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Predicting the sound transmission loss through finite-sized perforated brick walls using component mode synthesis

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ABSTRACT
Bricks are often perforated to decrease weight, resulting in a decreased material cost and easier handling on site. However, walls made of perforated brick have a lower airborne sound insulation than solid walls with similar surface mass. This can be partially explained by thickness resonances and orthotropy. Sound insulation prediction models that include the detailed perforation geometry of all individual bricks are computationally demanding since a refined mesh is needed in order to properly capture this geometry. However, a brick wall typically consists of a repeating unit cell of three bricks and a mortar bond. In this paper, Component Mode Synthesis (CMS) is employed to eliminate the internal degrees of freedom of the unit cell to form a superelement. Based on these superelements, a quarter wall model is constructed and the diffuse sound transmission loss is computed within the hybrid deterministic-statistical energy analysis framework. The model is validated with experimental data obtained at the KU Leuven Laboratory of Acoustics. The computed results show a good correspondence with the data, while retaining a relatively low computation time.

Keywords: Perforated brick wall, airborne sound insulation prediction, CMS
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

Load bearing wall systems composed of bricks with hollows are often used in the construction industry because of their light weight and easy handling. However, its light weight and perforation geometry lead to a strong reduction of the sound insulation. Due to the perforations, the sound insulation of this type of wall is generally lower than for a solid wall with the same surface mass. The prediction of the airborne sound insulation of hollow core walls is challenging since it is characterized by many parameters and

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physical phenomena. Experimental parametric studies by Fringuellino and Smith [1] and Guillen et al. [2] have shown that the airborne sound insulation of a hollow core wall depends mainly on the leaf thickness, its surface mass, material parameters and perforation pattern. All these parameters define an array of physical phenomena. The coincidence frequency for example, i.e. where the free bending wavelength of an infinite leaf matches the projected free wavelength in air, depends on the material parameters of the leaf, its perforation pattern and its thickness. As does the first thickness resonance, i.e. the resonance phenomenon where the first standing wave over the thickness of the wall occurs. All these different phenomena and input parameters make it hard to accurately predict the airborne sound insulation using a simplified model.

Existing prediction models can be divided into analytical and numerical models. Analytical models are used to gain insight into the main physical phenomena, e.g. coincidence. A low computational cost is achieved by assuming diffuse conditions in the transmission rooms and by using a simplified model for the vibrational behaviour of the leaf. This often leads to an inaccurate prediction of the sound insulation due to this simplified representation of the wall and since some physical phenomena are omitted, e.g. thickness resonances. Element-based numerical models, e.g Finite elements, manage to capture the vibratory behaviour of both the wall and the transmission rooms in full detail making it possible to accurately predict the single number rating. However, these models are not practical due to the large number of boundary and/or finite elements needed at high frequencies.

A prediction model for the airborne sound insulation of hollow core walls is developed with both a high prediction accuracy and a relatively low computational cost. A brick wall typically consists of a repeating unit cell of three bricks and a mortar bond. Jacqus et al. [3] use this unit cell to compute the equivalent material properties of an orthotropic plate. The transmission loss is then computed using a transfer matrix model. This approach gives good results above 500 Hz but it fails to capture the modal behaviour and the correct boundary conditions of the wall. In this paper Component Mode Synthesis (CMS) is used to form a superelement based on this unit cell by eliminating its internal degrees of freedom. Here, the Craig-Bampton approach with fixed interfaces is used. The superelements are in turn used in a quarter wall model with a combination of symmetric and anti-symmetric boundary conditions. In this way, both the boundary conditions and the complex perforation pattern of the bricks are taken into account. The sound fields in the sending and receiving rooms are modelled as diffuse. The hybrid Deterministic-Statistical Energy Analysis (DET-SEA) framework is adopted in this work to rigorously couple the diffuse sound fields to the deterministic wall model by employing the diffuse field reciprocity relation [4]. This framework has been chosen due to its low computational cost and high prediction accuracy [5,6]. The prediction model presented in this work is validated against experimental results obtained in the KULeuven Laboratory of Acoustics.

The deterministic model of the wall is explained in full detail and is subsequently coupled to the sound fields in the adjacent transmission rooms in section 2. In section 3, the experimental setup and test results for the measurements of the sound insulation of a hollow core brick wall is presented. The results of the model are compared with experimental results and are discussed. The paper concludes with some final remarks and conclusions in section 4.

2. AN EFFICIENT AND ACCURATE MODEL

In this section, a forward model with both a high prediction accuracy and a low computational cost is developed. The wall is modelled deterministically to capture its vibration behaviour while the sound fields in the sending and receiving rooms are modelled as diffuse.

The hollow core brick wall consists of a single type of bricks bonded to each-other with mortar in a specific pattern or bond. This pattern is repeated over the total area of the wall. Out of this pattern, a repeating unit cell can be selected as is shown in Fig. 1 for 1 full brick and 2 half bricks and the mortar in between. A detailed finite element model is made for this unit cell to eliminate a large set of internal degrees of freedom. The reduced model is then used to create a quarter wall model as shown in Fig. 1.

The hybrid DET-SEA modelling framework [5,6] is used to rigorously couple the diffuse sound fields in the transmission rooms to the deterministic wall model by employing the diffuse field reciprocity relationship [4]. In what follows, the deterministic model of the wall system is explained first. Subsequently, the interaction between the wall and the sound fields in the adjoining rooms is described.

2.1. Deterministic model of the wall

The considered wall system consists of a single thick leaf. In the first instance, the leaf is decoupled from the transmission rooms. The displacement field of the leaf, $\boldsymbol{u}(\boldsymbol{x},\omega)$, is approximated using a finite set of basis functions $\boldsymbol{\Phi}(\boldsymbol{x})$, that satisfy the boundary conditions, and corresponding generalized coordinates $q(\omega)$:

$$\boldsymbol{u}(\boldsymbol{x},\omega) \approx \sum_{k=1}^{n} \boldsymbol{\phi}_k(\boldsymbol{x}) q_k(\omega) = \boldsymbol{\Phi}(\boldsymbol{x})\, \boldsymbol{q}(\omega) \tag{1}$$

The choice of the basis functions $\boldsymbol{\Phi}(x)$ of the decoupled wall leaf will be discussed in detail below. This will result in a system of equations in terms of the generalized coordinates of the wall:

$$\boldsymbol{D}_d(\omega)\, \boldsymbol{q}(\omega) = \boldsymbol{f}(\omega) \tag{2}$$

with **f** the external fluid loading onto the wall leaf by the acoustic pressure in the adjoining rooms, and $\boldsymbol{D}_d$ the dynamic stiffness matrix of the leaf.

2.1.1. Component mode synthesis

Component mode synthesis (CMS) is a model reduction technique for large structural models. Firstly, the complete structure is divided into a number of separate components or substructures. Then, the finite element method is employed to formulate a model for each component. Here, the degrees of freedom of the individual models are reduced a subset of the physical coordinates of the full model and a set of generalized coordinates. In a second step, all the reduced models are assembled to formulate a global model for the complete structure. This results in a finite element model which is greatly reduced in size. The responses in the physical coordinates that are not included in the reduced model can be computed using back-substitution. The CMS scheme used in this paper is the fixed interface component mode synthesis [7]. This method consists of splitting the full model in multiple components, where the degrees of freedom (DOFs) of each component are grouped into DOFs that couple to other components, and internal DOFs. The response of a system is represented in terms of a set of 'component' modes and 'constraint' modes. The component modes are taken to be a subset of the local modes of a substructure when the boundary degrees of freedom are clamped.

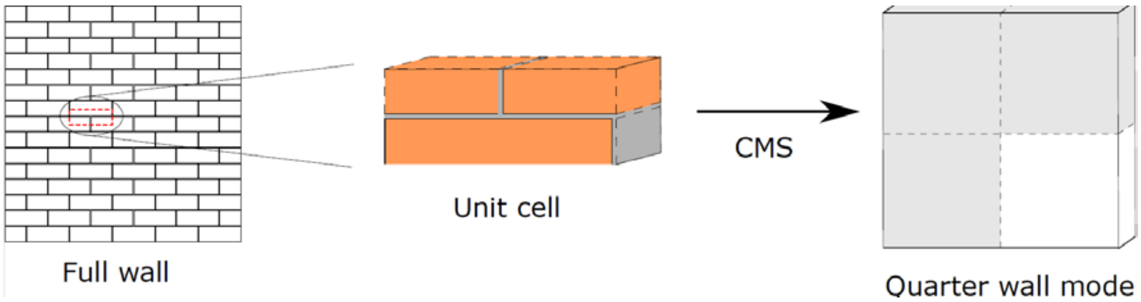

Figure 1: Schematic representation of the CMS procedure.

The constraint modes are given by the static response of the substructure when a unit displacement or rotation is applied to a given boundary degree of freedom while all other boundary degrees of freedom remain fixed. Converged results can typically be obtained by retaining component modes with frequencies less than twice the maximum frequency in the analysis. The number of component modal degrees of freedom is therefore typically much smaller than the number of original degrees of freedom of the unit cell. One of the advantages of using CMS in the context of a structure composed of a repeating unit cell is that the reduction only needs to be performed once and does not have to be re-evaluated. This therefore leads to a significant reduction in computational cost. The main advantage of using CMS over periodic structure theory is that the boundary conditions (BCs) of the thick wall can be represented more accurately. These BCs has been shown to have a significant impact on the diffuse sound transmission loss.

2.1.2. Quarter wall model

The brick wall has two planes of symmetry; at half width and at half height. By exploiting these symmetry planes, the number of degree of freedom can be reduced by a factor of four. Note that the plane at half depth is not taken as a symmetry plane in this paper since a wall with a plaster layer at one side is modelled. When the half depth plane is a symmetry plane, e.g. when the wall is plastered at both sides, the preceding reasoning can be extended into a one-eight wall model. Hence, the symmetry of the structure is used to reduce the computational cost with no loss of accuracy [7].

In a modal analysis of a structure that exhibits symmetry, the eigenmodes will be both symmetric and antisymmetric with respect to the symmetry planes [7]. The natural frequencies and the corresponding eigenmodes of the wall with two symmetry planes can therefore be computed by assuming all four combinations of symmetric and antisymmetric boundary conditions at the symmetry planes. By combining the results of the four eigenvalue problems, the solution of the full wall is found. The eigenmodes of the full wall are rescaled by a factor of $\frac{1}{\sqrt{4}}$ since the original eigenmodes of the wall have been scaled with respect to the mass matrix of one-fourth of the total wall.

2.2. Transmission suite model

In the previous section, the deterministic model of the homogenized wall was described in full detail. In the present section, this wall model is rigorously coupled to the sound fields in the adjoining rooms.

Within the hybrid DET-SEA framework, a transmission suite (room-wall-room) model has been developed by Reynders et al. [6]. In this model, which is adopted in the present work, the rooms are taken to carry a diffuse field, while the wall is modelled deterministically. In the room-wall-room setup, the hybrid model contains two diffuse

(SEA) subsystems - the sending and receiving rooms - and in the context of a sound transmission analysis, the quantity of interest is the so-called coupling loss factor between both rooms. If in a stationary situation, the sound power flow from room 1 to room 2 (through the wall) is denoted as P_{12}, then the coupling loss factor η_{12} is defined as [8]

$$\eta_{12} \coloneqq \frac{\omega n_1}{P_{12}}\left(\frac{E_1}{n_1} - \frac{E_2}{n_2}\right) \tag{3}$$

where the total acoustic energy of room k is denoted as E_k and its modal density (i.e., the expected number of modes per unit radial bandwidth) as n_k. Although the coupling loss factor is a random quantity (because the sound fields in the rooms are random, diffuse fields), only its mean value will be of interest in the present analysis as the intention is to predict the mean sound transmission loss of the wall. The coupling loss factor relates directly to the sound transmission coefficient, which is defined as the ratio between the power flow P_{12} from room 1 to room 2, and the incident sound power on the wall in room 1. The relationship reads [9]

$$\tau = \frac{4V_1\omega}{L_x L_y c \eta_{12}} \tag{4}$$

where V_1 denotes the volume of the sending room and c the speed of sound in air. The sound transmission loss (or airborne sound insulation) of the wall then immediately follows from

$$R \coloneqq 10\log\frac{1}{\tau} = 10\log\frac{L_x L_y c \eta_{12}}{4V_1\omega} \tag{5}$$

By considering the interaction between the wall and the direct field response of the rooms at their interfaces, the coupling loss factor η_{12} can be rigorously evaluated within

the hybrid DET-SEA framework [5,6,10]. The direct field response of a room is the sound field that would occur if the room would be of infinite extent, i.e., if the room would behave as an acoustic half-space as seen from the room-wall interface when that interface is embedded in an infinite planar baffle. The related acoustic dynamic stiffness matrix is then termed the direct field dynamic stiffness matrix of the room. For room 1 for example, this matrix describes the relationship between the displacements and forces at the interface with the wall leaf:

$$\boldsymbol{D}_{dir1}\boldsymbol{q} = \tilde{\boldsymbol{f}}_{dir1} \tag{6}$$

The forces, $\tilde{\boldsymbol{f}}_{dir1}$, act on the (generalized) degrees of freedom of the wall leaf $\mathbf{q}$ due to the pressure field in the acoustic half-space. The direct field dynamic stiffness matrix $\boldsymbol{D}_{dir1}$ is obtained by numerically evaluating the Rayleigh integral, e.g. using a wavelet discretization as in Langley [11].

Once the direct field acoustic dynamic stiffness matrices of both rooms have been computed, the coupling loss factor is obtained from [4]

$$\eta_{12} = \frac{2}{\pi\omega n_1}\sum_{rs} Im\left(\boldsymbol{D}_{dir2,rs}\right)\left(\boldsymbol{D}_{tot}^{-1} Im(\boldsymbol{D}_{dir1})\, \boldsymbol{D}_{tot}^{-H}\right)_{rs} \tag{7}$$

where

$$\boldsymbol{D}_{tot} \coloneqq \boldsymbol{D}_d + \boldsymbol{D}_{dir1} + \boldsymbol{D}_{dir2} \tag{8}$$

$\boldsymbol{D}_d$ denotes the dynamic stiffness matrix of the wall, and $\boldsymbol{D}_{dir1}$ and $\boldsymbol{D}_{dir2}$are the direct field acoustic dynamic stiffness matrices in terms of the (modal) wall coordinates **q**.

a) b)

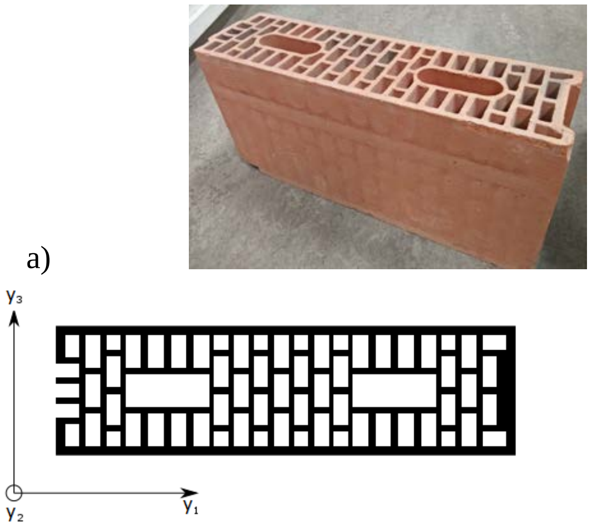

Figure 2: Perforation pattern of the hollow core brick under consideration (l_{y1} = 0.495 m, l_{y2} = 0.235 m, l_{y3} = 0.135 m and m = 12.78 kg). b) Cross-sectional view of the simplified model of the perforated brick. The handling holes are straightened and the tongue and groove connection is simplified to give flat edges.

3. RESULTS AND DISCUSSION

The model that was presented in the previous section is employed in the present section for predicting the airborne sound insulation of a hollow core brick wall. In order to assess the accuracy of the sound insulation prediction, it is compared with the results from measurements. The brick is shown in Fig. 2a. The perforation pattern of the brick is slightly simplified in the model as displayed in Fig. 2b; the rounded edges of the handling holes are straightened. The tongue of the tongue and groove connection is modelled inside the groove, this approach is valid since static periodic boundary conditions are applied at the brick faces.

3.1. Experimental setup

The test setup for the measurement of the airborne sound insulation of walls consists of two adjacent reverberation rooms separated by the test specimen. The sound insulation has been measured in the KU Leuven Laboratory of Acoustics. The test opening has a width of 3.25 m and a height of 2.95 m. The volumes of the transmission rooms are 87 m^3. The simplified perforation pattern of the considered brick is shown in Fig. 2b. The harmonic airborne sound insulation is modelled for 320 frequencies in the frequency range of 50-3150 Hz. These frequencies therefore correspond to the 1/12 band centre frequencies. The harmonic transmission losses are band-averaged over 1/3 octave bands for comparison with the experimental data.

The particular element type that is employed here is the Solid90 element from the Ansys finite element software; it is a twenty node element with three displacement degrees of freedom at each node. As the wavelength of deformation at high frequencies of the bricks and the dimensions of the web elements are small, a fine mesh is needed; in the present work, an element edge length of 1 mm is employed in the y1- and y3-

directions and 5 mm in the y2-direction. The boundary displacements in the middle plane are restrained.

3.2. Comparison with measurements

The wall is constructed using hollow bricks with an average density of 813 kg/m^3 and a width of 13.5 cm. The Young's modulus is taken to be 10 GPa in the y_1- and y_3-directions, as defined in Fig. 2b, with corresponding Poisson coefficients of 0.2. The Young's modulus of the terracotta in the y_2-direction, along the perforations, is 3.5 GPa

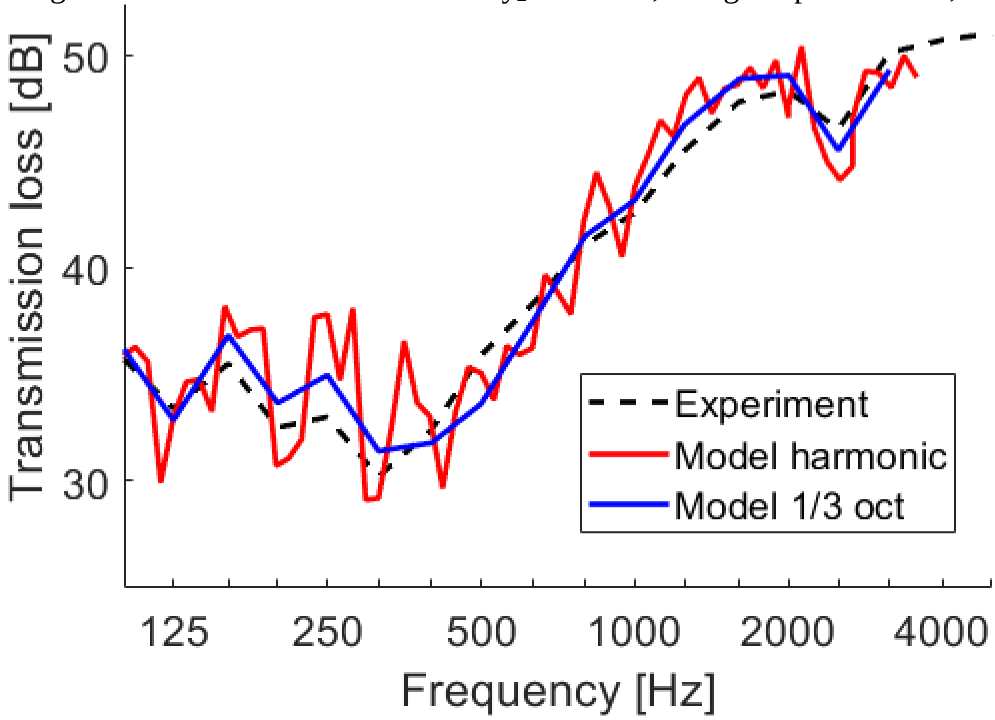

Figure 3: Comparison of the measured (black dashed line) and the predicted sound insulation curves for the perforated brick.

and is significantly lower than the other two directions, as in [12]. This modulus is computed to make sure that the measured first thickness resonance at 2484 Hz matches the eigenfrequency of the 1-1-thickness-mode of the homogenized brick wall. The damping loss factor η of the brick wall is based on the estimation of Craick for brick and concrete walls/floors in laboratory conditions [13]

$$\eta \approx \frac{2.5}{\sqrt{\omega}} + 0.01 \qquad (9)$$

A plaster layer of 1 cm with a density of 800 kg/m^3, a Young's modulus of 5 GPa and a Poisson ration of 0.2 is applied on one side.

The result of the model is presented in Fig. 3 both at the 1/12 band centre frequencies and for the 1/3 octave bands. The 1/3 octave band values are compared with the experimental data. The analysis is performed on a single personal computer with a 2.7 GHz Intel Core i7 processor and 16 GB RAM. All computations are performed in the Matlab software. The computation time is around 45 minutes.

3.3. Physical interpretation and comparison with experiments

An important resonance phenomenon for thick walls are the so-called thickness resonances, i.e. the frequency where the two interfaces of the leaf vibrate with a 90^o

shift in phase angle. As can be observed in Fig. 3, the prediction of the first thickness resonance frequency agrees well with the experimental findings. This comes to no surprise as the Young's modulus of the terracotta along the perforations has been calibrated to this frequency.

A dip in the sound insulation is observed at 339 Hz. This is the so-called coincidence dip. It occurs at the critical frequency of the leaf, i.e., the lowest frequency at which the free bending wavelength of an infinite wall matches the projected free wavelength in air. The theoretical value of the critical frequency is 248 Hz in the x_2-coordinate direction and 310 Hz in the x_1-coordinate direction for the first setup. The predicted coincidence dip matches the theoretical values well. At low frequencies, the modal behaviour of the leaf becomes important. Both the resonance and anti-resonance dips in the frequency range of 100-300 Hz are predicted accurately. From Fig.3, it can be observed that the predicted sound insulation agrees well with the experimental findings.

4. CONCLUSION

In this paper, an accurate and computationally efficient model is presented for the prediction of the airborne sound insulation of hollow core brick walls within the hybrid FE-SEA framework. The eigenmodes are used to approximate the vibration field of the wall leaf. Component mode synthesis is used on a periodic unit cell to reduce the computational cost. The sound insulation is computed at the 1/12 octave band centre frequencies for a frequency range of 50 - 3150 Hz for 320 frequency lines to include the oscillatory behaviour and is averaged over 1/3 octave bands for comparison with the experimental results. The computation time for the setup presented here is 45 minutes. The model has been validated against experimental data obtained at the KU Leuven Laboratory of Acoustics.

5. ACKNOWLEDGMENTS

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