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A PU probe array based panel noise contribution analysis whilst driving

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ABSTRACT

This paper presents new developments on hot wire anemometer based panel noise contribution analysis. The used sensor allows the direct measurement of particle velocity. Some historical remarks are given and the latest developments of the technique are reported.

Four steps are required to determine the panel noise contribution of the interior of a vehicle and to visualize the results in 3D.

In a first step the probes are positioned on the interior surfaces and their x,y,z coordinates are measured. Based on these data a 3D geometry model is created. The geometry data are acquired using a specially designed 3D digitizer.

The second step is a measurement in a certain mode of operation. This step can be done in a laboratory but it is also possible to perform the measurement whilst driving the vehicle on the road. Stationary as well as non stationary running conditions like e.g. run ups are accessible and do not limit the applicability of the method.

The third step is the determination of the transfer paths from the panels to a certain listening position. This measurement is done reciprocally.

In a fourth and last step the transfer paths are linked with the operational data gathered in step two. The results are then visualized using the 3D geometry model.

This paper describes the measurement of a conventional car with a resolution of 180 panels. Since an array of 45 probes was used step 2 and step 3 had to be repeated 4 times. The complete measurement typically takes approximately 3 days.

INTRODUCTION

Panel noise contribution is a measurement method to analyse and quantify the sound pressure contributions from certain interior panels to a reference listening position e.g. the driver ear. The method consists of two parts, the source strength determination and the transfer path determination.

Several methods exist to analyse sound sources inside vehicles. In the following the surface velocity method and the sound intensity method will be described.

The source strength can be determined either by sound intensity measurements or by particle velocity measurements. Both methods are used nowadays. In this paper the methods are described briefly. The focus will be on the velocity method because this method allows the panel noise measurement whilst driving.

The method is based on a so called particle velocity sensor. This sensor can be regarded as a micromachined hot wire anemometer, but based on *two* wires, instead of one as in the classical anemometer (Fig. 1). The two short, thin, closely spaced wires of silicon nitride coated with platinum are heated by a DC current to about 300˚C. Their resistance depends on the temperature.

A particle velocity signal in the perpendicular direction changes the temperature distribution instantaneously, because the upstream wire is cooled more by the airflow than the downstream wire. The resulting resistance difference is measured with a bridge circuit that provides a signal proportional to the particle velocity.

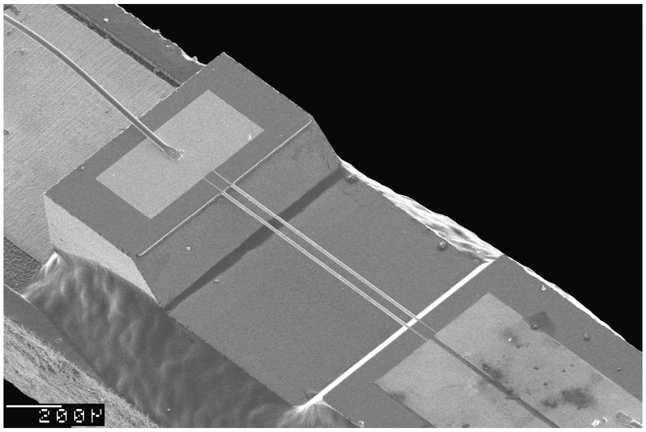

Fig. 1: The particle velocity sensor probe.

A HISTORY OF PU PROBE BASED PNC

As stated before, there are two methods to determine the noise emission of a panel. One method uses the surface velocity and the other method requires the measurement of the sound intensity (or better sound power).

Both methods require a measurement of the path from the source to a listener position. This is usually done by a reciprocal measurement. A monopole sound source is placed at the listener's position and the sound pressure is measured at the source position. The reciprocity principle states that the acoustical transfer path stays the same if source and receiver positions are interchanged.

Reciprocal measurements are often found in NVH applications because sound sources and sensors have very different space requirements. Therefore, interchanging both sound source and microphones, allows a much easier and faster measurement of acoustic transfer functions than the direct method.

The surface velocity measurement is described by Prof. Fahy (ISVR, England) and used by many companies [1], [2], [3]. The surface velocity, that is the particle velocity in close proximity of a surface, is used to determine the source strength.

Traditionally the surface velocity was approximated by measuring the structural vibration by the use of accelerometers or a laser vibrometer. These methods to measure the structural vibration are very time consuming. Apart from that, only the structural velocity is measured, airborne leaks cannot be handled. Many surfaces in a car cabin like carpets etc. are not suited for mounting accelerometers, and in some cases the mass loading will significantly influence the measurement.

A volume acceleration sensor is reported in [1]. This sensor should overcome these aforementioned problems but it turned out to be an impractical device; only one prototype was ever built.

Another acoustic and non contact way of measuring the noise emission is the measurement of sound intensity. It is preferably used when the noise sources can be considered incoherent. Two sources are considered incoherent if their resulting sound pressure at a certain position does not depend on the phase of the sources. This depends on the acoustic environment and usually sources are found to be incoherent at higher frequencies.

Traditionally PP intensity probes where used for this method. This PP intensity method is based on the gradient of two pressure microphones. This gradient represents the particle velocity. Together with the pressure value it is used to determine the intensity of a sound wave. However PP probes cannot be used in environments with a lot of extraneous noise sources and reflections (such as a car cavity). In order to be able to use a PP intensity probe it is common to fill up the complete car with heavy insulation/absorption material and at those locations where a measurement is taken, the material is removed and a 'window' is created. Therefore this method is also called 'the window method'. Drawbacks of the window method are the enormous effort, the disturbance of the interior acoustics and the fact that test runs on the road are almost impossible.

The method to measure with a sound intensity probe (the sound power) is presented by Verheij [4], [5]. The emitted sound power of the surface is measured and transformed into a quantity that represents the source strength of a point source. The transformation from sound power to monopole source strength is also applicable for surfaces with damping properties.

At lower frequencies noise sources may be coherent (i.e. the phase of the source influences the perceived sound pressure at the listener's position). Therefore, when using the intensity method this phase information is lost. This sets a lower frequency limit on the method. This limit depends on the vehicle under test but usually lies in the range of 200 – 400 Hz for passenger cars. In contrast to pressure based data, results of intensity measurements cannot be used for direct auralisation.

In 2004 the velocity method as proposed by prof. Fahy was realized with the use of the novel particle velocity sensors [6]. This method proved to be practical and reliable [7].

Inspired by this lecture, the method was also tested with the intensity based method using PU probes. The abbreviation PU stands for pressure (P) and velocity (U). The velocity is here measured directly and not indirectly deduced by evaluating the gradient of two pressure microphones. It has been reported that the quality of a PU intensity measurement is affected neither by extraneous noise sources nor by reflections [11] thus the traditional ‘window method’ can principally be used without the need of heavy damping/absorption material. This leads to a significant reduction of measurement time and effort [8].

Although the PU based intensity measurement does not require window masking material in order to be accurate, the panel noise method itself needs an acoustical damping mechanism inside the vehicle. This is necessary because the sum of all ingoing sound power contributions must be absorbed [7].

It turns out that the measurement of a part of an interior or a relative measurement [8] can be done quite accurately but for a complete vehicle cabin absorption material is still required [9]. This makes the intensity based method not suitable for measurements while driving on the road.

In 2007 it was shown that the velocity based method works accurately over a large bandwidth with an array of PU probes and with the use of a sound card based data acquisition system [10]. As reported already in 2004, the velocity method can be used whilst driving [6].

This paper describes how the method is completed with a digitizing system that allows getting a fast capture of the 3D coordinates of the vehicle interior. Dedicated MATLAB based software is used to visualize the measurement results on a 3D geometry model in both time and frequency domain.

The complete measurement takes approximately three days for a normal car. The method has also been tested in a helicopter during various flight conditions and in a TGV-train during a 300km/h test drive.

THEORY

The source path contribution technique is closely linked to the Helmholtz integral equation that relates the acoustic pressure and normal velocity on a closed boundary surface *S* of a vibrating object to the radiated pressure field inside the fluid domain:

$$p(\vec{x}) = \oiint_S \left\{ \frac{\partial G(r)}{\partial n_y} p(\vec{y}) + i\omega\rho G(r) v_{n_y}(\vec{y}) \right\} dS \qquad (1)$$

In a field point $\vec{x}$, the $p(\vec{x})$ can be calculated. The unit normal to the surface at source point $\vec{y}$, denoted as n_y, is pointed into the fluid domain. Distance *r* is the length of vector $\vec{r}$ that is directed from the source point $\vec{y}$ to the field point. In an unbounded fluid domain without reflecting objects (free space) the Green’s function *G(r)* reads:

$$G(r) = \frac{e^{-ikr}}{4\pi r} \qquad (2)$$

It can be understood that the Neumann Green’s function can be found experimentally by e.g. a reciprocal method when the surface is rigid. With such a measurement the sound pressure in a field point $p(\vec{x})$ is related to a normal particle velocity at a rigid surface. The latter is explained in more detail [1], [10].

The Green’s function and gradient of that Green’s function are determined experimentally by reciprocal measurements of the airborne transfer functions between sound pressure, particle velocity and volume velocity:

$$G(r) = \frac{i}{\omega\rho_0} \frac{p_r}{Q_r} \qquad (3)$$

The quantity p_r/Q_r represents the reciprocally obtained transfer function between a monopole sound source and the resulting surface pressure measured at the panel under test.

The sound pressure is measured using the pressure element of the PU probe, as shown in Fig. 2. In this way it is ensured that the measurement locations (where the velocity is measured) and the transfer function where the sound pressure is measured as a response of the sound source Q are the same.

The gradient of the measured Green’s function can be written as:

$$\frac{\partial G(r)}{\partial n_y} = \frac{v_r}{Q_r} \qquad (4)$$

Here, v_r/Q_r is the reciprocally obtained transfer function between the monopole sound source and the surface velocity measured at the position under test.

The velocity as a response of the source Q can be measured with the PU probe as well. However, this measurement can usually be neglected for high impedance surfaces as will be shown below.

The Helmholtz integral equation therefore alters to:

$$p(\vec{x}) = \oiint_S \left\{ \frac{v_r}{Q_r} p(\vec{y}) + \frac{p_r}{Q_r} v_{n_y}(\vec{y}) \right\} dS \qquad (5)$$

When the surface impedance is high (i.e. non absorbent), the reciprocally obtained transfer function $v_r/Q_r \times p(y)$ is low compared with $p_r/Q_r \times v(y)$ and the Helmholtz integral equation yields:

$$p(\vec{x}) = \oiint_S \frac{p_r}{Q_r} v_{n_y}(\vec{y})\, dS \qquad (6)$$

This relation states that in case of high surface impedance the sound pressure at a certain position $\vec{x}$ can be calculated by the surface integral of the surface velocity and the measured transfer function p_r/Q_r to that surface.

The measured transfer function p_r/Q_r is a measure for the acoustic environment and the surface velocity is a measure for the source strength in a certain operating condition.

The acoustic environment can be considered constant and has only to be measured once (in a quiet environment). Obviously the surface velocity has to be measured for each operating condition.

The surface velocity is measured directly with the particle velocity sensor and the transfer function p/Q is measured with a calibrated omni directional sound source with a known volume velocity [12] and a sound pressure microphone at the measurement location.

PU probes are used for the measurements. These sound probes are capable of simultaneously measuring the sound pressure (P) and the particle velocity (U) at the same position. An example of a PU probe is shown in Fig. 2.

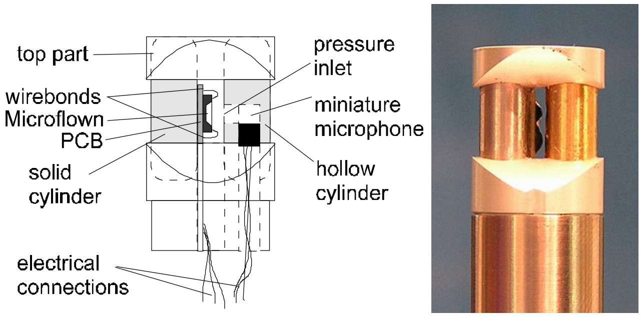

Fig. 2: A PU probe. Left the sketch and right the actual probe.

The diameter of the probe is ½”.

A TEST MEASUREMENT

The complete measurement procedure is tested and reported in this paper. The procedure consists of four phases.

The first step is the positioning of PU-probes and the determination of the measurement positions in a 3D measurement grid. This is done with a measurement arm that has been specially designed for this purpose.

The measurement locations for all probes are chosen by an acoustical expert selecting the most suitable positions. The positions are then labeled by special markers. This whole procedure takes typically a few hours.

After marking, special tape has to be deployed to enable the positioning of the probes later on. This takes some minutes per location; so a few hours for 180 positions.

With a 3D digitizer the location of the measurement points are measured. Around each measurement point a panel is defined and measured with the 3D digitizer. The complete procedure requires about 4 hours of measurement time for a normal car.

The 3D digitizer has been built especially for this application. It consists of three joints. These three joints are connected to a base allowing the joints to rotate in a horizontal and vertical orientation. All angles are measured in real time.

Two buttons (red and green, see Fig. 3) are used to mark a measurement location or to define a panel.

Fig. 3: The digitizer to capture the 3D coordinates of the vehicle interior and the location of the measurement points.

The second step is the measurement of the surface velocity of the panels. Since only 45 probes are used, the measurement has to be repeated four times in order to cover the whole interior vehicle cabin creating a measurement grid of 180 surface panels.

The probes are fixed onto the surface in a way as shown in Fig. 4. The probes are mechanically decoupled so that the probes do not vibrate due to the panel vibrations.

The sound emissions from the panels into the car interior are measured whilst driving the vehicle.

In Fig. 4 it is shown how the probes are mounted onto the right side of the car. Three additional measurement areas including roof, left side and floor are defined similarly.

Fig. 4: The PU probes are spatially distributed.

The preparation time for the positioning of the probes is about 1 hour per measurement. The measurements itself are done in the order of minutes. The sound pressure is measured at a certain reference position (usually at the position of the driver) for validation purposes.

The 96 channel data acquisition and data recording set up is located inside the trunk, see Fig. 5. The system is powered by the car battery.

Fig. 5: 96 channel data acquisition and recording equipment inside the trunk.

Step three is done after finishing each measurement in operating conditions: In a quite environment the transfer paths from the driver position to the probes are measured.

First an omni directional sound source of known volume velocity [12] is placed at the driver's ear position. Then the source is driven with a swept sine wave. The volume velocity of the source is measured with a reference particle velocity sensor and the sound pressure is measured using the pressure element of the PU probes. In principal both the sound pressure and the particle velocity could be measured but usually only the sound pressure is required as explained in the theory.

The complete procedure (so including set up time) of measuring the transfer paths takes approximately half an hour.

Step four is the last step and links the measured transfer paths with the measured velocity data taken in step two.

During the measurement whilst driving the car, a reference sound pressure measurement is taken. This measurement is used to validate if the synthesized sound pressure (that is the cumulated sound pressure in the time domain calculated from all the surface velocities and paths) is in agreement with the reality.

In Fig. 6 the validation measurement is shown. The measured sound pressure in dB is marked in blue and the synthesized, calculated sound pressure is displayed in red. As can be seen, the two curves are in reasonable agreement up to approximately 2 kHz.

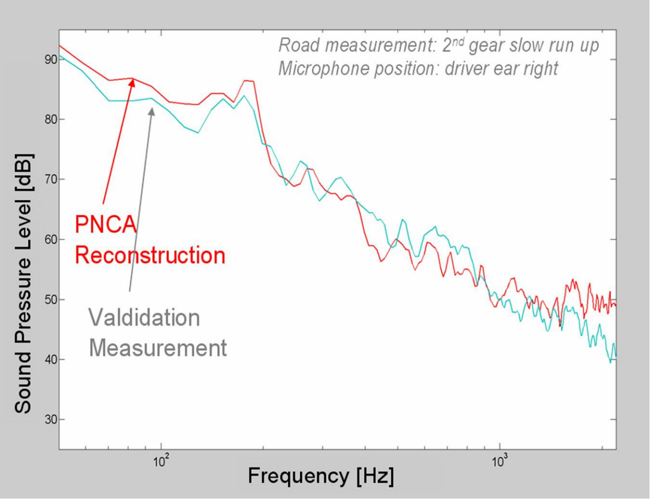

Fig. 6: Validation measurement result.

At higher frequencies the results start to deviate. This is because the spatial density of the sensor grid is not appropriate for higher frequencies: At these high frequencies the particle velocity cannot be assumed constant in one panel and therefore might vary. Since only one sensor per panel is selected an over or under estimation might occur which leads to this deviation.

There is a significant similarity between the measured and the synthesized sound pressure even at lower frequencies below 100 Hz. This is not expected since the panels are measured independently from each other in four series.

Normally the loss of phase relationship between the series should have a negative effect on the lower frequency limit. Further R&D must prove if the method as it is now really operates down to 40Hz as the curves might indicate. The typical range for the applicability of the method is usually between approximately 100 Hz and 2 kHz [10].

In general it can be stated that the smaller the number of independent measurements the better the lower frequency limit. In that sense only one single measurement would probably lead to no lower frequency limit at all. In contrast to this the traditional window method typically requires 20 to 30 phase independent measurements leading to a lower frequency limit of approximately 200 – 400 Hz depending on the vehicle.

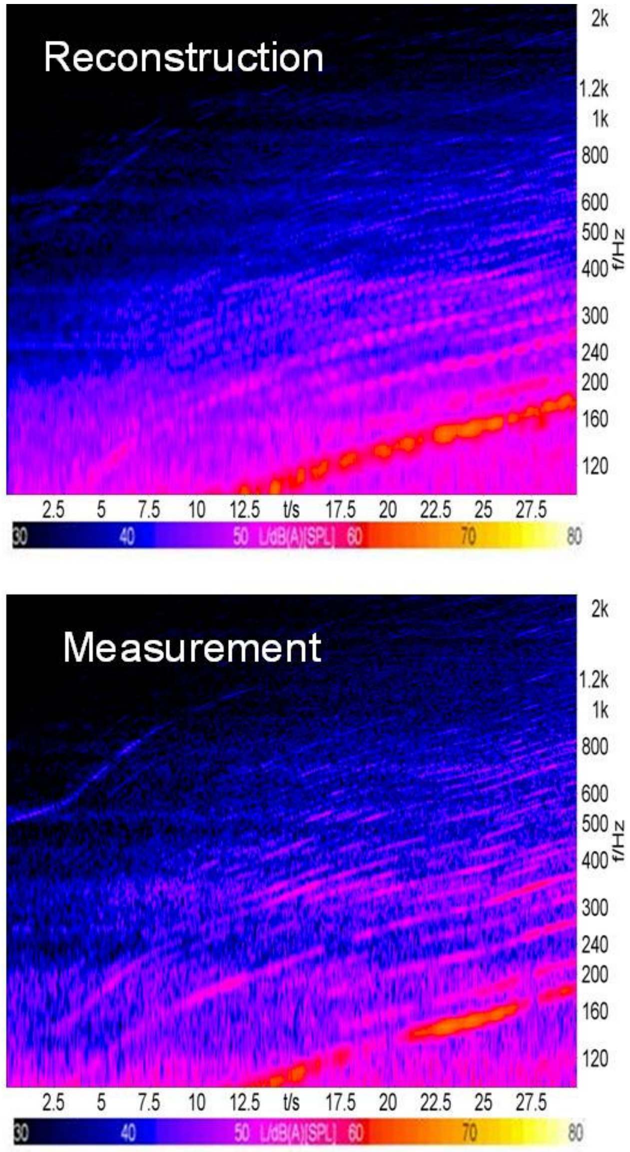

Fig. 7: Time frequency representation of the measured sound pressure (lower) and the reconstruction (upper).

Another method to verify the measurement results is comparing a time frequency representation of the measured sound pressure with the synthesized sound pressure. As can be seen in Fig. 7, they are also in reasonable agreement. This comparison has been reported also in previous publications proving the reproducibility of the method [6, 10].

Once the measurements prove to be consistent, a breakdown of the results is calculated and visualized in 3D.

The measurements can be displayed in both frequency and time domain.

The display in frequency domain shows the contributions for each desired bandwidth. Usually this is in 1/3rd octaves.

The display in time domain is done for a specific bandwidth (usually this is the A-weighed SPL). This representation is especially useful for non-stationary excitations e.g. engine run ups.

This can be seen in Fig. 8. The data were taken during a run up in second gear on a public road. The plot shows the time averaged result for the 160 Hz 3rd octave. The darker the color the higher the panel noise contribution to the sound pressure at the reference position (driver's ear).

For this car, the lower part of the front window seems to be highly contributing. Also the lower parts of the front doors seem to contribute significantly to the interior sound pressure.

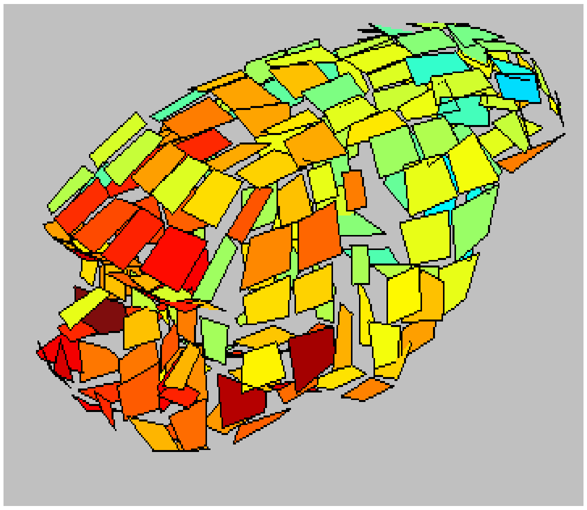

Fig. 8: 3D visualization of the measurement results (frequency domain, 160 Hz)

Switching to the time domain makes it is possible to analyze the acoustical behavior of the car for each point in time during run up.

The frequency range can be selected and the time of interest can be set. As an example Fig. 9 shows the result for the 160 Hz 3rd octave after 19 seconds and Fig. 10 after 29 seconds. The effect on the lower part of the windscreen is clearly visible.

This type of visualization helps acoustical engineers to quickly find acoustically weak areas in an intuitive way.

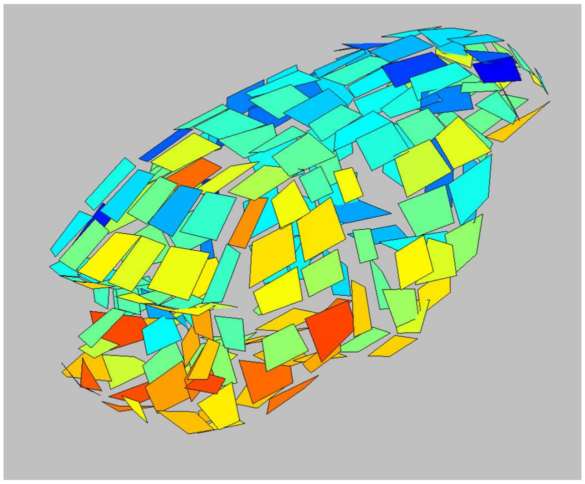

Fig. 9: 3D visualization of the measurement results (time domain, status after 19 seconds).

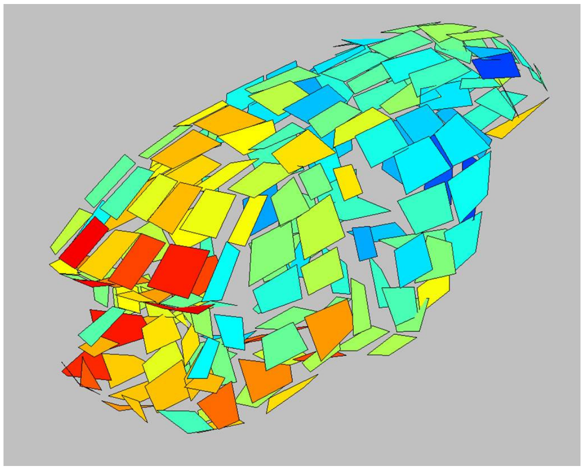

Fig. 10: 3D visualization of the measurement results (time domain, status after 29 seconds).

The figures display the true measurement results for the measured panels, so no smoothing or whatsoever takes place. It might be considered as a disadvantage that the 3D model used for the visualization of the results is not so beautiful but this is a matter of taste.

The advantage of the method is that only true measurements are shown which makes the detection of possible errors much easier. Since the panels are not exactly connected to each other it is possible to look through the 3D model and this appears to be very practical.

CONCLUSION

This paper presents the latest developments on hot wire based panel noise contribution analysis. The method requires the measurement of the particle velocity with specially designed sound probes that are capable of measuring sound pressure and particle velocity simultaneously at the same position. An array of 45 PU probes has been used.

A full analysis of 180 panels can be done in only three days. The method consists of four steps. First step is the selection of the measurement positions and the measurement of the locations with a specially designed 3D digitizer.

The second step is the measurement in running conditions. The method does not require special test locations; the measurements can easily be performed on the road. The method enables the full analysis of panel noise contributions for stationary as well as for non stationary test conditions.

The third step is the measurement of the airborne noise transfer paths from the sources to the listening positions by making use of the reciprocity principle.

In a fourth and last step the operational data are linked with the transfer functions and the results are visualized on a 3D model.

As has been already reported in previous publications, the method shows to be reproducible, operational and very practical.

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