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JASA LETTER TO THE EDITOR

Direct utilisation of impulse response data in reduction index assessment without intermediate reverberation time estimation (L)

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ABSTRACT:
An approach is proposed for reduction index measurement where impulse response data are utilised directly without relying on intermediate reverberation time estimation. The theoretical framework is presented and the main result is substantiated by shown equivalence to the conventional method for ideal exponential decay curves of acoustic energy. Additionally, the study introduces a formula for estimating effective reverberation time in cases of non-exponential decay curves. Further formulas for determining effective values of reverberation time and absorption area for general decay curve shapes are also suggested.
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I. INTRODUCTION

The normally applied measurement methodology for determining the sound reduction index, R, in dB, of building elements (walls, doors, windows, air inlets, etc.) relies on a reverberation time estimation as an intermediate step.[1] For the measurement, the building element to be investigated is placed as a partition between two rooms with diffuse sound fields: the sending room, with a noise source, and the receiving room. The reverberation time is normally estimated for the receiving room to determine the room losses, which, together with the diffuse-field sound pressure levels of the two rooms, determine the reduction index, usually in one-third octave bands within a prescribed frequency range. The reverberation time estimate is conventionally made using straight-line fits of sound pressure level decay curves, following a prescribed method using either interrupted noise or impulse response measurements.[1] The work presented here suggests an approach where the data from the impulse response measurements are used without estimating the reverberation time from them, thereby avoiding one of the error sources of the process.

II. THEORY

The diffuse sound field in the source room, $\tilde{p}_1$, has a diffuse-field intensity, I_{D1} [e.g., Ref. 2, Eq. (4.26), and Ref. 3],

$$I_{D1} = \frac{\tilde{p}_1^2}{4\rho c}, \tag{1}$$

which gives rise to a power-input, W_{in}, to the receiving room [e.g., Eq. (8.68) in Ref. 4],

$$W_{\text{in}} = I_{D1}\, S\, \tau, \tag{2}$$

where S is the area of the separating element and τ its (diffuse-field) transmission coefficient. Here, the density and the sound speed of the medium (air) are denoted by ρ and c, respectively. Figure 1 shows the problem setup with a separating wall as the test specimen. In the receiving room, the diffuse sound field, $\tilde{p}_2$, has a total energy, E_2, which can be formulated as [e.g., Eq. (7.11) in Ref. 2]

$$E_2 = \frac{\tilde{p}_2^2 V_2}{\rho c^2}, \tag{3}$$

where V_2 is the volume of the receiving room. The lost power of the receiving room due to dissipation is denoted by W_{d} in Fig. 1.

The modelling formulated above, in Eqs. (1)–(3), which can be found in many textbooks on building acoustics (e.g., Refs. 2, 5, and 6), is here to be combined with a result from Schroeder[7] for a sound field within a room [Eq. (6)],

$$N \int_t^\infty r^2(x)\mathrm{d}x = \langle s^2(t) \rangle, \tag{4}$$

where N is the input power of stationary noise to a room within a certain frequency band, r is the impulse response of the sound field within the room [normalised such that $r^2(0) = 1$], and s is a received signal where the brackets denote an ensemble average. The noise source is assumed to

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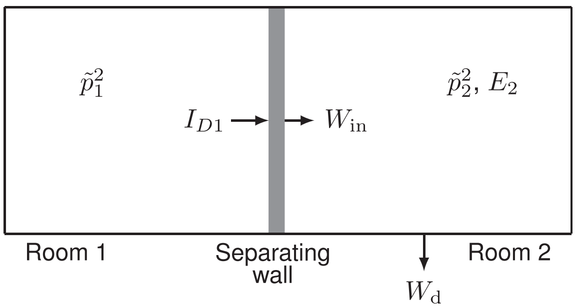

FIG. 1. Two rooms and separating wall with area S and transmission coefficient τ. The sending room (room 1) is to the left, and the receiving room (room 2) is to the right.

have provided the constant power over a time such that *steady state* has been reached, whereafter the source is turned off at time $t = 0$. With the notation used in Eqs. (1)–(3), N equals $W_{\rm in}$ and $\langle s^2(t)\rangle$ can be identified as the total energy of the receiving room, E_2, as in Eq. (3).

At $t = 0$ there is steady state, where the room-average of $\tilde{p}_2^2$ (and hence also E_2) is not increasing or decreasing over time, and N equals the lost power, $W_{\rm d}$ (i.e., $W_{\rm d} = \langle s^2(t)\rangle / \int_0^\infty r^2(x){\rm d}x$). Setting $t = 0$ in Eq. (4), replacing N by $W_{\rm in}$, using Eqs. (1)–(2), and replacing $\langle s^2(t)\rangle$ by $E_2 = \tilde{p}_2^2 V_2/(\rho c^2)$, from Eq. (3), gives

$$\frac{\tilde{p}_1^2}{4\rho c} S\tau \int_0^\infty r^2(x){\rm d}x = \frac{\tilde{p}_2^2 V_2}{\rho c^2}. \tag{5}$$

Simplifying and rearranging Eq. (5), solving for the reduction index, $R = -10\log(\tau)$, results in

$$R = 10\log\left(\frac{\tilde{p}_1^2}{\tilde{p}_2^2}\right) + 10\log\left(\frac{cS}{4V_2}\int_0^\infty r^2(x){\rm d}x\right), \tag{6}$$

where the term $10\log(\tilde{p}_1^2/\tilde{p}_2^2)$ equals the sound pressure level difference between the rooms, $D = L_{p1} - L_{p2}$. Equation (6) is the main result of the paper.

When applying Eq. (6) in real cases, background noise will be added to the decay curve of the impulse response. To estimate the value of the integral in Eq. (6) in the presence of background noise, a possible procedure may be to use the first 20 dB of the decay.[8] Another possibility may be to estimate the noise floor and use the last 10 dB of the decay above the noise floor as input to estimating the reminder of the decay.[9] Numerically, the integral can be calculated using a reverse-time integration, as suggested in the standard[1] and as also suggested by Schroeder.[7] A more complete decay curve analysis can be made using model-based nonlinear regression and Bayesian inference.[10]

III. EXEMPLIFYING RESULTS

The main result of the paper, Eq. (6), can be used to study some examples of interest, as shown in the following.

A. Confirming the result for an idealised decay process

The loss factor, η, may be defined as

$$\eta = \frac{E_{\rm d}}{2\pi E_0}, \tag{7}$$

where $E_{\rm d}$ is the dissipated energy over one cycle and E_0 is the initial energy [e.g., Eq. (3.122) in Ref. 2]. This relates with an exponential decay of energy, $E(t)$, which may be written as

$$E(t) = E_0 {\rm e}^{-\eta\omega t}, \tag{8}$$

where ω is the angular frequency such that the time of one cycle is $T_c = 2\pi/\omega$, or $T_c = 1/f$, where f is the frequency in hertz.

First, by assuming an idealised sound field decay, $\langle s^2(t)\rangle = E_0{\rm e}^{-\eta\omega t}$, such that $r(t)$ fulfills $r^2(t) = {\rm e}^{-\eta\omega t}$, one gets

$$\int_0^\infty r^2(t){\rm d}t = \frac{1}{\eta\omega}. \tag{9}$$

Then, theory linked with deriving Sabine's or Eyring's formula (e.g., Ref. 2, Chap. 4.5.1]) is used to relate the loss factor, η, with the absorption area, A. Using the decay formulation $E(t) = E_0{\rm e}^{-(Ac/4V)t}$, where V is the room volume [Ref. 2, Eq. (4.33)], and comparing with Eq. (8), one can identify

$$\frac{4V}{Ac} = \frac{1}{\eta\omega}. \tag{10}$$

Finally, by using Eqs. (9) and (10) (with $V = V_2$) in Eq. (6), one arrives at

$$R = L_{p1} - L_{p2} + 10\log\frac{S}{A}, \tag{11}$$

which is a commonly used equation for the reduction index as function of the sound pressure level difference and of the term $10\log(S/A)$, where the absorption area, A, is usually found from Sabine's formula using the estimated reverberation time, T, as $A = 0.16V/T$ (e.g., Ref. 1) Hence, it is shown that Eq. (6) gives the expected result known from literature when applied to the ideal exponential decay.

B. Identifying an effective loss factor for a broken decay curve

A decay process containing multiple modes, e.g., standing waves along horizontal and vertical room axes, may show a decay curve with a break, where the curve of sound pressure level versus time can be well fitted by one straight line in its early part and by a straight line with a different slope at a later part. Such a curve may be exemplified as

$$r^2(t) = a_1{\rm e}^{-\eta_1\omega t} + a_2{\rm e}^{-\eta_2\omega t}, \tag{12}$$

where the two terms on the right-hand side describe two decays with different loss factors, η_1 and η_2, with strengths a_1 and a_2, respectively, where $a_1 + a_2 = 1$ [such that $r^2(0) = 1$]. Performing the integration from zero to infinity gives

$$\int_0^\infty r^2(t)\mathrm{d}t = \frac{a_1}{\eta_1\omega} + \frac{a_2}{\eta_2\omega}. \quad (13)$$

By comparison with Eq. (9) a combined *effective* value for the loss factor, η_{eff}, may be defined from

$$\frac{1}{\eta_{\mathrm{eff}}} = \frac{a_1}{\eta_1} + \frac{a_2}{\eta_2} \quad (14)$$

and analogously for cases of more terms.

A similar analysis can be made also for the reverberation time, T (defined as the time it takes for the sound field to decay by 60 dB). Since the reverberation time is inversely proportional to the loss factor $(T = 6\ln(10)/(\omega\eta))$, an *effective* reverberation time, T_{eff}, for a broken curve may be defined as

$$T_{\mathrm{eff}} = a_1 T_1 + a_2 T_2. \quad (15)$$

As an example, if $a_1 = 0.9$, $a_2 = 0.1$, and $T_2 = 10\,T_1$, one would get $T_{\mathrm{eff}} = 1.9\,T_1$, i.e., a large difference from using only T_1 (resulting in a 2.8 dB error) or only T_2 (resulting in a 7.2 dB error).

These kinds of decays are sometimes called non-exponential (or nonlinear) and for a more general case of M terms,

$$r^2(t) = \sum_{m=1}^{M} a_m \mathrm{e}^{-\eta_m\omega t}, \quad (16)$$

normalised such that $\sum_{m=0}^{M} a_m = 1$, one can formulate an effective reverberation time as

$$T_{\mathrm{eff}} = \sum_{m=1}^{M} a_m T_m. \quad (17)$$

For the fully general case of an arbitrarily shaped decay curve, an effective value of the reverberation time may be formulated as

$$T_{\mathrm{eff}} = 6\,\ln(10)\int_0^\infty r^2(t)\mathrm{d}t \quad (18)$$

and a corresponding formulation for an effective value of the absorption area may be written as

$$A_{\mathrm{eff}} = \frac{4\,V}{c\cdot\int_0^\infty r^2(t)\mathrm{d}t}. \quad (19)$$

To fit the model to measured data, an approach suggested by Xiang *et al.*[11] may be used, for which it should be noted that two more terms need to be included for a complete modelling, linked with the noise contribution and with the finite time-length of the measured impulse response.

IV. CONCLUSION

An approach is presented for estimating room losses without an intermediate reverberation time estimate, with aimed applicability to reduction index measurements of building elements. The theory is presented, and the main result is substantiated by showed equivalence for the case of an ideal exponential decay curve of the acoustic energy. In addition, a formula is suggested for estimating an effective reverberation time in cases of non-exponential decay curves, i.e., when individual influential modes have different loss factors. Also, suggested formulas for effective values of reverberation time and of absorption area are presented for general shapes of decay curves.

AUTHOR DECLARATIONS

Conflict of Interest

The author has no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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