

# Assessing Engine Noise Using Particle Velocity Sensors

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It is important to apply an effective noise-reduction treatment to determine the contribution of different engine components to the total sound perceived inside an automobile cabin. Although accelerometer or laser-based vibration tests are usually performed, the sound contributions are not always captured accurately with such approaches. Microphone-based methods are strongly influenced by the many reflections and other sound sources inside the engine bay. It has been shown recently that engine radiation can be effectively measured using microphones combined with particle velocity sensors while the engine remains mounted in the car.<sup>6</sup> Similar results were obtained from a dismantled engine in an anechoic room. This article focuses on measuring the transfer path from the engine to the vehicle interior to calculate the sound pressure contribution of individual engine sections at the listener's position. To achieve a good signal-to-noise ratio during acoustic transfer paths, a novel monopole loudspeaker was designed. The measurement method and monopole sound source are presented along with results of a validation test.

To improve driver comfort, vehicle manufactures have been searching for ways to reduce the noise inside a car. Determining how much noise radiates from separate components is a first step in designing an effective acoustical treatment. However, sound source localization techniques, like beamforming, near-field acoustic holography, or intensity methods are hard to use in a car interior, because reflections affect the measurement methods themselves. Also, the way sound propagates from a source to the listener is often oversimplified or even disregarded. A method that does account for the sound propagation in detail is the panel noise contribution analysis (PNCA) method.

With PNCA, the radiating area is divided into several surfaces, and their contributions to the sound pressure at the listener's position are determined by combining a radiation test and a transfer path test. With PU probes that contain a sound pressure microphone and a particle velocity sensor, both tests can be performed easily even in reverberant conditions like a car. In the past, the PU-probe-based PNCA method has been used to determine the sound pressure contributions of panels inside a car and to ultimately assess the effect of sound damping material on the walls of the cabin.<sup>1-5</sup>

However, these measurements did not reveal the radiation of the source itself, because the PU probes were not installed near the source. In Reference 6, particle velocity probes were installed directly on the engine that was still mounted in the car and the radiation of separate components was captured. The results were in good agreement with those of an engine that was dismantled from the car and installed in an anechoic room. Still, only the radiated sound was measured in this direct engine test.

This article not only considers the radiation from the engine, but also the way sound propagates to the driver's ear. The acoustic transfer path from the radiating panels to the ear's position is determined using a monopole sound source. Sound waves are attenuated strongly as they propagate to the inside of the car due to the presence of acoustic treatments. To achieve a good signal-to-noise ratio, a new type of monopole loudspeaker is developed that is powerful enough.

A brief introduction of the PNCA theory and measurement method is presented in the next section. Thereafter, the principles and the measurement routine of the new monopole loudspeaker are presented. Finally, results of a PNCA validation test are shown.

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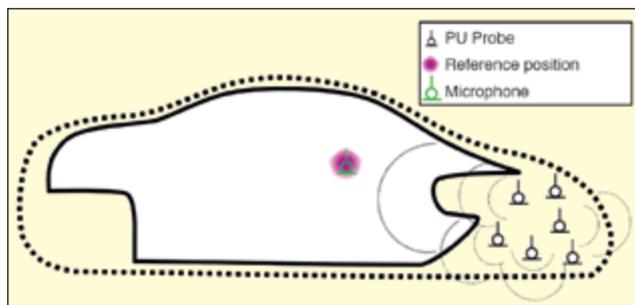


Figure 1. Sketch of measurement procedure in operational conditions.

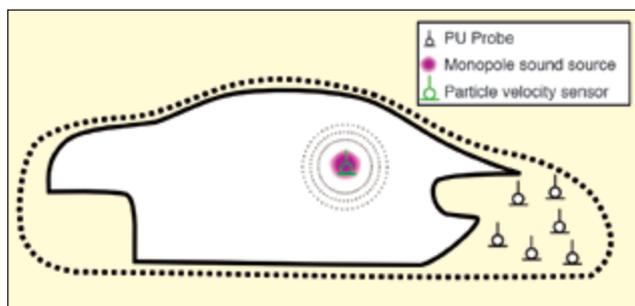


Figure 2. Sketch of procedure for the transfer path test.

## Theory and Measurement Methodology

With a continuous surface  $S$  that radiates and encloses a volume  $V$ , the sound pressure at reference position  $M$  is defined by:

$$p_{ref}(M) = \int_S \left[ \frac{p_{TF}(y)}{Q_M} u_{ny}(y) - \frac{u_{TF}(y)}{Q_M} p(y) \right] dS \quad (1)$$

where  $y$  is a position on surface  $S$ , and  $u_{ny}$  and  $p$  are the normal particle velocity and sound pressure, respectively.  $Q_M$  is the volume velocity of a monopole sound source at position  $M$ , and  $p_{TF}(y)/Q_M$  and  $u_{TF}(y)/Q_M$  are the transfer functions between this monopole and the sound pressure and particle velocity, respectively.

In practice, surface  $S$  is divided in a limited number of panels with size  $\Delta S$ . In the PNCA measurement procedure, first the acoustic excitation of the car's structure is evaluated in a stationary operational condition. For example, the car is driven on a road or installed on a roller bench while the radiated particle velocity and sound pressure near each panel are measured.<sup>4,5</sup> Figure 1 illustrates this step.

In the second step, the acoustic propagation paths from each part of the structure to the reference position are determined. The car engine is switched off, and sound is generated with a monopole loudspeaker at the reference position. The transfer paths are measured using sound pressure and particle velocity sensors at the same positions where the panel radiation was measured before. A particle velocity sensor is installed near the monopole loudspeaker to determine the volume velocity (see Figure 2.)

## Monopole Loudspeaker

Usually the reference position at which the sound pressure contributions are determined is the location of the driver's ear. A monopole loudspeaker is used for this transfer path measurement. To measure the acoustic transfer paths from the engine to the car interior, high enough sound levels should be generated to ensure that the sensors behind the highly attenuating firewall of the car have sufficient SNR (signal to noise ratio). For this purpose, a new loud monopole loudspeaker was developed and is presented here.



Figure 3. High-sound-level monopole loudspeaker.

**Hardware.** Monopole loudspeakers usually consist of a loudspeaker inside a box that is connected to a tube. Sound radiates omnidirectionally due to diffraction effects as long as the tube's diameter is small compared to the wavelength. However, a broadband omnidirectional sound source with sufficient sound power is complicated to manufacture because of its low radiation efficiency.<sup>8</sup> A large tube opening is required to generate enough sound power at low frequencies, while the opening should be small compared to the wavelength to ensure omnidirectional radiation at high frequencies. Often, multiple monopole loudspeakers with different frequency ranges are used to cover the entire bandwidth of interest.

For the development of this monopole loudspeaker, a compromise was made between accuracy and frequency range. Two loudspeaker drivers were mounted in a housing that together can generate high sound levels in a wide frequency range (see Figure 3). The low-frequency driver was placed behind an inverted horn with an opening diameter of 56 mm. The high-frequency driver was connected to a tube with an inner diameter of 22 mm. An electronic filter was used to ensure that all sound radiated from the low-frequency driver at low frequencies and from the high-frequency driver at high frequencies.

Pairs of sound pressure microphones are sometimes used as reference sensors for measuring the radiated volume velocity. However, methods involving these sensors can be susceptible to temperature variations, sound-field nonlinearities at high sound levels, and reflections from surrounding objects.

Measuring volume velocity with a particle velocity sensor seems logical, because volume velocity is defined by the product of particle velocity and the radiation area. In the past, several monopole loudspeakers have been developed with such sensors at the monopole entrance.<sup>8</sup> However, the sound source described here generates such high sound levels and sound induced turbulences that particle velocity sensors would overload with existing configurations.

Two measures are taken to avoid this problem: the particle velocity sensor is placed a short distance away from the opening of the monopole (or about 64 mm), and a cap with a small hole is placed over the sensor to reduce the perceived signals. The distance between the sensor and the monopole center is not increased to avoid strong influences from reflections. Such influences are smaller on particle velocity than on sound pressure due to near-field effects.

**Calculating Volume Velocity and Sound Pressure.** This section describes how the sound pressure at a distance from the monopole

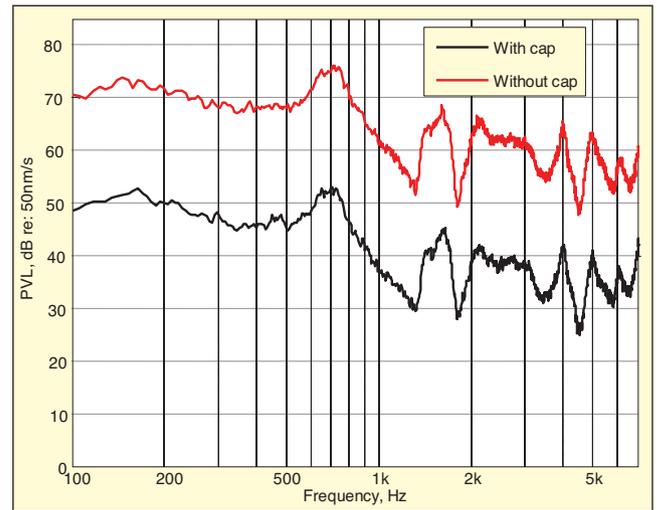


Figure 4. Particle velocity level perceived by probe with and without cap.

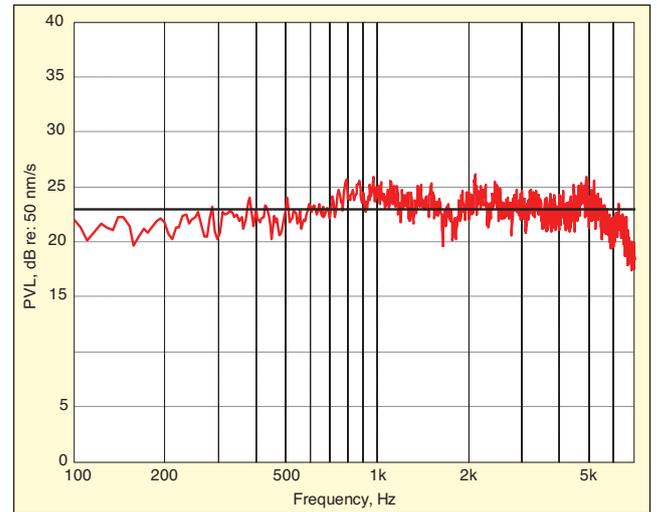


Figure 5. Difference in particle velocity level with and without cap.

is calculated using the particle velocity measured by the PU probe near the monopole. The sound pressure  $p$  at distance  $r$  from a monopole source in the free field is given by:<sup>8,9</sup>

$$p(r) = ik\rho c \frac{Q}{4\pi r} e^{-ikr} \quad (2)$$

where  $r$  is the density of air,  $c$  is the speed of sound in air,  $Q$  is the volume velocity, and  $k$  is the wave number. The radial particle velocity  $u_r$  at the same position is:

$$u_r(r) = i \frac{Q}{4\pi} \frac{ikr + 1}{r^2} e^{-ikr} \quad (3)$$

So, sound pressure at distance  $r_1$  can be calculated using the particle velocity measured by a PU probe at distance  $r_2$  and by combining Equations 2 and 3:

$$p(r_1) = ik\rho c \frac{r_2^2}{r_1} \frac{u(r_2)}{ikr_2 + 1} e^{ik(r_2 - r_1)} \quad (4)$$

**Pinhole Cap.** Previous monopole loudspeakers contained a special high-sound-level particle velocity sensor consisting of a sensor surrounded by plates perforated with miniature holes. Dedicated procedures were required to manufacture and calibrate this sensor.

On the monopole loudspeaker described here, a standard mini-PU probe can be mounted and is a probe type commonly used in PNCA tests.<sup>2, 4-6</sup> To reduce sound levels, the probe is surrounded by a housing with a small 1.1-mm-diameter hole. Figure 4 shows an example of the particle velocity level measured with and without the pinhole cap. Figure 5 shows the difference between these levels. The offset is similar across frequency; that is, the noise reduction achieved with the pinhole cap is approximately 23 dB.

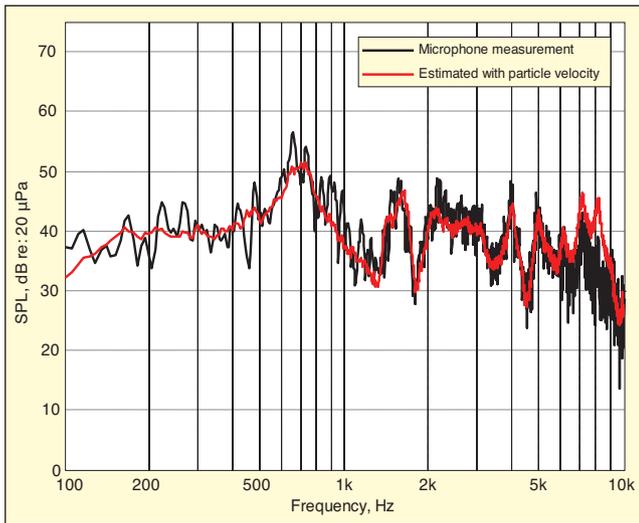


Figure 6. Measured versus estimated sound pressure.

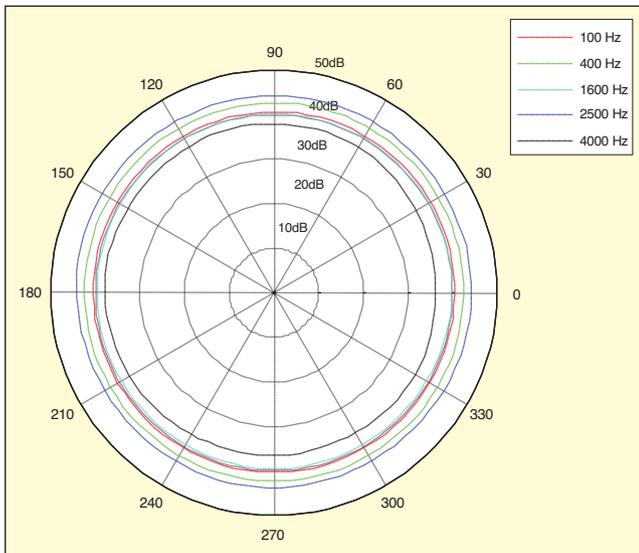


Figure 7. Directivity in horizontal plane.

The standard calibration values of the probe and the 23-dB damping value can be used in calculations to determine the particle velocity up to 7 kHz. Above this frequency, the measured level difference starts to deviate substantially from the 23-dB constant, because the cap is an acoustic obstacle, with its size comparable in size to the wavelength of sound.

To determine the accuracy of the sound pressure estimation, the sound pressure measured at one meter is compared to the predicted sound pressure using the particle velocity measured by a PU probe with the pinhole cap near the center of the sound source. Figure 6 shows the sound pressure at 1 meter from the center of the monopole loudspeaker in a room with some damping materials on the wall. The measured and estimated sound pressure levels are similar, although the result from the microphone measurement fluctuates more with frequency due to room reflections, which hardly affect the particle velocity near the center of the monopole loudspeaker.

The frequency response of this sound source is rather flat compared with the response of typical monopole loudspeakers with long tubes.<sup>8</sup> In tubes, many standing waves occur, and the effect is hard to correct electronically, because temperature variations alter the frequencies of resonance.

**Directivity.** To determine if the monopole loudspeaker radiates equally in all directions, a microphone was installed at a fixed position in a room with few reflections while the monopole loudspeaker was placed on a rotating table. The microphone response was measured for every 20 degrees of incidence. Figures 7 and 8 show the results for the horizontal and vertical plane, respectively.

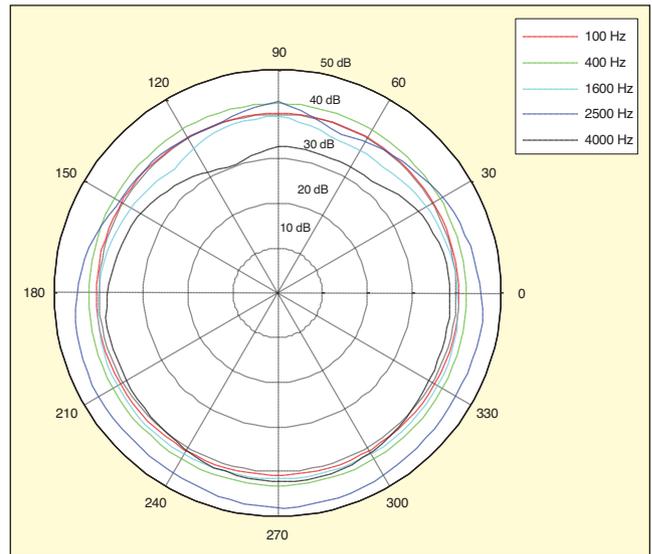


Figure 8. Directivity in vertical plane.

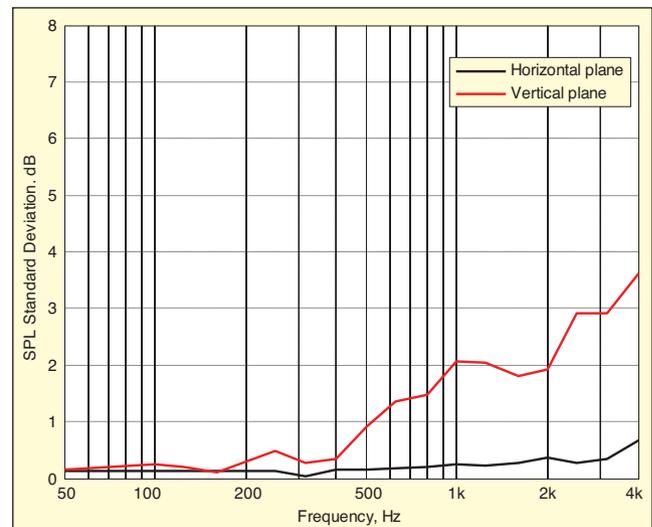


Figure 9. Sound pressure standard deviation at different angles.

As expected, the radiation is similar for all angles of incidence in the horizontal plane, because the geometry of the monopole loudspeaker has nearly rotation symmetry. In the vertical plane, some deviations are found at higher frequencies; these are caused by the loudspeaker's geometry. Figure 9 shows the standard deviation of the sound pressure for all angles for these two planes.

**Maximum Output.** The maximum output of the monopole loudspeaker was determined using a sine-sweep signal from a 200-W amplifier. Figure 10 shows in third-octave bands the particle velocity level at the probe position, the volume velocity level, and the sound pressure level at 1 meter.

## PNCA Tests on an Engine

**Measurement Description.** A test was performed to demonstrate the panel noise contribution principle on an engine. PU probes were installed near the surface of the engine measuring the sound pressure and particle velocity to calculate the sound pressure contribution of parts of the surface. Only six probes were used, so only the rear of the engine was measured, which was assumed to contribute most to the sound pressure inside the vehicle. The vehicle speed was zero during the test, while the engine was kept in idle conditions at 900 RPM. To avoid transmission of structural vibrations, the probes were installed near the engine with goosenecks and a frame of steel pipes that was freely suspended from the car (see Figure 11). For measuring the acoustic transfer paths the monopole loudspeaker was positioned at the reference position (driver's ear position). Installing all equipment and performing the tests took around 50 minutes.

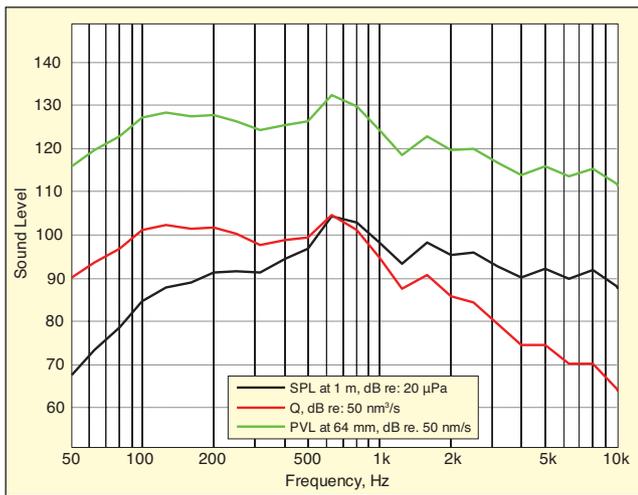


Figure 10. Maximum output levels of monopole in third-octave bands.

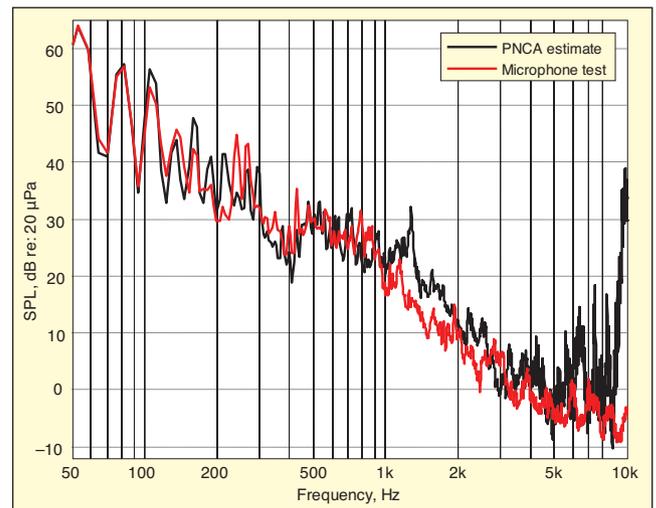


Figure 12. Comparison of estimated and measured SPL.

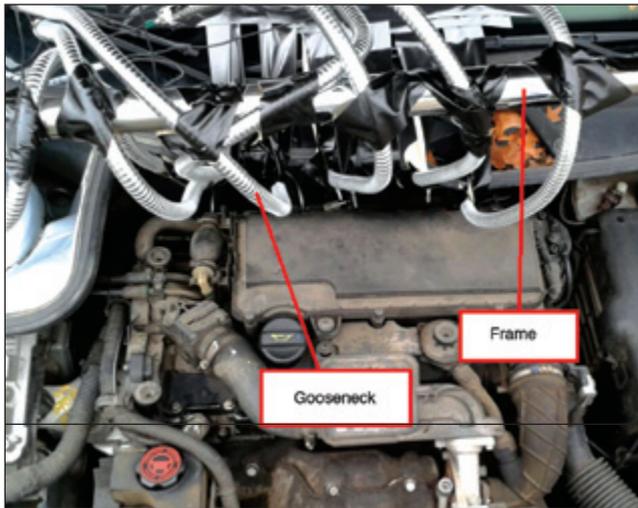


Figure 11. PU probes mounted near engine using goosenecks.

**Measurement Results.** The sound pressure at the reference position in the car was measured with a microphone and estimated using the PNCA measurement method. Figure 12 shows the results. Although the engine radiation is only determined in six positions, the estimated sound pressure matches the direct measurement rather well, especially below 1 kHz. Some discrepancies occur between 1 kHz and 2 kHz; perhaps because not all contributions of the engine were been considered. However, the good agreement between both measurements suggests that the noise sources with the highest contributions in the low-mid-frequency range have been captured rather accurately and that the monopole loudspeaker is suitable for such testing procedures.

## Conclusions

The PU-probe-based PNCA method can be used to determine the sound pressure contributions of separate components to a specific reference position. Several applications have emerged in the past, but measuring the contributions from car engine components directly remained difficult up to now. Recently, suitable probes for measuring the radiation of engine components directly have become available. In this article, a procedure was described to measure the acoustic transfer path from the source to the receiver, involving a loud monopole loudspeaker to achieve a sufficiently high SNR.

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