

Panel Contribution Analysis in a Vehicle Cabin using a Dual Layer Handheld Array with Integrated Position Measurement

Jørgen Hald and Jakob Mørkholt

Brüel & Kjær Sound & Vibration Measurement A/S

Copyright © 2009 SAE International

ABSTRACT

The paper describes an array-based method for measurement of panel contributions in a cabin. Both the FRF measurements and the operational measurements are taken with a dual layer microphone array, and the required sound field data on a panel surface mesh are calculated using the SONAH patch holography algorithm. Multiple array positions can be measured to cover the needed mesh area, and area-integration of contributions is then performed on the surface mesh. Measurement or alignment of surface mesh geometry and measurement of array positions is performed using an integrated 3D position measurement system. After a theoretical description the method is evaluated through simulated and actual measurements.

INTRODUCTION

We shall consider the problem of estimating in a cabin environment, typically in a car cabin, the sound pressure contribution at a listening position from a section of the inner surface. Sound will enter the cabin as radiation from vibrating panels and from external noise that leaks into the cabin through small gaps and imperfect seals. Contributions from specific sections of the inner cabin surface are at the moment typically estimated by one of the following three methods, see for example reference [1]:

1. Masking: Materials that prevent noise radiation (typically lead) are mounted on all other surfaces, so that only the desired contribution will be present in the cabin.
2. Air-borne Source Quantification (ASQ): The contributions from each one of a set of surface/panel

segments are estimated as the product of the operational panel vibration velocity, u_i , and the corresponding Frequency Response Function (FRF), H_i , from panel velocity to pressure at the listening position. H_i are measured reciprocally from a Volume Velocity Source (VVS) at the listening position to a set of microphones mounted on the panel segments, and u_i are obtained from a set of measured indicator pressures by the solution of an inverse problem. The inverse problem involves the measurement of the FRF from each indicator to every panel segment.

3. Traditional Panel Contribution Analysis (TPCA): The principle of this technique is very similar to that of ASQ, the only fundamental difference being the method for measurement of the operational panel velocities u_i . In TPCA these velocities are measured directly, typically by mounting an accelerometer on each panel segment. Alternatively, a laser vibrometer can be used.

The main disadvantage of the Masking technique is the enormous work associated with covering all inner surfaces except the section of interest. But the masking material will of course also modify the acoustical environment, and to some extent the panel vibration.

For the ASQ method, a main disadvantage is the huge number of FRF's that need to be measured between indicators and panel segments. The inverse approach requires that all surfaces contributing to the noise at the indicators are included in the investigation. Basically this will require that the full inner cabin surface is included. So the method is not suited for a quick investigation of the contribution from one or a few small surface segments. Also, microphones need to be mounted on

the panel surface segments for measurement of all the FRF's, and then at the indicator positions for the operational pressure measurements.

The TPCA method avoids the inverse solution for the panel vibration data. It is therefore suited for analysis of the contributions from only small parts of the inner surfaces. But because vibration is measured directly, airborne leaks cannot be handled, and it requires the mounting of a lot of transducers on the panels: Microphones for FRF measurements and accelerometers for operational velocity measurements. Many surfaces in for example a car cabin are not so suited for mounting of accelerometers, and in some cases the mass loading will significantly influence the measurement. Also, segments may be required to be very small in order that their velocities can be represented by the accelerometer measurements. For the FRF measurements, the integration surface is implicitly assumed to be rigid, see section 2 below.

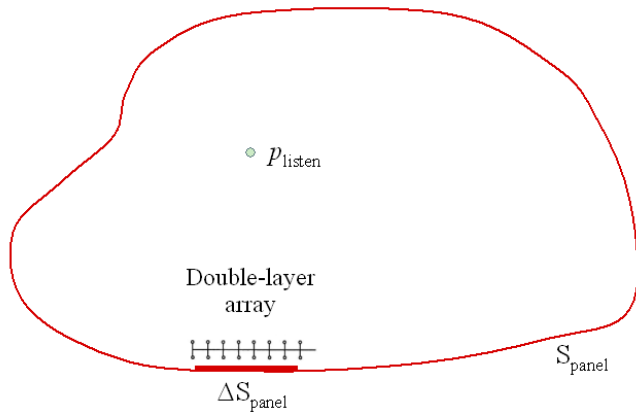


Figure 1. Illustration for Array-based Panel Contribution Analysis

THE PROPOSED ARRAY-BASED METHOD

The principle of the proposed Array-based Panel Contribution Analysis (APCA) is illustrated in Figure 1: We seek the contribution to the sound pressure p_{listen} at a position in a cabin from a section ΔS_{panel} of the inner cabin surface. The basic principle is very similar to ASQ, but it is based on two measurements with the shown double-layer microphone array taken at a small distance from the panel section:

- The operational pressures are measured similar to the indicators in ASQ. But instead of solving an inverse problem based on measured FRF's to obtain the surface velocity, we use the SONAH patch holography algorithm, [2-3], to estimate the same data on or very near the panel surface.
- To get the FRF's, a VVS is positioned at the listening position, and a recording is taken with the array at the same position as for the operational measurement. The SONAH algorithm is then used to extrapolate the FRF's from the array position to the operational data positions on the panel surface.

The method is well suited for measuring only parts of the inner surface, it involves no mounting of transducers on the panels, and the measured data provides automatically the possibility of mapping for example FRF's and operational sound intensity on/near the panels. Since the operational surface velocity is derived from acoustic measurements, both panel radiation and acoustic leaks will be included.

A first description of the method was given in reference [4]. The present paper adds some theory on the properties of the method when used on panels with extended reaction. And most important, the method is improved by doing the area integrations of contributions across a source surface mesh instead of on rectangular planar patches of the same size as the array. Finally, the method is explored much further through simulated and real measurements.

THEORY OF ARRAY-BASED PANEL CONTRIBUTION MEASUREMENT

Figure 2 illustrates the type of geometry that we shall consider in the following. The interior of a cabin is bounded by the panel surface S_{panel} , and inside the cabin is a Head And Torso Simulator (HATS) with surface S_{HATS} . The vibrating panels, and possible acoustic leaks through the panels, generate a sound pressure p_{ear} on the blocked opening S_{ear} of the left ear of the HATS. We seek a mathematical formula for the contribution Δp_{ear} to the ear pressure p_{ear} from a section ΔS_{panel} of the panel surface S_{panel} .

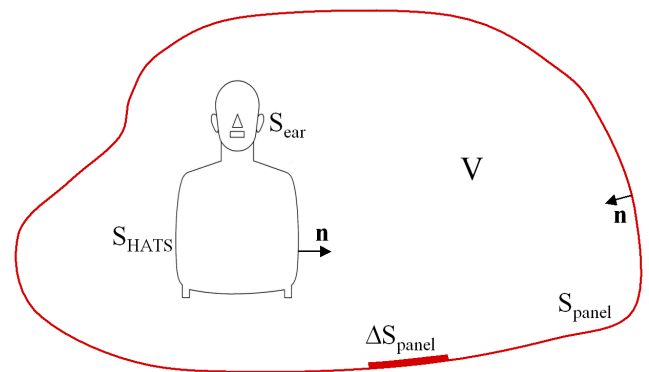


Figure 2. Illustration of geometry for the contribution formula.

We define the surface S as the combination of S_{panel} and S_{HATS} . Thus, the volume V bounded by S is the source free and homogeneous interior of the cabin. Also, the surfaces S_{ear} and S_{HATS} are defined in such a way that S_{ear} is part of S_{HATS} :

$$S \equiv S_{panel} \cup S_{HATS}, \quad S_{ear} \subset S_{HATS} \quad (1)$$

The volume V containing the listening position must be source free, but actually both the density ρ of the medium and the propagation speed of sound c are allowed to depend on position in V . If $(p_1, \mathbf{u}_1)$ and $(p_2, \mathbf{u}_2)$ are the sound pressure and the particle velocity vector of two arbitrary sound fields in V , then according to reference [5] the following reciprocity relation will hold:

$$\iint_S \mathbf{u}_2 \cdot \mathbf{n} p_1 dS = \iint_S \mathbf{u}_1 \cdot \mathbf{n} p_2 dS \quad (2)$$

where $\mathbf{n}$ is a surface normal vector pointing into the volume V . The two sound fields must have the same medium inside the volume V , but outside V the conditions can be completely different.

We let $(p_1, \mathbf{u}_1)$ be the operational sound field $(p, \mathbf{u})$ with sources outside S_{panel} . For this sound field, the surface S_{ear} is blocked (rigid) and we seek the pressure p_{ear} on the blocked surface. Further, we let $(p_2, \mathbf{u}_2)$ be the sound field $(p_Q, \mathbf{u}_Q)$ created by a source inside the ear canal with the ear canal open. The Volume Velocity Q through S_{ear} must in this case be known (measured). We now split up the integral on the left-hand side of equation (2) in contributions from the partial surfaces ($S_{\text{HATS}} \setminus S_{\text{ear}}$ is the HATS surface except the ear canal):

$$\begin{aligned} \iint_S \mathbf{u}_2 \cdot \mathbf{n} p_1 dS &= \iint_S \mathbf{u}_Q \cdot \mathbf{n} p dS \\ &= \iint_{S_{\text{panel}}} \mathbf{u}_Q \cdot \mathbf{n} p dS + \iint_{S_{\text{ear}}} \mathbf{u}_Q \cdot \mathbf{n} p dS + \iint_{S_{\text{HATS}} \setminus S_{\text{ear}}} \mathbf{u}_Q \cdot \mathbf{n} p dS \end{aligned} \quad (3)$$

and from the assumption of a rigid HATS surface and an additional assumption of a constant operational sound pressure $p = p_{\text{ear}}$ across the blocked ear canal, S_{ear} , we get:

$$\begin{aligned} \iint_S \mathbf{u}_2 \cdot \mathbf{n} p_1 dS &\approx \iint_{S_{\text{panel}}} \mathbf{u}_Q \cdot \mathbf{n} p dS + p_{\text{ear}} \iint_{S_{\text{ear}}} \mathbf{u}_Q \cdot \mathbf{n} dS \\ &\approx \iint_{S_{\text{panel}}} \mathbf{u}_Q \cdot \mathbf{n} p dS + p_{\text{ear}} Q \end{aligned} \quad (4)$$

For the integral on the right-hand side of (2) we get similarly:

$$\iint_S \mathbf{u}_1 \cdot \mathbf{n} p_2 dS = \iint_S \mathbf{u} \cdot \mathbf{n} p_Q dS \approx \iint_{S_{\text{panel}}} \mathbf{u} \cdot \mathbf{n} p_Q dS \quad (5)$$

because of the rigid HATS surface and because of the fact that the ear canal surface S_{ear} is blocked for the operational sound field: $\mathbf{u} \cdot \mathbf{n} = 0$ on S_{ear} . When we insert equations (4) and (5) in (2) we obtain the following formula for the operational pressure on the blocked ear canal:

$$p_{\text{ear}} Q = \iint_{S_{\text{panel}}} \mathbf{u} \cdot \mathbf{n} p_Q dS - \iint_{S_{\text{panel}}} \mathbf{u}_Q \cdot \mathbf{n} p dS \quad (6)$$

or

$$\begin{aligned} p_{\text{ear}} &= \iint_{S_{\text{panel}}} \left[\mathbf{u} \cdot \mathbf{n} \frac{p_Q}{Q} - \frac{\mathbf{u}_Q \cdot \mathbf{n}}{Q} p \right] dS \\ &= \iint_{S_{\text{panel}}} \left[\frac{p_Q}{Q} u_n - \frac{u_{Q,n}}{Q} p \right] dS \\ &= \iint_{S_{\text{panel}}} [H_{Q,p} u_n - H_{Q,u} p] dS \end{aligned} \quad (7)$$

where u_n and $u_{Q,n}$ are the normal components of $\mathbf{u}$ and $\mathbf{u}_Q$, respectively, and where $H_{Q,p}$ and $H_{Q,u}$ are the two FRF's from volume velocity to pressure and velocity, respectively:

$$H_{Q,p} \equiv \frac{p_Q}{Q} \quad (8)$$

$$H_{Q,u} \equiv \frac{u_{Q,n}}{Q} \quad (9)$$

We will now make use of the fact that the operational measurement and the FRF measurement can have different media outside S . If the boundary S_{panel} is or if it is changed to be almost rigid during the measurement of $H_{Q,p}$ and $H_{Q,u}$, then $u_{Q,n} = 0$ and the following reduced expression is obtained from (7):

$$p_{\text{ear}} = \iint_{S_{\text{panel}}} H_{Q,p} u_n dS \quad (10)$$

which is the formula used in ASQ and TPCA, see section 1. By the use of the full expression (7) instead of (10) we can avoid the requirement for a rigid boundary (panel) during the FRF measurements. The boundary can therefore for example include an impedance surface, the opening of a duct or a virtual boundary not following entirely the true panel surface.

In order to obtain the contribution Δp_{ear} to the ear pressure p_{ear} from a segment ΔS_{panel} of the panel surface S_{panel} we integrate only over that part of the boundary:

$$\Delta p_{\text{ear}} = \iint_{\Delta S_{\text{panel}}} [H_{Q,p} u_n - H_{Q,u} p] dS \quad (11)$$

The subsequent sub-sections will discuss some properties of contributions obtained from equation (11).

Using a Dual Layer Array (DLA) of microphones and a corresponding implementation of SONAH, [2-3], both sound fields p and p_Q can be measured (in turn) at some small distance from the panel surfaces and used for calculation of pressure and velocity data on the panels. The calculated sound field data are then used for the integration in equation (11).

Using a HATS-based VVS in the FRF measurement will provide contributions to the sound pressure in the blocked ear canal, as described above. One could, however, use any other VVS with known volume velocity output to obtain contributions to the operational sound pressure at the blocked opening of that source. As a limiting case, a small monopole point source can be used to provide contributions to the operational pressure at the location of the monopole.

CONTRIBUTIONS FROM LOCALLY REACTING IMPEDANCE SURFACES

Assume that a panel segment, from which we measure the contribution, is a perfect locally reacting impedance surface with (position dependent) impedance Z . Also, assume that without a sound pressure acting on the surface, the panel would have an (position dependent) operational vibration velocity, $u_{S,n}$. Then the particle velocities normal to the surface for the operational and the FRF measurements are given as follows:

$$u_n = u_{S,n} + \frac{p}{Z} \quad \text{and} \quad u_{Q,n} = \frac{p_Q}{Z} \quad \text{on} \quad \Delta S_{\text{panel}} \quad (12)$$

When equation (12) is used in the contribution formula (11) we get:

$$\begin{aligned} \Delta p_{\text{ear}} &= \iint_{\Delta S_{\text{panel}}} [H_{Q,p} u_n - H_{Q,u} p] dS \\ &= \iint_{\Delta S_{\text{panel}}} \left[\frac{p_Q}{Q} (u_{S,n} + \frac{p}{Z}) - \frac{p_Q}{ZQ} p \right] dS \quad (13) \\ &= \iint_{\Delta S_{\text{panel}}} \frac{p_Q}{Q} u_{S,n} dS \end{aligned}$$

So the contribution formula (11) will allocate no contribution to a passive locally reacting impedance surface, i.e. where $u_{S,n} = 0$ in equation (12), no matter how big or small the surface is. Such areas therefore do not need to be measured, and it makes no difference, if we should include a segment of such an area in the integration. In a cabin with a single small actively radiating panel segment (for example an impedance surface with $u_{S,n} \neq 0$) and otherwise passive locally reacting impedance surfaces, the full and correct contribution will be allocated to a small area segment

covering the active panel. The simplified contribution formula (10) would in general predict a contribution from the passive impedance surfaces, and the contribution from an active, locally reacting area (with $u_{S,n} \neq 0$) would have an error that can be associated with the change $u_{S,n} - u_n$ in operational surface velocity due to the operational sound pressure.

In comparison, a masking technique would of course also predict no contribution from the passive impedance surfaces, but it would not in general predict the correct contribution from an active area because the acoustic environment would be modified by the masking.

Often an internal vibration velocity, $u_{S,n}$, will cover several panel segments. To get the total contribution at the listening position from that internal panel vibration, the contributions from all these segments have to be added taking into account mutual phase.

CONTRIBUTIONS FROM NON-LOCALLY REACTING SURFACES

While passive, locally reacting panel surfaces can be partially included without affecting contribution estimation, the same does not hold for passive, non-locally reacting panels.

To investigate the case of non-local reaction, assume that the panel surface velocity is the sum of an unloaded component and a component due to sound pressure loading:

$$\begin{aligned} u_n(\mathbf{r}) &= \iint_{S_{\text{panel}}} G(\mathbf{r}', \mathbf{r}) p(\mathbf{r}') dS' + u_{S,n}(\mathbf{r}) \\ u_{Q,n}(\mathbf{r}) &= \iint_{S_{\text{panel}}} G(\mathbf{r}', \mathbf{r}) p_Q(\mathbf{r}') dS' \end{aligned} \quad (14)$$

where dS' is a surface element at $\mathbf{r}'$. We need to assume reciprocity of the panel reaction:

$$G(\mathbf{r}, \mathbf{r}') = G(\mathbf{r}', \mathbf{r}). \quad (15)$$

If we insert the expressions of Eq. (14) for the panel velocities in the panel contribution equation (11), then we obtain:

$$\begin{aligned} \Delta p_{\text{ear}} &= \iint_{\Delta S_{\text{panel}}} \frac{p_Q(\mathbf{r})}{Q} u_{S,n}(\mathbf{r}) dS \\ &+ \iint_{\Delta S_{\text{panel}}} \iint_{S_{\text{panel}}} \frac{p_Q(\mathbf{r})}{Q} G(\mathbf{r}', \mathbf{r}) p(\mathbf{r}') dS' dS \\ &- \iint_{\Delta S_{\text{panel}}} \iint_{S_{\text{panel}}} \frac{p_Q(\mathbf{r}')}{Q} G(\mathbf{r}', \mathbf{r}) p(\mathbf{r}) dS' dS \end{aligned} \quad (16)$$