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ON THE LOCAL PLANE WAVE METHODS FOR IN SITU MEASUREMENT OF ACOUSTIC ABSORPTION

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In this paper we address a series of so-called local plane wave methods (LPW) to measure acoustic absorption. As opposed to other methods, these methods do not rely on assumptions of the global sound field, like e.g. a plane wave or diffuse field, but are based on a local plane wave assumption. Therefore, the LPW methods can be used for any given surface/absorbing material and any arbitrary sound field. The absorption coefficient can be calculated based on a measurement of the acoustic pressure in a number of points in the vicinity of the absorbing surface. The local plane wave methods are illustrated by some numerical and experimental examples.

1. Introduction

In recent years, the University of Twente has developed a method to, in-situ, measure the acoustic absorption coefficient of a material/surface in an a-priori unknown sound field [1, 3, 4, 5]. This allows the acoustician to assess whether the acoustic material is used efficiently in the application at hand. For instance, car manufacturers can now assess if the absorption material used inside a car, also efficiently absorbs the actual sound field in the car, e.g. as the car is driving. This a-priori unknown sound field is obviously not diffuse, nor does it consist of normal incident, plane or spherical waves. Its spectrum could be very specific (changing from point to point) and will most probably vary from car to car. Hence, a normal incident absorption coefficient or an absorption coefficient for a diffuse field, although it very well quantifies the absorption characteristics of the material, will not tell us how much of the in situ acoustic energy is actually being absorbed and hence if the material is used as efficiently as possible. As the newly developed method does not need any prior information about the sound field near the absorbing surface (it just measures it!), it provides the needed information about the actual efficiency of the material to absorb the sound at that particular position.

In this paper, we will give a short introduction to the method and try to explain its benefits and pitfalls. As the method does not make any assumptions about the sound field, it is inherently different from other in situ methods, which do assume and hence require the presence of a certain given sound field. Therefore, we can only make a comparison with these other methods if the sound field is the actual sound field prescribed by that other method. Such a comparison is given elsewhere, see [3]. In this paper, we will illustrate the method (numerically) by a Louvre door example, an impedance surface and shortly address a study how the method is used (experimentally) to measure car seats and noise barriers.

2. Theory

The absorption coefficient is defined as the fraction of the incoming sound energy being absorbed by the surface. Altough, from a energy point of view inconsistent, the absorption coefficient is defined as:

$$\alpha = \frac{W_{ac}}{W_{in}}, \tag{1}$$

where $W_{ac} = \int \mathbf{I_{ac}} \cdot \mathbf{n} d\Gamma$ is the active (net) acoustic power ($\mathbf{I_{ac}} = \frac{1}{2}\Re\{P\bar{\mathbf{U}} \cdot \mathbf{n}\}$ denotes the active intensity vector, P the complex acoustic pressure, $\bar{\mathbf{U}}$ the complex conjugate of the complex particle velocity vector and $\mathbf{n}$ a normal vector pointing into the surface) flowing through a surface and $W_{in} = \int I_{in} d\Gamma$ is the power flowing through that same surface, if there was no reflection. This is illustrated in figure 1.

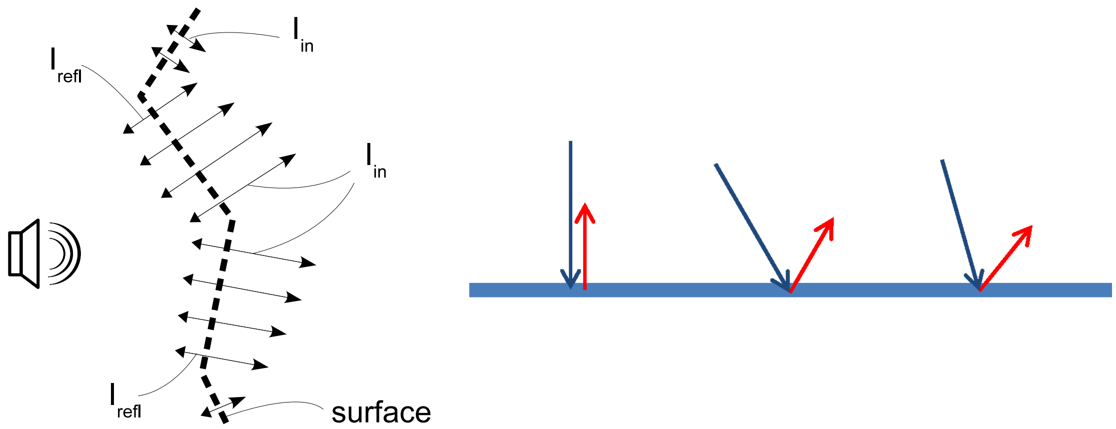

Figure 1. The incident and reflected intensity, shown as vectors (left) and an illustration of the LPW (left), LSPW (middle) and LAPW method (right).

The active intensity, given in equation 1, can easily be measured with an intensity probe for any in situ sound field. Spatial integration (or time integration assuming a constant scanning speed) of the active intensity then results in the active power W_{ac}, see [7].

The incident intensity, however, can not be measured directly as the total sound field is comprised of both the incident as well as the reflected pressure waves. To derive the incident intensity from a measurement of the total sound field, all existing methods rely on assumed, a priori, knowledge of the global incident and reflected sound fields. If, indeed, one knows that the incident- and reflected sound field consist of plane waves only (as in an impedance tube), one can derive expressions for the absorption coefficient based microphone signals obtained at different positions within the field. If this knowledge is however not available or we want to know the absorption coefficient for the in situ sound field, we can still approximate the incident intensity, as we propose, assuming that the pressure measured at a specific point near the absorbing surface (so locally!) is the result of 2 plane waves; one plane wave of a (to be determined) amplitude, impinging on the absorbing surface at a (to be determined) angle of incidence (polar and azimuthal) and one plane wave of a (to be determined) amplitude, reflecting from the absorbing surface at a (to be determined) angle of reflection (polar and azimuthal). Note that all these unknowns may vary with location and thus do not require a known global sound field. By means of a measurement of a number of pressures near the reflecting surface, it is thus possible to determine the incident and the reflected field from measurement of the total sound field. As we will explain, an entire series of methods can be derived from this local plane wave assumption by making additional assumptions.

Starting with the most simple version, but also the most inaccurate version, (as this was the first method we derived, we refer to it as the local plane wave method (LPW)) we assume that the angle of incidence and reflection is zero, see figure 1. The total sound field at a certain location in front of the absorber is thus described by a normal plane wave impinging on the surface and a normal plane wave emitting from the surface. Note that this does not imply that the waves need to imping normal to the surface, it only means that we describe it using only these two waves. Then, only two unknown (complex) amplitudes (amplitude A for the incidence wave and amplitude B for the reflected wave) need to be determined. This only requires the measurement of 2 pressures at two different locations (the distance from the measurement surface need to be different) or a pressure and a particle velocity close to the absorbing surface. The amplitudes are thus calculated similarly as in the 2-pressure method in a regular impedance tube.

A second method, called the local specular plane wave method (LSPW), is also shown in figure 1. Here we assume that the incident wave is specularly reflected, i.e. the angle of reflection equals the angle of incidence. Then, the unknowns to be solved are the complex amplitudes of the incident and reflected wave (A and B), the polar angle (θ, the angle of incidence) and the azimuthal angle ϕ. These 2 additional angles require the measurement of at least 1 additional complex pressure, thus requiring 3 pressure probes close to the absorbing surface. For most materials/sound fields this method is sufficiently accurate.

The most general method is the local arbitrary plane wave method (LAPW), see figure 1. Here the polar and azimuthal angle of the incident plane wave can be different from the angles of the reflected wave and at least 4 complex pressures need to be measured to set up a system of equations to solve all unknowns; a method which is needed for non-locally reacting materials.

Additional accuracy may be obtained if more measurement probes are used. The various unknowns in the LPW, LSPW and LAPW can then be calculated using a least squares approach. We use 8 MEMS microphones in a cubic configuration to achieve the high accuracy and robustness.

2.1 LPW

To illustrate the concept, we will start with the explanation of the LPW-method. Restricting ourselves to the frequency domain, the assumption of a local plane wave indicates that the complex pressure amplitude, in the vicinity of the absorbing surface, can be described by:

$$P = Ae^{-ikx} + Be^{ikx}, \tag{2}$$

where A is the complex amplitude of the incident wave, B the complex amplitude of the reflected wave, k denotes the wavenumber and x is a local spatial coordinate, aligned with the normal direction of the surface, pointing into the absorbing surface. Setting the origin $x = 0$ at the position of a first measuring microphone, the position of the second microphone at $x = s$, the pressure at both microphone positions is thus:

$$P_1 = A + B \tag{3}$$

$$P_2 = Ae^{-iks} + Be^{iks}, \tag{4}$$

where P_m denotes the pressure at microphone m. This results in:

$$A = \frac{P_1 e^{iks} - P_2}{2sinh(iks)} \tag{5}$$

$$B = \frac{-P_1 e^{-iks} + P_2}{2sinh(iks)} \tag{6}$$

The intensity (into the absorbing surface) associated with the incident wave is then $I_{in} = A\bar{A}/(2\rho c)$, where ρ is the density and c the speed of sound. Integrating the incident intensity over the measured surface then yields the incident power and the absorption coefficient follows from equation 1.

2.2 LSPW

In the LSPW method we assume that the angle of reflection equals the angle of incidence. From a larger than strictly necessary number of microphones, we can obtain the amplitudes of the incident and reflected wave and the angle of incidence (polar and azimuthal) by solving a least squares problem (solving the so-called normal equations). Assuming the xy-plane to be parallel to the absorbing surface and the z coordinate to be aligned with the outward normal of the absorbing surface, the pressure at a microphone m with location (x_m, y_m, z_m) is described by:

$$P_m = Ae^{-iks_{i_m}} + Be^{-iks_{r_m}}, \tag{7}$$

where

$$s_{i_m}(\phi,\theta) = -ik(x_m cos(\phi)sin(\theta) + y_m sin(\phi)sin(\theta) - z_m cos(\theta)) \text{ and} \tag{8}$$

$$s_{r_m}(\phi,\theta) = -ik(x_m cos(\phi)sin(\theta) + y_m sin(\phi)sin(\theta) + z_m cos(\theta)). \tag{9}$$

The following non-linear set of equations should thus be solved in a least squares sense:

$$\begin{bmatrix} e^{-iks_{i_1}(\phi,\theta)} & e^{-iks_{r_1}(\phi,\theta)} \\ e^{-iks_{i_2}(\phi,\theta)} & e^{-iks_{r_2}(\phi,\theta)} \\ \vdots & \vdots \\ e^{-iks_{i_M}(\phi,\theta)} & e^{-iks_{r_M}(\phi,\theta)} \end{bmatrix} \begin{Bmatrix} A \\ B \end{Bmatrix} = \begin{Bmatrix} P_1 \\ P_2 \\ \vdots \\ P_M \end{Bmatrix}, \tag{10}$$

if M pressure signals are available. The system is non-linear in ϕ and θ but can quite easily be numerically solved, using the normal equations by solving A and B for a number of desired values of ϕ and θ and taking the solution with the lowest residual norm.

For the measurement of the active intensity and additional information of the method (given the method in terms of auto and cross spectra, etc), the reader is refered to [3, 4, 5].

3. Examples

3.1 Numerical example: Louvre door

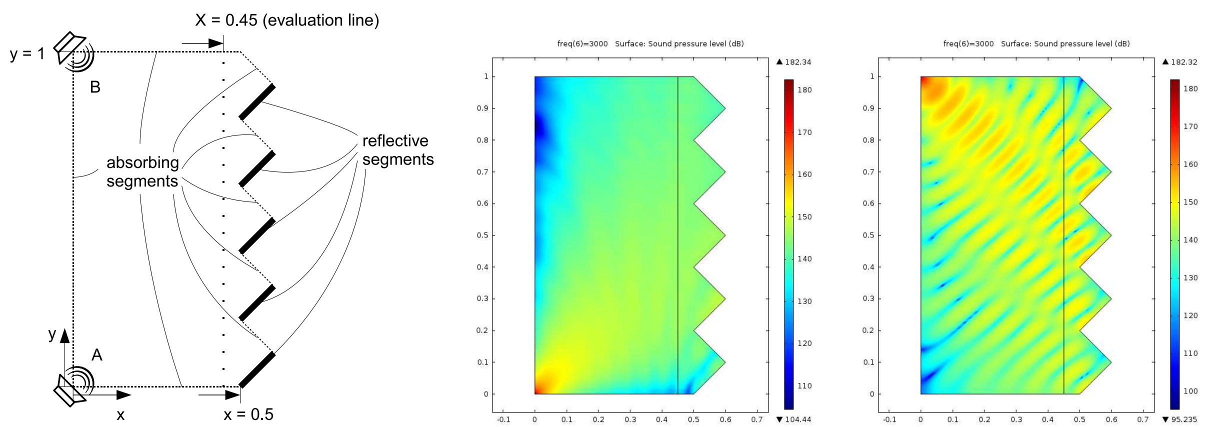

Figure 2. The Louvre door (left) and pressure field at 3000 Hz, due to a source in A (middle) and B (right)

The next example, a Louvre door, is based on the geometry as given in [2]. The definition of the absorption coefficient was however different in that publication. We adopt the same geometry here, as it is very illustrative to show the dependency of the actual sound field (the position of the sound source) on the absorption coefficient. The geometry is given in figure 2. The geometry contains reflective surfaces and absorbing surfaces which mimic the openings in the Louvre door. At the latter surfaces, for convenience, the impedance is assumed to equal the plane wave impedance ρc but any other value could have been used. We simulate the sound field, using finite elements (a Comsol model was used), for 2 positions of a point source. In one calculation, we position the source in A, (the left bottom corner of figure 2). In the other calculation, we assume a source in position B.

It can be seen from figure 2 that reflection is induced by the reflective segments only if the source is in B. In that case, one can observe nodes and antinodes, indicating the interference of the incident and reflected wave. Indeed, one may expect reflection if the normal vector of that reflective surface points in the direction of the source. If the source is in A, as shown in the middle figure, the acoustic wave mainly 'sees' the absorbing segments and the wave is largely absorbed.

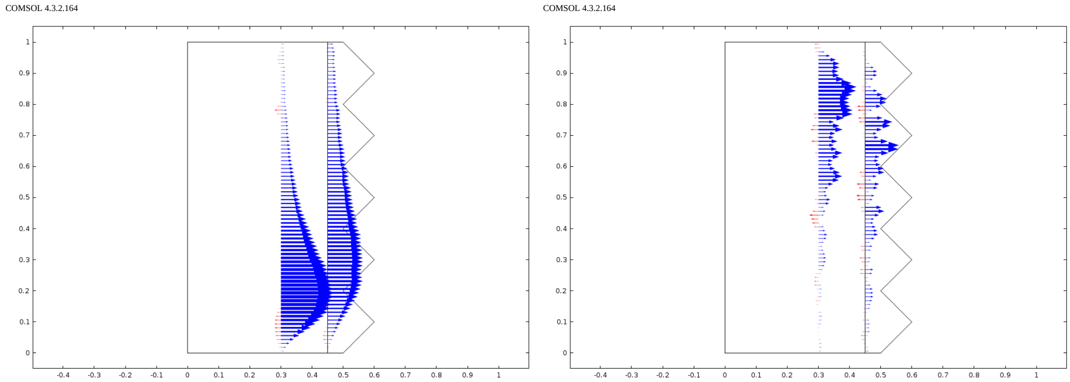

Figure 3. The incident (blue) and reflected intensity (red) at 3000 Hz, due to a source in A (left) and B (right)

This behaviour also follows from the calculated incident and reflected intensity ($I_{refl} = B\bar{B}/(2\rho c)$), as well as the absorption coefficient obtained using the LPW method. Both intensities, evaluated for the lines at $x = 0.3$ and $x = 0.45$, are shown in figure 3 as vectors for a 3000 Hz sound. (The scaling of both intensities is not exactly the same. The relative difference in magnitude between the incident intensity (shown in blue) and reflected intensity (shown in red) is thus not exact.) One can however clearly see that if the source is positioned in A, the incident intensity is a smooth function. The reflected intensity is small and only near $y = 0.05$, one can see some reflected intensity, induced by the reflective segment near $x = 0.55$ and $y = 0.05$. If the source is in B, one can see various positions where the reflected intensity is large. Also the incident intensity is clearly seen to vary along the coordinate. This is also what one would expect; there are various openings through which the incident intensity flows.

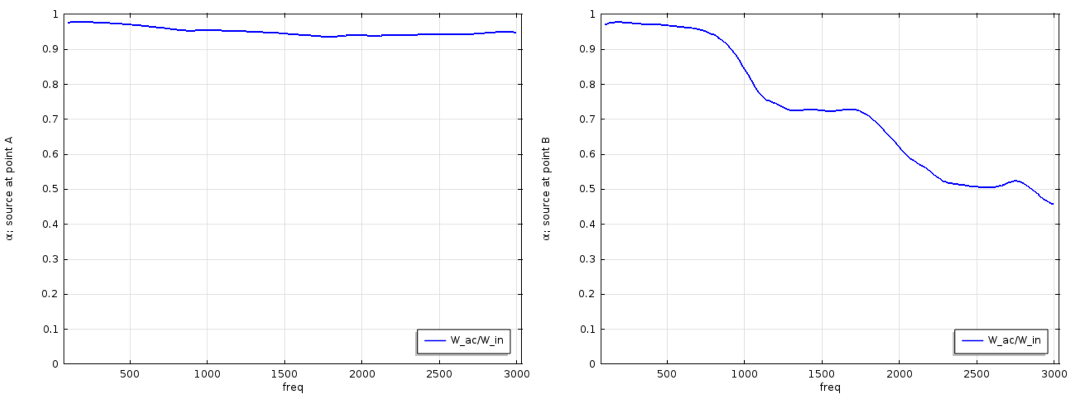

Figure 4. The absorption coefficient due to a source in A (left) and B (right)

The calculated absorption coefficient, as a function of frequency, is shown in figure 4. The absorption coefficient has been evaluated for the line at $x = 0.45$ (just in front of the sample). Indeed, the absorption coefficient of the Louvre door when the source is in B, is substantially less than if the source is in A; the absorption coefficient being close to unity in the latter case. This example illustrates the fact that the absorption coefficient is not a property of absorbing material/surfaces alone; it also depends on the actual sound field. For this specific example, the Louvre door is a good absorber if the sound source is in A. It absorbs less sound if the source is in B.

3.2 Numerical example: impedance boundary

Applying the LPW methods for less absorbing materials may erroneously result in higher absorption values than expected, if the scanning area is not large enough or if the distance between the absorbing surface and the scanning area is too large. This is caused by the energy flow parallel to the non-absorbing surface. If this energy flow is not measured, it is not accounted for and higher absorption values are predicted.

This is illustrated by the numerical example shown in figure 5. The figure shows the acoustic pressure and calculated active intensity vectors due to a source in front of a less absorbing surface. If one thus only scans an area which is parallel to the absorbing surface and a couple of centimeters in front of it, the active power in the gap between the scanning area and the absorbing surface is not measured. This error can be circumvented by scanning also this narrow circumferential gap and applying the method proposed also for this area.

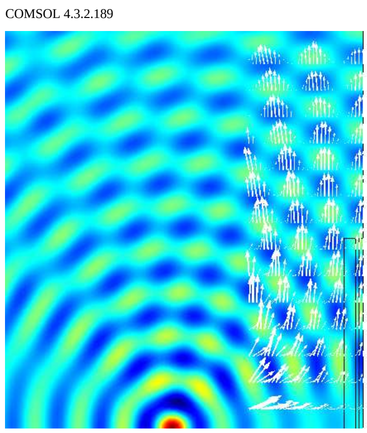

Figure 5. Leaking of energy parallel to the surface of less absorbing surfaces

3.3 Engineering example: car seat

As we only make use of a local plane wave assumption, the LPW methods also allows us to measure a local absorption coefficient, i.e. the ratio of intensities $\mathbf{I_{ac}} \cdot \mathbf{n}/I_{in}$. An example of such a measurement is shown in figure 6.

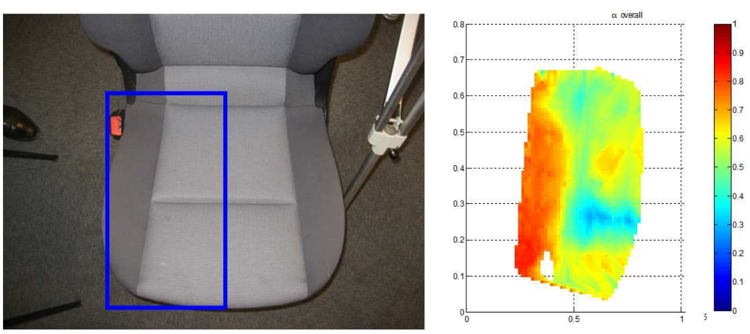

Figure 6. Application of the LPW method; the in situ measurement of the local absorption coefficient

The area of the car seat within the blue line (shown in the left picture), was scanned using an intensity probe. The sound source was a loudspeaker, positioned above the car seat. The position was tracked using a tracking system. Hence, at each time instance, the position of the intensity probe and associated active intensity was known. Based on the LPW method also the incident intensity was derived and the local absorption coefficient, shown in figure 6 on the right, could thus be calculated. Note that the values shown are the overall absorption values for frequencies between 100 and 4000 Hz. From the results, it is clear that the stitching of the car seat, significantly reduces the absorption coefficient.

3.4 Engineering example: Noise barriers

The LPW method was succesfully used in a recent study by Sulzer Pumps, Mechatronik, Experimentelle Dynamik und Akustik, Winthherthur, Switzerland, see [6]. Sulzer was able to measure the absorption coefficient of noise barriers, consisting of large stones framed by steel wires, see figure 7. As an illustration, the figure also shows the measured absorption coefficient. In this study, a loudspeaker was used, but, as the method does not rely on the sound source, also the noise of the cars driving by could have been used as sound source.

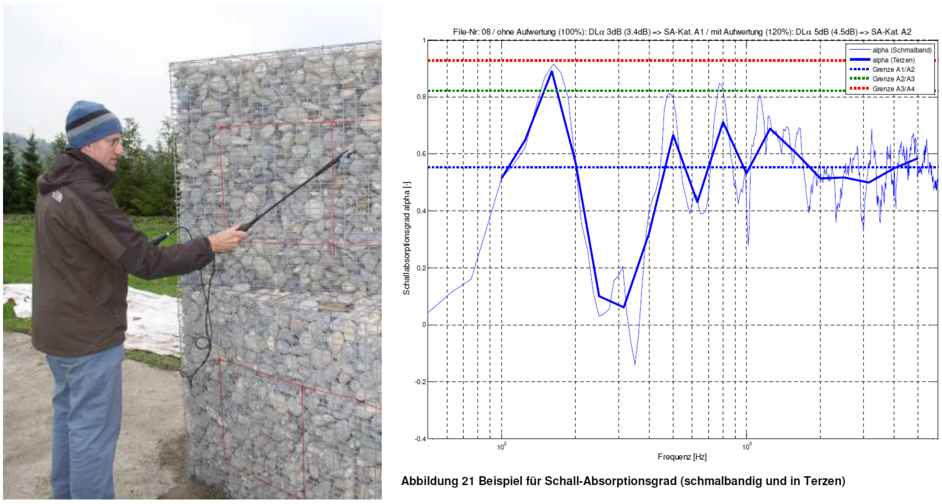

Figure 7. Application of the LPW method; one can easily measure the absorption coefficient of noise barriers by simple scanning the surface. Taken from [6]

4. Conclusion

In this paper, we discuss the so-called local plane wave methods (LPW, LSPW and LAPW). These methods allow one to measure the absorption coefficient of a surface for any sound field impinging on that surface. The method, as opposed to other methods, does not rely on, depend upon or require any prior knowledge of the global sound field. Hence it makes it very suitable for in situ applications. In its most general and accurate form, at least 4 microphones are required to measure acoustic pressures close to the absorbing surface. Based on these pressures, the unknown amplitudes of the incident and reflected wave, the a-priori unknown polar and azimuthal angle of the incident wave and the unknown polar and azimuthal angle of the reflected wave can be determined. Additional assumptions may aleviate the requirement to use 4 microphones. In its simplest form only two microphones are needed and hence an intensity probe suffices. On the other hand, using more microphones and solving a least squares problem, the measurement accuracy can be increased and the expense of additional postprocessing.

5. Acknowledgement

The permission from Sulzer to use the photo and measurement graph in figure 7 is gratefully acknowledged.

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