Particle velocity based p-u sound probes for car panel noise analysis

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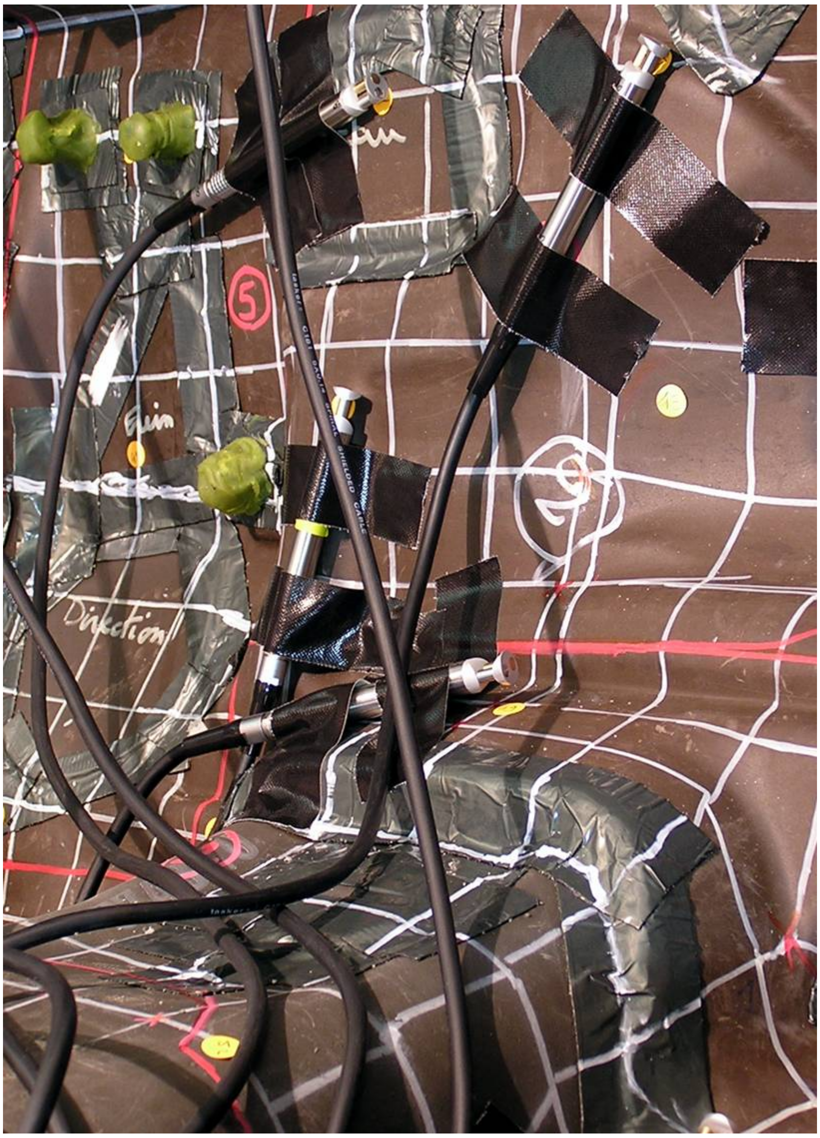

The use of particle velocity based fully integrated p-u sound probes allows the development of new sound power based measurement methods to optimize the acoustical packages for car interiors.

As compared to traditional methods, lead times can be reduced by 60 – 80 %, and the number of man-hours involved as well in a similar amount.

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The new method is broad banded up to 20 kHz, covering the entire range where acoustical packages can improve comfort levels.

Reciprocal measurements can be carried out easily.

Tests under driving conditions on the road are feasible.
Traditionally, for finding an optimal acoustical package for the car interior, often so-called car panel noise contribution measurements are used based upon p-p based sound intensity probes.

The method comprises of three consecutive stages:

- Mocking up the passenger compartment with sound absorbing materials
- Measuring noise contribution of each individual panel
- Establishing transfer functions from the panel to a certain position, normally the driver seat

This method has drawbacks that are basically caused by the characteristics of pressure transducers.

The application of the insulation package is very time consuming, the weight of the package alters the structure of the vehicle, and the volume of the package normally prohibits testing under realistic driving conditions.

The method requires significant lead times, and has a limited frequency range that doesn't match the frequency range up to 10 kHz where acoustical packages do have an impact.

Furthermore the method depends to some extent upon qualified, but subjective, engineering judgment that varies from site to site.
For safety reasons, no testing under actual driving conditions occurs.

Traditional method

For optimizing sound packages, BEM and FEM analysis is used in the lower frequency range.
For higher frequency ranges, statistical energy analysis is used.

The traditional window method can be divided in three stages.

1) Mock up: the complete car interior has to be damped in order to avoid a too large intensity index of the intensity measurement.
2) Car panel sound power measurement. The complete interior is divided in 100 to 150 so called panels. From each panel the sound power emission is measured.
3) Determination of the transfer functions from each panel to the ear position.

With these three steps the noise contribution of each panel is determined.
Once the contribution is known, the acoustic problems can be determined and the effect of changing acoustic properties can be predicted.

This method is based upon the availability of pressure transducers only.

The availability of dedicated Microflown acoustical particle velocity sensors offers new opportunities.

Sheer particle velocity based measurements don't take into account the existence of dipoles that radiate alternating, but don't contribute to the noise level in the passenger compartment.

The use of fully integrated miniature and broad banded particle velocity based sound probes allow sound power measurements.

The three stages are examined closer:

1. Mock up

First stage of the measurement is to mockup the entire interior with acoustic damping material. This might take several man and calendar weeks to complete.

The mock up reduces the structure of the vehicle and affects the reverberation time and thus the reactivity index (= ratio between pressure and intensity).

Without the mock up the index is too high and the traditional intensity measurements cannot be carried out.
The passenger seats are removed.

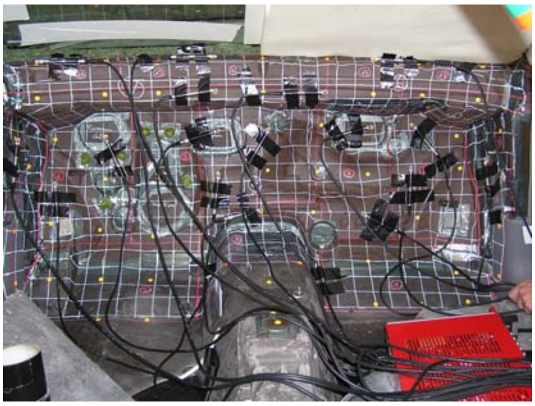


Fig. 1: Measurement of the engine noise contribution. Left: measurement grid and placement of sound probes. Right: detail of mock up insulation package

2. Car panel sound power measurements

The car interior has to be divided into 100 -150 panels. Each panel should be about flat, size about of 40 * 40 cm^2.
The measurements are carried out by placing the transducers normal to the bended chassis parts.

Two measurement method in order to determine the sound power emission of a panel:

- Point by point
- Scanning

Point by point (interior without seats)

Each panel has equidistant points of about 5 cm. In total this totals to approximately thirty measurements per panel, outcome is one value sound power per panel. The impact of the reactivity index is important. Therefore, the measurement is carried at about 7 cm distance. This is a subjective empirical value.

Scanning method (interior without seats)

Two scanning measurements are carried out along two different routes per panel. The impact of the reactivity index is important. Therefore, the measurement is carried at about 7 cm distance. This is a subjective empirical value.

It is estimated that between 500 and 1000 man-hours are spent on these measurements, causing a lead time in between 2 and 4 weeks.

3. Transfer functions ear position driver seat to each panel

The entire mock up is removed and seats are put in place in order to get a proper transfer function under realistic conditions.
With a sound source and a pressure microphone at the ear, and one up to five pressure mikes at each panel at an equidistance of 15 cm, a measurements sequence takes place.

It is estimated that this takes between 100 and 200 hours and 1 –2 weeks lead time.

Intrinsic drawback of pressure transducers

Sound intensity measurements are always difficult, but until now it is the only way to find out the contribution of noise of each car panel.

Measurements of sound pressure or particle velocity alone are not very valuable to determine the car panel noise contribution. This can be understood by an example. If a panel is vibrating in the 2-1 mode a dipole is created.

The sound pressure and particle velocity contribution of each individual maximum of the dipole is large however the sound power contribution (i.e. de amount of sound that is emitted) is low.

Therefore sound intensity has to be measured.

In the interior of the car two sound fields are dominant:
- diffuse sound fields and
- near fields

In a pure diffuse sound field sound is propagating in all directions with the same magnitude.

Similar as in a pure reactive sound field, in a pure diffuse sound field the sound energy has a value and the intensity is zero: the sound energy is not propagating.

The difference between a reactive sound field and a diffuse sound field is that in a pure reactive sound wave the phase shift is 90 degrees and in a diffuse sound field the phase shift is random.

In a reactive sound field the reactive intensity high and in a diffuse sound field the reactive intensity zero.

In a diffuse sound field both active and reactive intensity are zero, the sound pressure and particle velocity level however are large (compared to the intensity level).

With a traditional p-p sound intensity probe the determination of the sound power contribution of each panel can only be obtained when the reactivity index is low.
The error that is made with a traditional p-p probe is given by [3]:

$$\hat{I}_r \simeq I_r - \frac{\varphi_{\text{pe}}}{k\Delta r}\frac{p_{\text{rms}}^2}{\rho c} \; ; \; I_r\left(1 - \frac{\varphi_{\text{pe}}}{k\Delta r}\frac{p_{\text{rms}}^2/\rho c}{I_r}\right),$$

where I_r is the 'true' intensity (unaffected by phase mismatch), p_{rms} is the rms value of the sound pressure and c is the speed of sound.

This expression shows that the effect of a given phase error is
- inversely proportional to the frequency and the microphone separation distance and I
- proportional to the ratio of the mean square sound pressure to the sound intensity.

If this ratio is large then even the small phase errors mentioned above will give rise to significant bias errors.

To reduce the diffusivity the car has to be filled with damping material. For this the seats have to be removed too.

In other words: to be able to measure the contribution of the panels with a p-p probe the car interior has to be changed.

Due to this the procedure has to be repeated when the car is returned in into it original state to be able to determine the transfer function to each panel.

The key problem of the traditional method is that the p-p method requires a low pressure intensity index environment.

Possibilities with p-u based methods

The PU based sound intensity method is not affected by any pressure-intensity index. This is proven in [1,2,3].

Because the key problem is avoided by this new probe there is no need for mock up.

And because there is no need for mock up, the sound power determination of each panel and the transfer function of each panel can be done at the same time. This saves a lot of time, up to 80%!

A high diffusivity will not affect the accuracy of a PU sound intensity probe but the measurement error will be influenced by the reactivity of the sound field. The expression of the error is given by [3]:

$$\hat{I}_r = \tfrac{1}{2}\,\mathrm{Re}\left\{\hat{p}\hat{u}_r^* \mathrm{e}^{-\mathrm{j}\varphi_{\mathrm{ue}}}\right\} = I_r + \varphi_{\mathrm{ue}} J_r \ \text{ where } \ J_r = \tfrac{1}{2}\,\mathrm{Im}\left\{p u_r^*\right\}$$

To measure the car panel sound radiation, the intensity probes are placed relative close to the panels. Therefore a high reactive sound field can be expected. In diffuse sound fields the reactive intensity J is zero so such fields do not have any influence on the measurement error.

However in this application the frequency of interest is relatively high (f>400Hz) and therefore the reactivity is expected not too high.

In one study [3], similar measurements are done **<u>and even with poor calibration</u>**, the error was only increasing for frequencies below 200Hz. The distance to the source in [3] was about 10cm.

As stated, two out of three stages can be skipped in the measurement procedure.

The use of PU based probes is not influenced by reactivity. Therefore, the need for making and putting in place the mock up is eliminated. As a consequence, the transfer functions can be obtained simultaneously with the sound power measurements.

On top of it, the measurements will be more uniform / standardized, since the subjective element in the scanning and point by point measurements vanish as well.

The quality of the measurements will be improved.

In the traditional transfer function a factor is used that compensates for the reflection at the place of the pressure microphone. This factor is related to the diffuse reflection coefficient and needed when sound pressure measurements are taken. This factor can be measured in situ with the PU array. Therefore the quality of the measurement improves.

It is also possible to use another transfer function that is based on sound intensity measurements. If this method is used, there is no need for the alpha factor.

For the remaining measurements, namely the combined sound power + transfer function determination, the number of man hours can be reduced significantly.

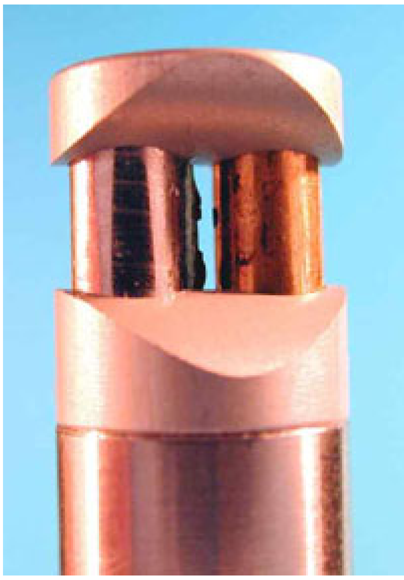
First of all, readjusting the mock up for another panel measurement is no longer needed.

Secondly, the time to readjust and fix the sensors can be reduced by using a fixed array of PU-Probes.

To summarize, between 60 and 80% on both man hours and development lead time can be saved.

A realization of a PU based method

As shown above, the PU method reduces both required man hours and lead time significantly, whilst increasing reproducibility and accuracy and adding the possibility of testing under realistic driving conditions on the road.



To make the method robust and to avoid possible calibration errors it is wise to make an array of PU intensity probes and to maintain a certain distance between the panel and the probes. This has two reasons:

1) If the PU-Probes are not very close to the vibrating surface the reactive intensity is lower and the risk of calibration errors reduces. A 7cm distance is advisable because this was tested by the traditional method and according [3] very small errors may be expected for frequencies higher than 400Hz.
2) If the probes are not close to the surface, it is not necessary to adjust the probes so that they are oriented normal to the surface. This saves installing time

If the array is not mounted very close to the surface, the sound power can be considered to be emitted from an imaginary rigid box with an open bottom where sound radiates.

Now two methods can be used:

1) An imaginary box with PU-Probes in all the 5 surfaces (in fact this is done with the traditional method, however the side surfaces where not measured). The intensity in

the side surfaces have to be measured and summed with the sound power of the lid, the larger main surface.

2) An imaginary box with rigid side surfaces. If the side surfaces are rigid, the sound is reflected and therefore all sound propagates through the lid.

Calibration

Both a standing wave tube and a near field calibration technique can be used.

The 70 cm calibration tube of Microflown Technologies can be used in a frequency range of 50~100Hz up to 4200Hz.
The near field calibration technique is still experimental, but covers the entire frequency up to 10 kHz as well.

Standing wave tube

References

[1] H-E de Bree et al., Sound intensity measurements with the Microflown sensor (invited paper), Internoise 2004

[2] W.F. Druyvesteyn et al, A new sound intensity probe; comparison to the Bruel & Kjaer p-p probe, J. audio Eng. Soc., Vol. 48, 2000 No. ½ January/February

[3] Finn Jacobsen et al, a comparison of p-p and p-u sound intensity measurement systems, ICSV 2004