simply consists in averaging the temporal decay of a certain frequency band (usually octave or third octave bands from 100 Hz onward) to calculate T_{60}. In case of non-diffuse field, the decay curve may not be approximated by a straight line across the entire range of the 60 dB decay. This is due to the fact that, given a certain frequency band, the shape of the curve depends on room modes that fall in that octave or third octave band, and on the interaction between them. If within the considered frequency band there are two modes (with different decay times), the resulting decay curve presents two different slopes, entailing a non-linear sound decay of that particular band [18]. Thus, in non-diffuse field conditions, evaluation of reverberation time of each single room mode (T_n), main cause of high uncertainty in one-third octave band and deterioration of sound quality and unwanted rumble effects, is more useful and more representative of the real physical situation. Considering a rectangular room with reactive surfaces and dissipative properties, it is supposed to supply energy to a resonant system through a sound source emitting a sinusoidal signal at a resonant frequency. Actually, although the generation of a single resonant frequency, at the beginning and at the end of sound radiation energy is distributed by the system among its modal frequencies, and so all modes are temporarily excited [19]. When the source emission is interrupted, at time $t = 0$, wave continues its path: part of its energy is reflected by the walls, and another part is dissipated by the boundary walls and the air in the room.

Considering the decay of a single nth mode, the squared sound pressure proportional to its energy becomes:

$$p^2(t) = p^2(0)\exp(-2\delta_n t) \tag{1}$$

where δ_n is the decay constant of the nth mode, or the modal damping constant [20] and gives information about the half bandwidth of the resonant frequency $\Delta f_{-3\mathrm{dB}}$ according to the formula:

$$\Delta f_{-3\mathrm{dB}} = \frac{\delta_n}{\pi} \tag{2}$$

In order to evaluate the reverberation time of a single mode after a decay of 60 dB, the following formulations are obtained:

$$\begin{aligned} &L(T_n) - L(0) = 10\,log_{10}\left(\frac{p^2(T_n)}{p^2(0)}\right) = -60\ \mathrm{dB};\\ &\left(\frac{p^2(T_n)}{p^2(0)}\right) = \exp(-2\delta_n T_n) = 10^{-6};\\ &2\delta_n T_n = 6\ln(10);\\ &\Delta f_{-3\mathrm{dB}} = \frac{\delta_n}{\pi} = \frac{3\ln(10)}{\pi\,T_n} = \frac{2.2}{T_n} \end{aligned} \tag{3}$$

and so the modal reverberation time of a single mode can be expressed by

$$T_n = \frac{2.2}{\Delta f_{-3\mathrm{dB}}} \tag{4}$$

In this way a relation between the resonance half bandwidth and the modal reverberation time is obtained. Such result allows to perform an indirect measurement of modal reverberation time through the evaluation of the resonant half bandwidth.

3. Measurement setup and procedures

The new approach is based on the decay of individual resonant frequencies (f_n) of rectangular rooms, or modal reverberation times, instead of one-third octave band analysis required by ISO 3382. Two measurement methods, derived from background theory, were experimentally evaluated: a direct method, based on the interrupted signal method, but with different measurement positions and acoustic source signals (statistical or sinusoidal) with respect to ISO Standard. Such method, which directly evaluates sound decays, is considered as the reference for accuracy. The integrated impulse response method was unfortunately neglected since it could not be possible to get high resolution frequency analysis. The second is an indirect method based on resonant half bandwidth measurements. This is the first experimental verification of Eq. (4). Different source signals were also evaluated. Measurement tests are reported in the corresponding Sections.

Measurements were performed in the receiving room of the impact sound insulation laboratory at INRIM which is completely empty and has a rectangular shape with dimensions $L_x = 4.02$ m,