Applied Acoustics 92 (2015) 27–41

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Predicting sound absorption coefficients of lightweight multilayer curtains using the equivalent circuit method

Reto Pieren *, Kurt Heutschi

Empa, Swiss Federal Laboratories for Materials Science and Technology, 8600 Duebendorf, Switzerland

ARTICLE INFO

Article history:
Received 13 June 2014
Received in revised form 18 December 2014
Accepted 6 January 2015
Available online 29 January 2015

Keywords:
Sound absorption
Textiles
Curtains
Equivalent circuit

ABSTRACT

A theoretical model to predict the sound absorption of lightweight multilayer curtains is presented. The fabric sheets of the curtain are represented by a network of discrete impedances describing the vibration and the airflow through the fabric. It is shown that the equivalent circuit method (EC) with correct modeling of the air cavities by distributed elements and the impedance transfer method (ITM) yield identical impedance relations. Formulas for the oblique incidence and the statistical absorption coefficient for curtains with an acoustically hard backing and without backing, i.e. freely hanging, are deduced. The model was validated by measurements on a set of 24 lightweight, woven fabrics. For the normal incidence absorption coefficient excellent agreement was achieved with mean value and standard deviation of the differences of 0.01 ± 0.05. Based on the proposed model the following conclusions for the application of lightweight multilayer curtains can be drawn: (1) Sound-induced vibrations of the fabrics are an acoustically relevant aspect in the design of lightweight curtains. (2) The optimal specific airflow resistances of the individual layers may not be given in a compact analytical form but have to be determined by an optimization procedure. (3) The sound energy absorbed by curtains placed in the diffuse field of a room is in the same order of magnitude as the absorption by comparable curtains mounted in front of a wall. (4) For given mass and extension, multilayer arrangements perform superiorly to single layer curtains.

1. Introduction

The application of curtains as sound absorbers for room acoustical purposes has several substantial advantages: Curtains are relatively cost-effective, lightweight, flexible, easy to handle and they enable variable room acoustics. Already in 1970 it was reported that the sound absorption of curtains depends on the mounting distance to the wall, the airflow resistance and the surface mass density of the fabric as well as the draping [1]. In 1990 it was phenomenologically shown that the intrinsic parameters of a textile, i.e. its microstructure, have a substantial influence on the sound absorption coefficient [2]. Since then several authors have successfully predicted absorption coefficients of textiles based on geometrical parameters [3–6].

A thorough theoretical and numerical investigation on the dissipation of acoustical energy in a thin, lightweight, poroelastic sheet is given in [7] where the analytical solution is obtained based on a Helmholtz integral formulation. Parametric studies revealed that thin, lightweight, poroelastic sheets can provide high absorption coefficients—even at low frequencies [7,8].

The influence of the finite mass of lightweight curtains on the absorption coefficient was already discussed in special cases. For a single, freely hanging fabric sheet the absorption coefficients at specific angles of sound incidence are discussed in [9]. A single fabric with a rigidly backed air cavity was discussed in [6] for normal sound incidence. It was concluded that for lightweight curtains the influence of the finite mass on the absorption coefficient should be taken into account.

Structures consisting of multiple infinitely extended, thin sheets separated by extended air cavities have been widely investigated in the context of micro-perforated plates (MPP) [10,11]. So called multiple-leaf MPPs can be used in order to broaden the frequency range of absorption or to get rid of the rigid backing [12–15]. Recently also a combination of MPPs and a permeable membrane has been studied [16]. Different methods to model the acoustical behavior of such multilayer structures have been adopted and compared, e.g. the transfer matrix method (TMM) [17,18], the impedance transfer method (ITM) [13,19,20] and the equivalent circuit method (EC) [13,14,21]. An alternative approach using a neuronal network was recently applied to nonwoven multilayer absorbers [22].

* Corresponding author.
E-mail addresses: reto.pieren@empa.ch (R. Pieren), kurt.heutschi@empa.ch (K. Heutschi).

http://dx.doi.org/10.1016/j.apacoust.2015.01.003
0003-682X/

In this article the equivalent circuit method will be adopted in order to obtain absorption coefficients of multilayer curtain systems. There are two main reasons for this choice: (1) The combined acousto-mechanical system can be well visualized, interpreted and analysed using this method. (2) In the past decades there seems to have been some confusion in the literature about modeling of layered absorber structures by equivalent electrical networks. By improper representation of air cavities in the analogue electrical network, the results may get wrong. Based on comparisons with measurements or other analysis methods, some authors have concluded that the equivalent circuit method is inaccurate in the application of multi-leaf MPPs [12,13,20,21,23]. Here we show that theses apparent inaccuracies can be avoided by using a correct equivalent network and that the obtained analytical results are identical to other methods such as ITM or TMM.

This article is the continuation of the work published in [6,24]. Compared to our previous study [6] the calculation model presented in Section 2 has been substantially improved and extended. In this article a more refined model for the airflow through the fabric taking into account the intrayarn airflow and the shape of the pore cross-sections is developed. The formulas for absorbers consisting of multiple fabric sheets are established and recently published formula for statistical absorption coefficients measured in the reverberation chamber are employed. In Section 3 a validation of the presented model performed on a large set of 24 different fabrics is accomplished. Absorption coefficients obtained from impedance tube measurements are compared to predicted values. The latter are calculated from geometrical parameters extracted from macroscopic photographs of the fabrics. By using this refined model, the standard deviation of the differences between measured and calculated absorption coefficients could be reduced by a factor of 2 compared to [6]. Section 4 is dedicated to the application of the presented model. Predictions show that the absorption characteristics of a curtain system can be significantly improved by using multiple textile sheets even if the total surface mass density and distance to the wall is kept constant. The article ends with conclusions in Section 5.

2. Model

In this section a theoretical model to predict sound absorption coefficients of lightweight multilayer curtains is gradually developed using analogue electrical networks. The presented model consists of a comprehensive compilation of already published models and formulas which are combined in order to adequately predict statistical sound absorption coefficients of multilayer curtain systems. The model only considers the predominant acoustical and mechanical effects and merely uses a few easily measurable parameters, which ensures its applicability in the design and optimization of entire curtain systems.

In a first step the air cavities between the fabric sheets are treated. In a second step the fabric sheets are characterized. Finally the obtained networks are connected and formulas for different absorption coefficients are deduced.

2.1. Description of the absorbent structure

The curtain system is assumed to be infinitely extended in two dimensions, y and z, and only varying in x-direction. This implies that no draping is allowed. Throughout this article generally 0% fullness is assumed, corresponding to flat curtains. An experimental investigation on the influence of the fullness on statistical sound absorption coefficients can be found in [25]. The curtain consists of multiple, parallel, porous fabric sheets separated by air layers of defined extents. Fig. 1 illustrates a multilayer curtain

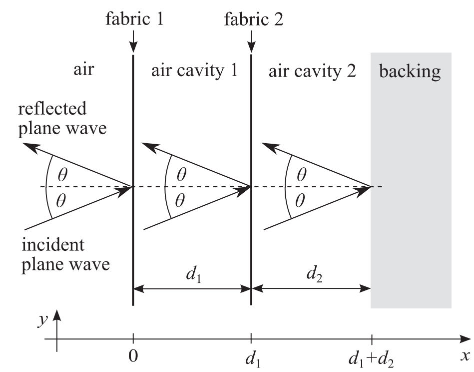

Fig. 1. Illustration of a layered absorber consisting of two air layers, two fabric sheets and a backing (gray area).

system with two fabric sheets with the corresponding air cavities of extents d_1 and d_2. For the backing of the curtain, mainly two cases are of practical relevance: (1) an acoustically hard backing and (2) no backing (i.e. air), which means a freely hanging curtain. It is assumed that a plane wave coming from air impinges upon this structure at an angle θ to the normal vector of the absorber surface.

2.2. Analogue electrical networks

Equivalent electrical networks of acoustical systems can be found by establishing an analogy between the acoustical quantities sound pressure p and sound particle velocity v or volume flow q and the electrical quantities voltage U and current I. Widely used is the pU–vI analogy where the potential quantity p is mapped onto U and the flow quantity v or q onto I. Similarly mechanical systems can be represented by electrical networks as well. Once the analogy is established, fundamental structures in acoustical and mechanical systems can be identified and described by corresponding electrical network elements.

2.2.1. Lumped elements

Short tubes that represent acoustic masses and small cavities that represent acoustic compliances (short and small with respect to the shortest wavelength of interest) can be considered as lumped elements. An important property of lumped elements is the missing of sound propagation due to the element size. Consequently they can be represented by two-poles. The acoustic mass corresponds to an inductance and the compliance to a capacitance as analogue electrical elements.

2.2.2. Distributed elements representing a long tube

Distributed elements represent structures that allow for sound propagation. An important and often encountered distributed element is an extended tube-like configuration carrying a plane wave in axial direction. The length of the element is assumed to be d where d is not small compared to the wavelength. A first approach to handle such structures is to subdivide them into smaller sections that fulfill the condition of lumped elements. A long tube can be thought of a pile of cylinders of small height. The air contained in each of these cylinder elements can be accelerated and compressed. These two properties are represented by a serial inductance and a shunt capacitance in the analogue electrical circuit. A sequence of these elements approximates the behavior of the long tube (Fig. 2).

The network in Fig. 2 corresponds to a lossless electrical transmission line. While the behavior of such networks can easily be investigated numerically with help of network analysis tools such