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Measurement of Absorption Coefficient, Radiated and Absorbed Intensity on the Panels of a Vehicle Cabin using a Dual Layer Array with Integrated Position Measurement*

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In some cases it is important to be able to measure not only the total sound intensity on a panel surface in a vehicle cabin, but also the components of that intensity due to sound radiation and due to absorption from the incident field. For example, these intensity components may be needed for calibration of energy flow models of the cabin noise. A robust method based on surface absorption coefficient measurement is presented in his paper.

Key Words: **NVH, Holography, Absorption (12. Vibration, Noise, Air Conditioning)**

1. INTRODUCTION

Consider the radiation of sound from a small surface segment in a cabin environment. Such a surface segment may radiate sound energy because of external forcing, causing the surface to vibrate, and it may absorb energy from an incident sound field because of finite surface acoustic impedance. When measuring the sound intensity over the surface segment with an intensity probe, the total intensity I_{tot} will be measured. Assuming the radiated field and the incident field to be mutually incoherent, the total intensity is equal to the sum of the radiated sound intensity I_{rad} that would exist with no incident field and the sound intensity component I_{abs} due to absorption from the incident field:

$$I_{tot} = I_{rad} + I_{abs} \tag{1}$$

Considering the intensity in the outward normal direction on the panel surface, the radiated intensity will typically be positive, while the component due to absorption will typically be negative. So for vibrating panels with an absorptive surface, the total measured intensity may be small although the radiated intensity is relatively high. Often it is of interest to know not only the total intensity, but also the components due to radiation and absorption. For example, this kind of information is needed in energy based modeling that describes the energy flow between sub-systems, [1].

The method is based on separation of different sound field components via the spatial sound field information provided by an array. The radiated intensity is estimated as the intensity that would exist, if the incident and scatted field components could be taken away. So a free-field radiation condition is simulated. The idea is to first separate the incident field component, then use separately measured information about the scattering properties of the panel to calculate the scattered field, and finally subtract the incident and scattered fields from the total sound field. The method needs the panel geometry, which is either imported as CAD or measured with a 3D digitizer and then uses a measured map of absorption coefficient. The separate measurement of the surface absorption coefficient is taken with loudspeaker excitation.

2. DESCRIPTION OF METHODOLOGY

The array measurements considered here are cross-spectral measurements of the full cross spectral matrix between all array microphones, and then derive a Principal Component sound field representation based on that [2]. As a consequence no phase information is available between different array positions, so a separate patch holography calculation has to be performed for each position. We used a Double Layer Array (DLA), and the processing was performed using Statistically Optimized NAH (SONAH), [3-4]. In the following we will consider only a single Principal Component, i.e. a spatially coherent sound field with coherent sources. We shall use a complex time harmonic representation with the time variation $e^{j\omega t}$ suppressed.

2.1. Extraction of the Incident Field

A basic array processing task is that of extracting the incident sound field from the total sound field. Considering the sound field on a small panel segment in a cabin, the distinction between the incident field and the radiated field is, however, not obvious, even when we look at the field very near the panel segment. Because of coherent vibration components and significant mutual radiation impedances between neighboring panel segments, some neighboring segments should be included as sources of the radiated field. Figure 1 illustrates how this distinction can be made in practice with a DLA. Using SONAH holography on a DLA measurement, the sound field components $(p^-,\mathbf{u}^-)$ and $(p^+,\mathbf{u}^+)$ with sources on different sides of the array plane can be separated, [3,4]:

$$(p_{total}, \mathbf{u}_{total}) = (p^-, \mathbf{u}^-) + (p^+, \mathbf{u}^+) \tag{2}$$

The array must then be used in such a way that the pressure p^- and the velocity vector $\mathbf{u}^-$ represent the field incident on the source area of interest, while the outward propagating field component $(p^+,\mathbf{u}^+)$ is the sum of the scattered and radiated fields:

$$(p^+, \mathbf{u}^+) = (p_{sct}, \mathbf{u}_{sct}) + (p_{rad}, \mathbf{u}_{rad}) \tag{3}$$

Figure 1a illustrates the case of an isolated source object, where the incident and outward propagating field components are well defined. They could be determined for example based

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on measurements across two concentric spherical surfaces that enclose the test object. Figure 1b illustrates the case of measurement with a DLA on a panel section in a cabin. Here, the measurement plane will define the distinction between sources of the incident field and sources of the outward propagating field. The distinction will, however, not be sharp due to the limited angular resolution of a practical array.

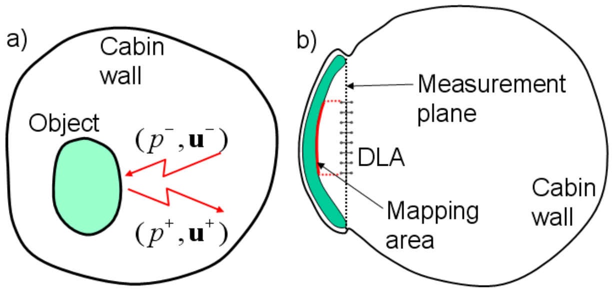

Figure 1: Separation of inward (incident) and outward propagating field components (p^-,$\mathbf{u}^-$) and (p^+,$\mathbf{u}^+$): a) Clearly separated sources. b) Smooth transition between sources.

2.2. Solution of the Scattering Problem

Provided the incident and radiated fields are mutually incoherent, then Eq. (1) is the basis for a simple and robust energy based method. The basic assumption is that we can measure a local absorption coefficient α at each point $\mathbf{r}$ on the source surface such that that the normal components I^- and I_{abs} of the incident and absorbed intensities are related by:

$$I_{abs}(\mathbf{r}) = \alpha(\mathbf{r})\, I^-(\mathbf{r}) \qquad (4)$$

In general the ratio $I_{abs}(\mathbf{r})/I^-(\mathbf{r})$ between the two intensities will depend on the form of the incident field. If, however, the coefficient $\alpha(\mathbf{r})$ is measured with an incident field that is sufficiently similar with the incident field under operational conditions, then Eq. (4) can provide good results with the operational field.

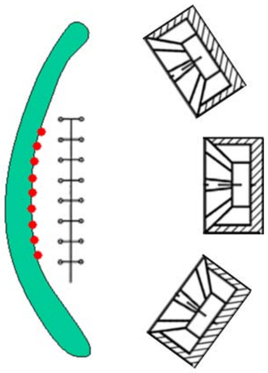

Figure 2: Cabin panel section with surface calculation points covered by a specific array position. Speakers for measurement of surface properties are shown.

The method requires a separate set of DLA measurements with artificial speaker excitation. Figure 2 illustrates a set-up with a set of incoherently excited speakers to create an incident field similar to the field incident under for example flight conditions in an aircraft. As mentioned already, the DLA/SONAH measurement can provide the total and incident components of the loudspeaker-generated sound field on the panel surface. Since in this case the absorbed intensity is equal to the total intensity, then in accordance with Eq. (4) the absorption coefficient is calculated as the ratio between the total and the incident intensities. Accurate measurement of the array positions relative to the panel geometry using an integrated position measurement system allows the admittances and absorption coefficients to be calculated at pre-defined points on the panel surface, see Figure 2.

For the case of car cabin application, the surface property measurement will typically be performed with the car not driving, while the operational measurement will be performed during driving. Often, a single surface property measurement will be applied with several operational measurements, corresponding to different operational conditions.

Once an operational measurement has been taken, the associated total, incident and outgoing field components on the panel surface can be estimated using SONAH. The absorbed intensity is estimated using Eq. (4), and the radiated intensity is then obtained using Eq. (1).

3. MEASUREMENT

3.1. Measurement System

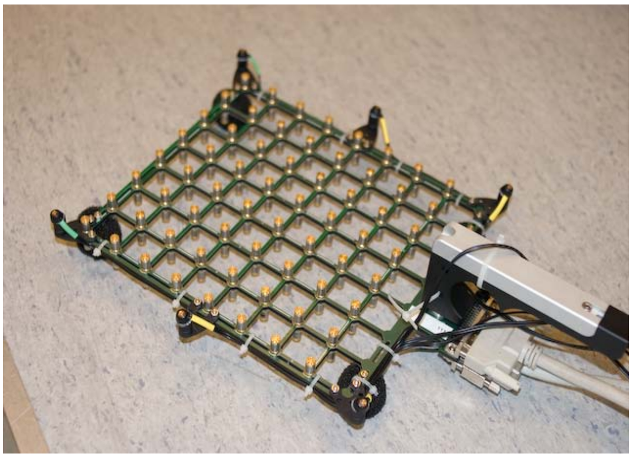

Figure 3: Double-layer array (DLA) mounted with six IR LEDs.

The system for data acquisition is based around the DLA shown in Figure 3. The array has 8x8 microphones mounted in 2 layers, resulting in a total of 128 microphones. The microphones are spaced 30 mm apart in both directions and with a spacing of 31 mm between the two layers. This results in an upper frequency limit for the array of 5.7 kHz (spatial sampling limit). Also mounted on the array are six infrared LEDs which are used in connection with a position measurement system monitoring the array position and orientation on-line. This system is based around the integrated camera unit. The camera unit has 3 built-in line cameras that determine the LED positions. The camera unit is connected to a controller box which again communicates with a PC via RS-232. The LEDs on the array are also connected to this controller box. The position measurement system also has associated with it a wireless pointing device for measuring 3D point positions. This device can be used in connection with the measurement software to record 3D position data on the surfaces under investigation.

The DLA is connected to two 65 channel frontends which are again connected to the controlling PC via LAN. A third frontend with generator units is used for driving artificial excitation speakers through power amplifiers.

3.2. Measurement Procedure

The DLA is placed in positions close to the surfaces under investigation to sample the near field sound pressure. The position of the array is recorded online via the position measurement system and microphone time histories are recorded for each array position. The array is placed in slightly overlapping positions to cover the investigated surfaces patch by patch. The data acquisition software displays the position of current and past array positions in 3D along with the surface model. In this way the user can identify which parts of the surface have been covered with the array and which parts still need to be covered.

When measuring for the estimation of surface absorption, a number of loudspeakers are distributed in the cabin interior and driven by uncorrelated noise sources, to create a distributed and (close-to) diffuse excitation field. Measurement for the actual estimation of entering intensity is of course performed in operating conditions with these sources turned off. All recorded data are stored to a database.

3.3. Data Processing

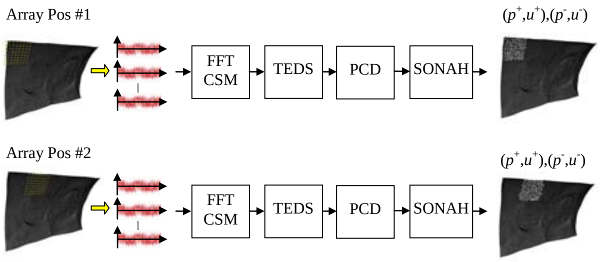

Figure 4. Processing steps for each array position.

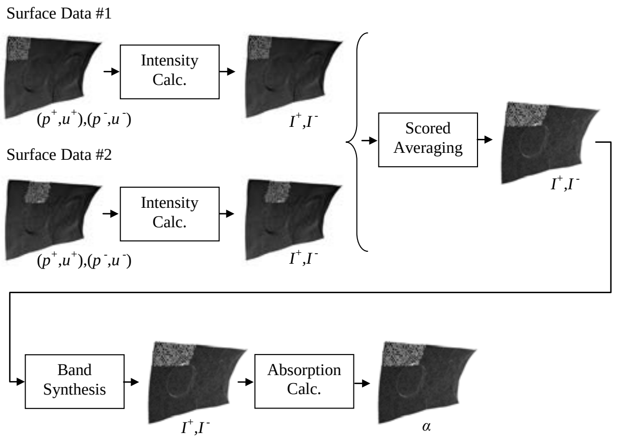

Figure 5: Processing for absorption coefficient estimation.

The post-processing software application retrieves all data from the database. A surface mesh is created based on the parametric surface description. A number of mesh areas may be defined in this process. These can be used for averaging of e.g. absorption coefficient.

The time histories measured in each array position are processed as shown in Figure 4. First the full cross spectral matrix for all signals is calculated by FFT and the frequency responses corrected with response correction data from the individual microphones (TEDS). Then a principal component decomposition (PCD) is performed to determine the most significant incoherent components. Each component is finally processed via SONAH to determine the corresponding incoming and outgoing sound field quantities on the source surface.

Provided From this point on, the processing depends on the quantity to be determined. The case of absorption coefficient estimation is illustrated in Figure 5. Based on the partial sound field quantities, the total incoming and outgoing surface intensity components are calculated for surface points corresponding to each array patch. Results from different patches are then averaged on the surface mesh using a scoring method. Each mesh node- to-array position combination is assigned a score depending on how the node is positioned relative to the array. If more than one array contributes to a node, the results for that node are averaged using the scores. In this way, a contribution estimated with a “well-positioned” array will be given more weight in the averaging. The surface intensity values are then band-synthesized into e.g. 1/3 octave bands and optionally averaged over pre-defined averaging areas. Finally, the absorption coefficient is estimated in each node using eq. 4.

3.4. Mapping of Absorption Coefficient in a Car Cabin

To illustrate the use of the proposed techniques in an automotive application, measurements were made with the DLA system in the cabin of a Volvo S60 passenger car to determine the in-situ absorption coefficient of selected surfaces in the cabin. Firstly, the cabin surfaces to be investigated were digitized using the 3D position measurement system and dedicated digitizing software. Next, array measurements were made with the DLA covering the surfaces patch by patch. Four loudspeakers were distributed in the cabin and driven by white noise to provide the acoustic excitation needed for the estimation of the absorption coefficient

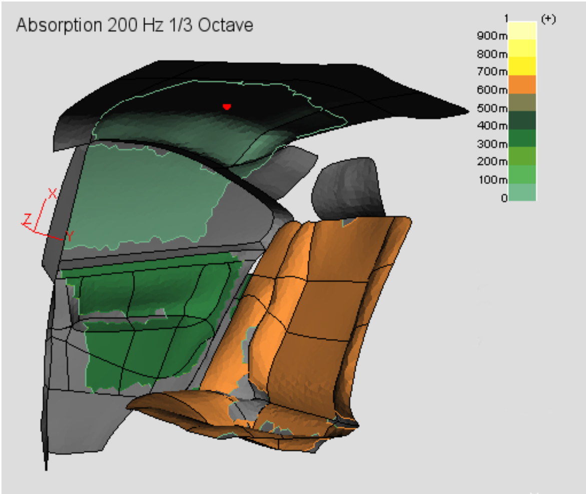

Figure 6: A contour plot of the estimated absorption coefficient of seat, door, window and roof in a car cabin. Results are shown for the 200 Hz 1/3-octave band. Note that results are averaged also over the respective areas.

Figure 6 shows a 3D contour plot of the estimated absorption coefficient on the cabin surfaces for the 200 Hz 1/3 octave band. The absorption coefficient was estimated by first doing 1/3 octave band synthesizing of the estimated total and incident intensities estimated locally on the surfaces and then doing area averaging of these quantities over e.g. the seat or window surface before estimating the final absorption coefficient as the ratio between the two. The figure shows how in this frequency band the seat has quite a high absorption coefficient compared to the door, window and roof.

Figure 7 shows the estimated average absorption coefficients in 1/3 octave bands for the roof (A), the seat (B) and the window (C). The roof was covered by a thin layer of foam material which could be expected to have an absorption coefficient increasing with frequency as the graph shows. The seat shows an absorption coefficient decreasing with frequency, which could be explained by the seat material being a leather type of material which is probably acoustically “hard” at higher frequencies. Finally, the window shows quite a low absorption coefficient throughout the whole frequency range under investigation, as could be expected.

4. CONCLUSION

A method for measuring the absorption coefficient, radiated and absorbed intensity on the panels of a vehicle cabin has been described and it was shown how the method can be used to map e.g. the absorption coefficient on the interior surfaces of a car cabin. The method is based on a Dual Layer Array with integrated position measurement. The method has shown good ability to determine the actual radiated sound intensity in the presence of a diffuse field in the cabin.

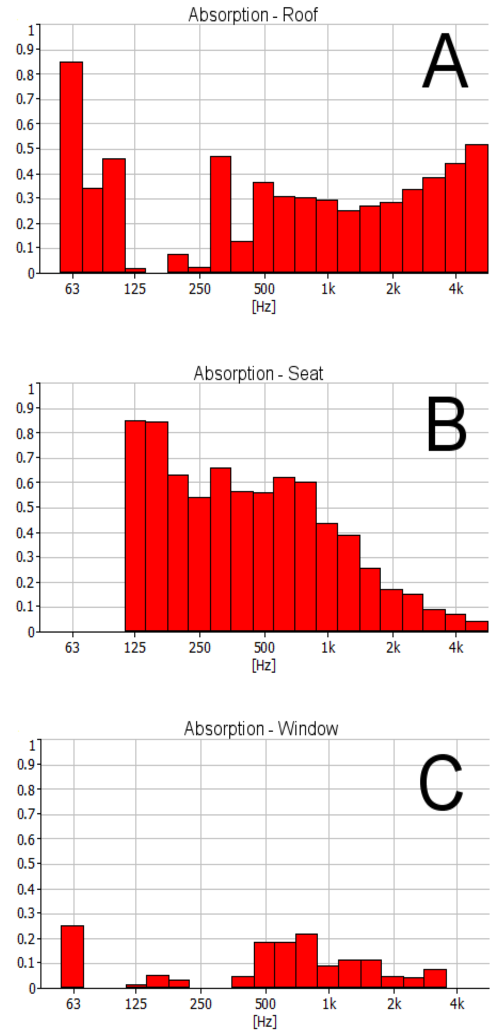

Figure 7: Estimated absorption coefficient on the roof, seat and window of the car cabin as functions of frequency. Results are shown in 1/3 octave bands

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