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Assessment of the sound reduction index of building elements by near field excitation through an array of loudspeakers and structural response measurements by laser Doppler vibrometry

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ABSTRACT

At low frequencies the assessment of the sound reduction index of building elements in the laboratory according to the standard ISO 10140-2:2010 is burdened by a large variation in the measurement results. This is due to the fact that at low frequencies the acoustic field is not sufficiently diffuse.

This paper discusses a measurement procedure in which a diffuse field is created in the source room by means of an array of loudspeakers positioned closely to the building insulation element under test. This procedure exploits the acoustic near field of the loudspeaker array.

The problems related to the breakdown of the diffuse field assumption of the receiving room are eliminated by measuring the structural response of the building insulation element under test by means of laser Doppler vibrometry and the application of the Rayleigh integral to compute the radiated sound power. The sound reduction index is determined from the ratio of the incident sound power, created by the loudspeaker array, and the radiated sound power.

The measurement approach is validated by means of a measurement of the sound reduction index of a single layer glazing. Comparisons are made with an analytical model and with a standardized ISO 10140-2:2010 measurement. Although the method offers clear, strong points in terms of removing room acoustic effects from the measurements in the lower frequency range, a point of concern is the measurement effort.

1. Introduction

Insufficient low-frequency sound insulation between dwellings combined with the use of powerful music reproduction systems is one aspect why inhabitants are often disturbed by their neighbors. Over the last years, an increased interest in sound insulation at low frequencies can be observed. Although in current standards the assessment of sound insulation in the frequency range down to 50 Hz is still optional [1,2], most studies recommend the inclusion of frequencies below 100 Hz [3,4]. However, it is also well known that measurents of the sound reduction index according to the standard ISO 10140:2010 [5] at frequencies below 100 Hz are affected by a large uncertainty [6–8]. The reason for this uncertainty is the reduced modal density of the acoustic eigenmodes at lower frequencies, in both the source room and the receiving room of the test facility. The resulting modal behavior cause the acoustic field to deviate from the ideal diffuse field [9–11]. This makes the measurement results obtained in a specific testing laboratory strongly dependent on the chosen microphone positions and therefore uncertain. Moreover, as the obtained measurement result is dependent on the specific geometry of the transmission suite, it also causes a poor reproducibility between laboratories [12,13].

In the works of Bravo, Maury and Elliott [12,14] the breakdown of the diffuse field assumption of the source room was reduced by using a number of suitably driven loudspeakers close to the building insulation element under test to create a diffuse incident field as closely as possible. To assess the acoustic power transmitted through the element under test, they measured the acoustic sound intensity at a dense array of points at the receiving side, close to the element. However, the effect of the receiving room was found not to be reduced in this way. The influence of the receiving room on the transmitted power, using the

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sound intensity approach, can only be reduced by the use of moving diffusers in the receiving room, or if a larger and more anechoic receiving room is used [12].

Roozen et al. [15] showed that the sound power radiated by a building insulation element under test at low frequencies can be determined from the vibration pattern of the building element, using laser Doppler vibrometry (LDV) or other vibration measurement techniques. The radiated sound power was calculated from the measurement data by means of the Rayleigh integral, in which an infinite half space is assumed for the 'receiving room'. In this manner the computed sound power is not affected by the room acoustic modes of the receiving room.

In the present paper the works of Bravo et al. [14] and Roozen et al. [15] are combined. The diffuse excitation field is created by a loudspeaker array closely positioned to the building element under test, and the radiated sound power is determined by means of laser Doppler vibrometry.

The paper is organized as follows. Section 2 treats the synthesis of the diffuse sound field by means of a loudspeaker array. This section also discusses the computation of the radiated sound power level, using conditioned spectral analysis. Section 3 reports about measurements on a single glazing, and validates the results by means of an analytical model. A comparison with a standardized ISO 10140:2010 [5] measurement is given as well. Section 4 draws the conclusions of the work.

2. Theory for the synthesis of a diffuse field and the analysis of the measurement data

The theory to synthesize spatially correlated random pressure fields is well documented in literature [16]. In this section it is briefly summarized for the sake of completeness. In addition to this brief summary, a proposal is elaborated to perform the analysis of the measurement data by means of a conditioned spectral analysis, which is different from the approach taken by Elliott, Bravo and Maury et al. [14,16–18].

2.1. *The synthesis of spatially correlated random pressure fields*

Piersol [19] showed that the cross spectral density of the sound pressure of a diffuse acoustic field, measured between two points i and j separated at a distance r from each other, is given by (see also [20–23])

$$S_{dd}(i,j) = S_D \frac{\sin(kr)}{kr} \tag{1}$$

where $k = \frac{\omega}{c}$ is the acoustic wavenumber, ω is the angular frequency ($\omega = 2\pi f$) and S_D is the autopower spectrum of the desired diffuse acoustic field. S_D is a frequency dependent scalar, independent of the position in the room.

Let the matrix with desired cross spectral densities at the N_{mic} control microphone positions, based on Eq. (1), be denoted by $\mathbf{S_{dd}}$. The subscript $\mathbf{_d}$ indicates the desired diffuse field. The control microphones are positioned on the surface of the building element in a rectangular grid, between the loudspeaker array and the building element. The matrix $\mathbf{S_{dd}}$ has a dimension $N_{mic} \times N_{mic}$ for each frequency being considered, and the rank of this matrix is equal to N_{mic}.

To approximate the acoustic field with the above mentioned cross spectral density as closely as possible a discrete number of loudspeakers, N_{LS}, is used. The number of control microphone positions, N_{mic}, is normally larger than the number of loudspeakers, N_{LS}. However, having N_{LS} signals available to create the desired acoustic field, that field cannot have a rank higher than N_{LS}. Therefore, a limited number of uncorrelated principal components of the desired acoustic field are considered, following Elliott et al. [16]. For this purpose the matrix $\mathbf{S_{dd}}$ is decomposed in its eigenvectors $\mathbf{V}$ and its eigenvalues Λ:

$$\mathbf{S_{dd}} = \mathbf{V\Lambda V}^* \tag{2}$$

where $*$ denotes the complex conjugate.

The best least-squares approximation to $\mathbf{S_{dd}}$ with rank N_{LS} can be obtained by taking the N_{LS} terms with the largest eigenvalues:

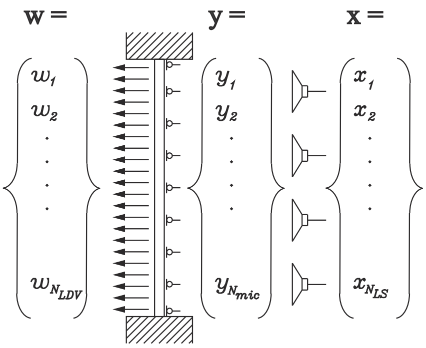

Fig. 1. System diagram with input signals to the loudspeaker amplifiers $\mathbf{x}$, microphone control signals $\mathbf{y}$, and response of the building insulation element under test $\mathbf{w}$.

$$\widetilde{\mathbf{S}}_{\mathbf{dd}} = \widetilde{\mathbf{V}}\widetilde{\mathbf{\Lambda}}\widetilde{\mathbf{V}}^* \tag{3}$$

where $\widetilde{\mathbf{\Lambda}}$ is a diagonal matrix that contains the N_{LS} largest eigenvalues, and the matrix $\widetilde{\mathbf{V}}$ contains the N_{LS} largest eigenvectors. The tilde ~ indicates that the variable is the best least-squares approximation with rank N_{LS}. In the approximation of interest, the rank of matrix $\widetilde{\mathbf{S}}_{\mathbf{dd}}$ is forced to be equal to the number of loudspeakers of the loudspeaker array, N_{LS}, being the maximal feasible rank the can be created by the array.

The N_{LS} input signals to the loudspeaker amplifiers required to generate the desired cross spectral matrix $\widetilde{\mathbf{S}}_{\mathbf{dd}}$ at the control microphones can be constructed as follows. A measurement is performed to relate the N_{LS} input signals $\mathbf{x}$ to the pressures $\mathbf{y}$ as measured at the N_{mic} control microphone positions (for a system diagram, see Fig. 1). This results in a relationship in the frequency domain that reads

$$\mathbf{Y} = \mathbf{HX} \tag{4}$$

where $\mathbf{H}$ is a matrix of transfer functions having a dimension $N_{mic} \times N_{LS}$ for each frequency being considered, vector $\mathbf{Y}$ is the Fourier transform of the control microphone signals, having a dimension $N_{mic} \times 1$, for each frequency being considered, and vector $\mathbf{X}$ is the Fourier transform of the input signals to the loudspeaker amplifiers, having a dimension $N_{LS} \times 1$ for each frequency being considered. The matrix with optimal control filters $\mathbf{W}_{opt}$ can be computed from

$$\mathbf{W}_{opt} = (\mathbf{H}^*\mathbf{H})^{-1}\mathbf{H}^*\widetilde{\mathbf{U}}\widetilde{\mathbf{\Lambda}}^{\frac{1}{2}} \tag{5}$$

where $\widetilde{\mathbf{U}}$ represents N_{LS} uncorrelated random signals with unitary variances in the frequency domain. Using this matrix with optimal control filters, the optimal input signals to the loudspeaker amplifiers $\mathbf{X}$ can be computed with

$$\mathbf{X} = \mathbf{W}_{opt}\widetilde{\mathbf{U}} \tag{6}$$

The time domain signals $\mathbf{x}$ to drive the loudspeaker array can be obtained from the matrix $\mathbf{X}$ by means of an inverse Fourier transform. For a more extensive description of the synthesis of a diffuse field by means of a loudspeaker array, see Elliott et al. [16].

2.2. *Analysis of measurement data by means of conditioned spectral analysis, CSA*

Using the optimal loudspeaker signals $\mathbf{x}$, a diffuse acoustic field with cross spectral matrix $\widetilde{\mathbf{S}}_{\mathbf{dd}}$ is obtained. As this excitation field consists of N_{LS} uncorrelated principal components, as discussed in the previous section, also the structural response $\mathbf{w}$ of the building insulation element under test will consists of the same number of principal components. These N_{LS} uncorrelated response components are denoted by $\mathbf{w}^{(k)}$, with $k = 1 \ldots N_{LS}$.

The uncorrelated response components can be extracted by means