

# The PU Mini Probe – A Multipurpose Acoustics Sensor

Andrea Grosso and Jeroen Verbeek, Microflow Technologies, Zevenaar, The Netherlands

Sensors for acoustics are usually based on the measurement of sound pressure at the diaphragm of the transducer. Another means of describing a sound field, the vector value acoustic particle velocity, is only directly measurable with Microflow PU probes. These MEMS technology-based transducers utilize two very thin, heated, platinum wires as a particle velocity sensor and a microphone as a sound pressure sensor.

The Microflow PU Mini probe for vibroacoustic testing provides new capabilities for industry from product development to production quality control. The transducer shown in Figure 1 measures both sound pressure and acoustic particle velocity at one point. In 2009, a new version of the probe was developed in close cooperation with a well known test lab and a car manufacturer, both located in the UK. Goals for the redesign included flexibility and the ability to handle near-field applications such as panel noise contribution analysis, scan and listen, near-field acoustic camera and more. The new PU Mini and accessories are well suited for specific acoustic measurements on cars, aircraft, trains, helicopters and space structures.

## Working Principle

Any sound field can be described completely by knowing the following dimensions:

- Scalar sound pressure
- Acoustic particle velocity vector

If sound pressure is the acoustical equivalent of voltage, acoustic particle velocity is the acoustical equivalent of current. Based on MEMS (Micro Electro Mechanical Systems) technology, the Microflow sensor working principle uses two extremely sensitive heated platinum wires that have very little thermal resistance (see Figure 2). If air flow occurs around these wires, heat transfer will take place, causing the upstream wire to be cooled and the air flow to be heated. As a consequence, the downstream wire is cooled just a bit less. The temperature difference that takes place in the sensing region happens to be a direct measurement of the acoustic particle velocity. The sensor voltage output is linear.

The influence of background noise and reflections when using Microflow sensors in the near field is very low. This can be explained by three main effects: directionality of particle velocity; incoming sound waves to a surface – low surface particle velocity and high surface pressure; and outgoing sound waves from the surface of a sound source – high surface particle velocity and low surface pressure.



Figure 1. Redesigned PU Mini probe with “clickable” LEMO connector.

**Directionality of Particle Velocity.** A sound pressure microphone is omnidirectional and measures the sound field in all directions. A PU Mini measures the particle velocity in one direction. Therefore in a diffuse sound field, a PU Mini picks up only one third of the sound field, while a pressure microphone measures the total sound field.

**Incoming Sound Waves to a Surface.** Concerning background noise, the sound pressure level and particle velocity level are of similar magnitude in the free field. If the sound

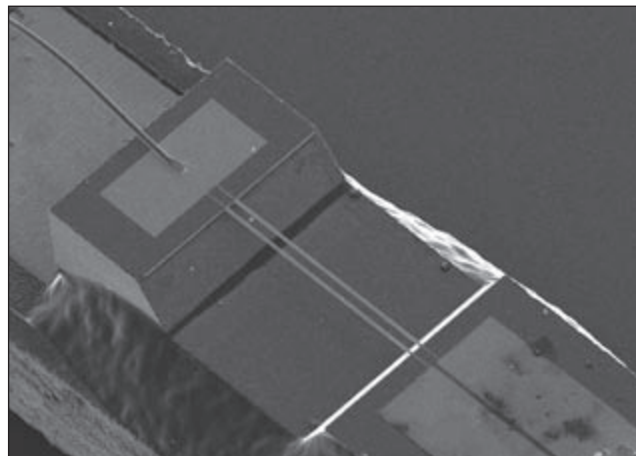


Figure 2. Working principle of the MEMS Microflow sensor.

waves are reflected by a rigid surface, the sound pressure doubles and the particle velocity reduces to zero. Therefore the particle velocity component of the background noise at the surface is often negligible, ensuring that the test object itself is indeed analyzed.

**Outgoing Sound Waves from Surface.** At the surface of a test object close to a vibrating (sound-emitting) surface, the sound pressure level is still low as compared to the particle velocity level that coincides with the structural velocity.

Therefore, to identify a sound source in the acoustic near field, measuring the acoustic particle velocity rather than the sound pressure alone has some distinct benefits.

## Sound Intensity Measurement

According to the mathematics, sound intensity is simply the product of the sound pressure and acoustic particle velocity. The Microflow PU Mini is the world's only sensor directly measuring acoustic particle velocity, so it provides a new approach for measuring sound intensity. PU probes are broad-band transducers (20 Hz-20 kHz) and don't require spacers between sensors. The small size of the sensor allows testing on small objects with high spatial resolution such as computer hard drives or cell phones. Furthermore, PU probes can be used outside of an anechoic room or in reverberant conditions. The sensor is not affected by situations where there is a high sound pressure over intensity ratio. This allows sound intensity measurements on large structures, such as the turbo machinery shown in Figure 3, that cannot be tested in an anechoic room for obvious reasons.

## Scan and Listen

A unique single probe testing method is known as “scan and listen.” Acoustic particle velocity can be made audible when a PU Mini is equipped with a headset, as shown in Figure 4. For example, it allows for the analysis of nonstationary problems or even transients like squeak and rattle. Human ears are like traditional microphones that are sensitive to scalar omnidirectional sound pressure. A combination of a Microflow PU Mini with scan-and-listen hardware allows our ears to be capable of listening to particle velocity! You can really listen to what nobody has heard before. Locating sound sources in actual environments can be difficult. Just listening to particle velocity may provide better results than extensive, detailed FFT analysis. Performing quick scans instead of a time-consuming series of measurements is an intuitive method for sound source location. Acoustic leakages can be detected quickly

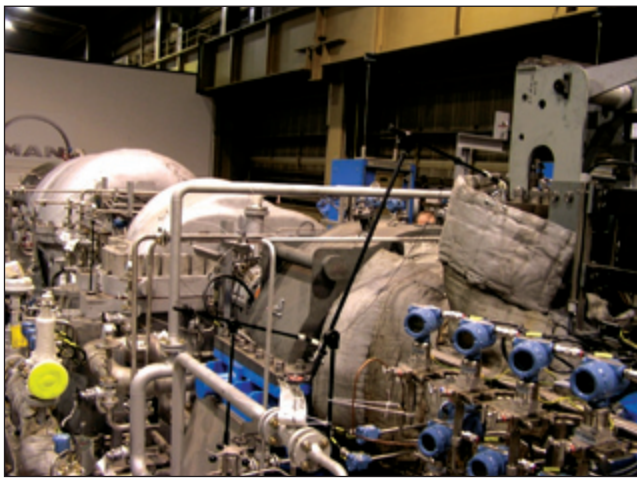


Figure 3. Sound intensity measurements on large turbo machinery under reverberant conditions.



Figure 4. Scan-and-listen operation inside vehicle.

and accurately with the system. The system also has the option to simultaneously record while listening.

### Scan & Paint

The PU Mini can be used in conjunction with a webcam to merge acoustic and video data. Scan & Paint is a new tool to visualize stationary sound fields. Scan & Paint offers a fast method to visualize sound fields over a broad frequency range and can be used in environments with a high level of background noise or lots of reflections.

In practice, there are many cases where ideal acoustical conditions are not available, such as in an engine bay or car interior, as shown in Figure 5. To assess sound quality in terms of radiated sound intensity, a very large number of measurement points is often required. A quick method is now available where the position of the probe is filmed while recording the sound. With synchronization of the sound and position data, a powerful tool can now be used to assess large surfaces in reverberant conditions. Outdoor measurements are also possible (see Figure 6). Furthermore, the same technique can be used for the *in-situ* acoustic testing of materials. Scanning the surface with the *in-situ* absorption setup using scan-and-paint technology will provide high-resolution visualization of surfaces in terms of impedance, absorption and reflection.

### In-Situ Absorption Measurements

The PU Mini can assess the acoustical properties of sound absorption materials (see Figures 7 and 8). The PU Mini-based *in situ* absorption method is a promising new technique. A PU Mini combined with a well defined spherical loudspeaker can test materials nondestructively. As impedance measurements are relative, the loudspeaker can be calibrated independently before

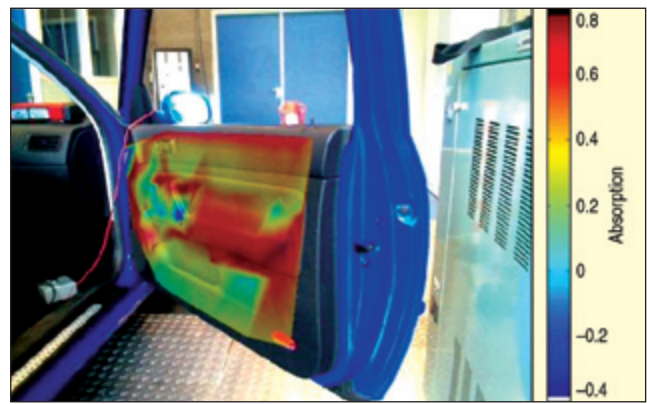


Figure 5. High-resolution Scan & Paint sound absorption mapping of an automobile door panel.

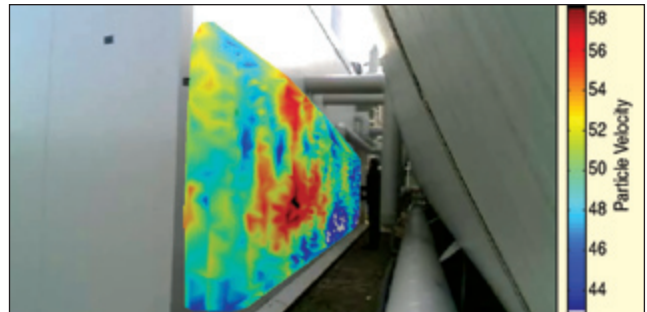


Figure 6. Outdoor Scan & Paint sound particle velocity mapping of the enclosure of a large power generator system.



Figure 7. In-situ absorption measurements in an aircraft.

measuring with the sound source close to the tested material. The sound pressure and acoustic particle velocity are measured right at the surface of the material. The impedance can be derived from the ratio of sound pressure and particle velocity. From this, the material reflection and absorption can be calculated. See the following formulas for impedance, reflection and absorption:

$$Z = \frac{P}{u}$$

$$R = \frac{Z - \rho c}{Z + \rho c}$$

$$\alpha = 1 - |R|^2$$

where:

$Z$  = acoustic impedance, N-sec/m<sup>3</sup>

$P$  = sound pressure, N/m<sup>2</sup>

$u$  = particle velocity, m/sec

$\rho$  = air density, kg/m<sup>3</sup>

$c$  = sound velocity, m/sec

$R$  = sound reflection coefficient (ratio)

$\alpha$  = sound absorption coefficient (ratio)



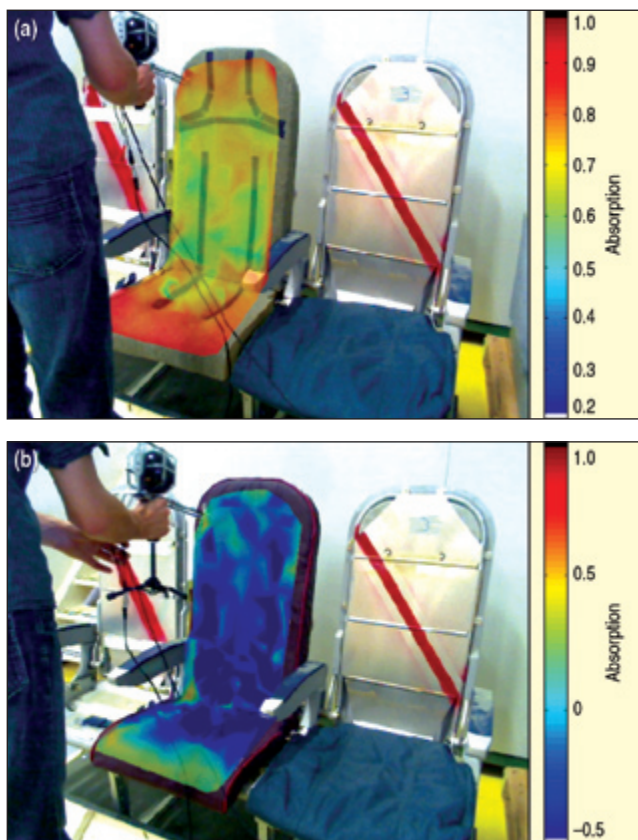


Figure 8. Comparison of airplane seat absorption properties excluding and including fire cover.

The system is able to measure within the audible range, but the lower frequency limit of the method is currently 300 Hz. This is due to the low sound pressure emission from the loudspeaker at low frequencies (and the limited dimensions of the sample). The current usable bandwidth for the method is 300 Hz-10 kHz. Measurements can be made at various angles, high spatial resolution of just a few millimeters, and on all types of materials and sample sizes.

### Near-Field Acoustic Camera

For nonstationary problems where a simple Scan & Paint is insufficient, arrays of PU mini probes can be used. The probes can be mounted in either a fixed grid or in a scattered configuration. The Microflow PU-based near-field acoustic camera shown in Figure 9 is a very fast and accurate system for sound source localization. The PU Mini only needs a single measurement point to determine the acoustic properties of a surface at each probe position. Due to the simplicity of the system and because all quantities are measured, the system can be used within the frequency range of 20 Hz-20 kHz, with a dynamic range of over 40 dB and be able to provide a spatial resolution of a few centimeters. The system can be used to visualize transient sound field properties such as pressure, velocity, and sound intensity in real time. The PU probes are mounted on a 2D array that makes it possible to quickly scan objects and obtain the results almost immediately. A camera is mounted on the grid to reference the measurements to grid location.

### Sound Power Measurements

Automobile manufacturers use components made by many other suppliers in developing modern engines. During the development stage, manufacturers have to comply with technical specifications on each engine component, including noise emissions. Assembled engine components can exhibit different acoustic behavior compared to a free-field noise measurement of each component. Detailed analyses of the radiated sound field from each engine component is required. An acoustical specification is typically given in terms of a sound power emission target. PU probes are very small and cover a broad frequency range without any spacing requirements. Because the sensor is so compact, it can easily



Figure 9. Near-field acoustic camera.

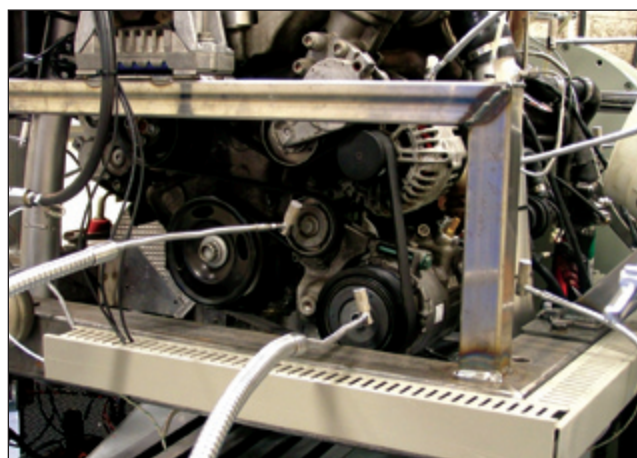


Figure 10. Flexible gooseneck positioning of PU probes make accurate sound power measurements of an automotive engine.

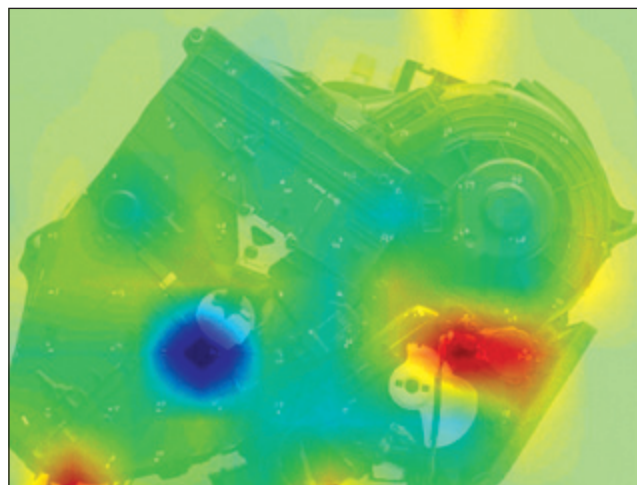


Figure 11. Surface velocity map of an HVAC unit.

be positioned very close to a sound-emitting surface. Direct measurement of particle velocity allows point-to-point measurements instead of a more laborious scanning method.

The use of an array of PU probes as shown in Figure 10 also makes it possible to cover a complete engine with a single measurement. From a technical point of view, a scanning intensity technique can only be used to measure stationary problems. With an array of PU probes, evaluating multipoint measurements in stationary problems becomes possible. As the entire engine is covered and the complete measurement is done in one run, all



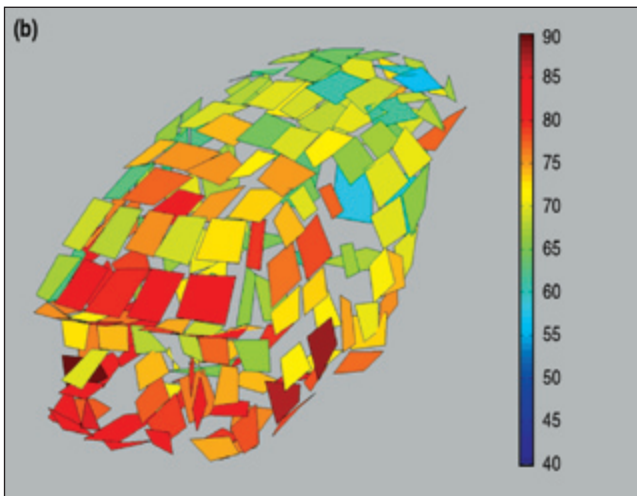


Figure 12. (a) Scattered probe array mounted in an automobile interior; (b) measurement result plotted on a 3D model.

phase information is retained, and accurate results are achieved even at low frequencies. The measurements can even be made in reverberant conditions.

Verifying or improving the acoustical performance of each component provides the information needed to reduce the global noise emission of an engine. The results can be used for development but also benchmarking and comparing results with a database of historical measurements. An additional benefit is that the surface particle velocity measurements can be used for other purposes, such as TPA (Transfer Path Analysis) as the entire engine is measured in one sweep, including phase information (see Figure 11).

### Panel Noise Contribution Analysis

The Microflown PU-based panel noise contribution analysis is a fast and accurate method to measure and analyze sound source distributions inside vehicles. The total measurement can be performed in just one day. Three steps are required to determine a very high spatial resolution detail of 180 panel noise contributions of the interior of a vehicle and to visualize the results in 2D or even in 3D.

The first step is a measurement in the test vehicle during a mode of operation. This step can be done in a laboratory on a roller test bench dynamometer or a wind tunnel, but it is also possible to perform the measurements while driving the vehicle on the road to include wind and tire noise. Stationary as well as nonstationary running conditions, such as run-ups, are accessible and do not limit applicability. The source strengths are determined by measuring the acoustic particle velocity close to the panel surfaces. The second step is determining the transfer paths from the panels to a certain listening position. This measurement is done reciprocally by using an omnidirectional sound source at the listener's position and measuring the sound pressures at the panels.



Figure 13. Three PU Mini probes mounted together as one acoustic vector sensor for outdoor noise measurements.

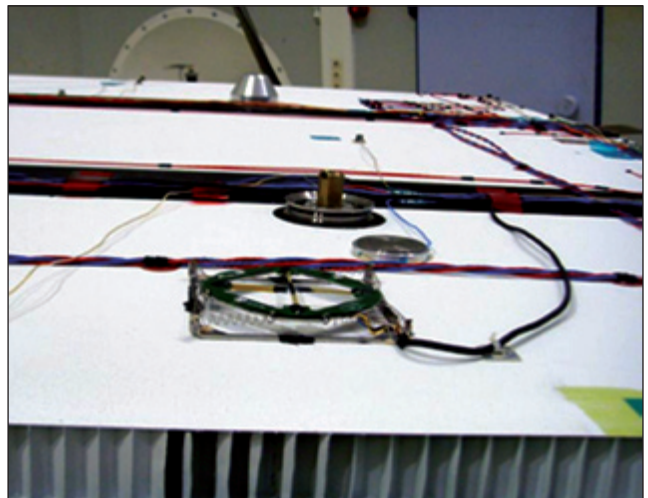


Figure 14. Materials being tested in a reverberant room using a scattered array of probes.

In the final step, the transfer paths of Step 2 are linked with the operational data gathered in Step 1. The results can be analyzed in both the frequency and time domain. A method for panel noise contribution analysis based on PU sound intensity measurements was developed by Faurecia,<sup>1</sup> showing significant benefits over traditional test methods (see Figure 12).

### More Test Methods

**Triple PU Mini System Far-Field Applications.** Three PU probes can be mounted orthogonally to create a triple-PU acoustic vector sensor as shown in Figure 13. This system provides significant benefits for sound source localization compared to pressure measurements. Acoustic vector sensors are unique, since they capture both amplitude and phase information. Thus, powerful signal processing routines can be applied to detect a large number of airborne sound sources. This method has no frequency limitation compared with traditional far-field methods using sound-pressure-based beam-forming arrays.

A single vector sensor can be used to detect two sound sources (indicating both bearing and elevation). Two vector sensors can be used to detect two sound sources (indicating not only bearing and elevation, but also range).  $N$  acoustic vector sensors can be used to locate up to:

- $4N/2$  narrow-band sound sources
- $8N/2$  broad-band sound sources

This is implemented by applying the PARAFAC and MUSIC algorithms.<sup>2,3</sup>

**Noncontact Vibration Measurements.** The Microflown sensor can also be used as an alternative to accelerometers and laser vibrometers for measuring vibration. Close to a rigid object, Microflown acoustical particle velocity sensors can be used for the noncontact measurement of the normal component of the structural velocity.


Close to a vibrating surface, in the so called very near field, the first layer of air is incompressible; therefore, the structural velocity of the surface and the acoustic particle velocity in the neighboring air are of the same magnitude. The Microflown sensor covers the frequency range from 0.1 Hz up to 25 kHz. The sensor can be used on all types of materials and doesn't need line-of-sight positioning. Furthermore, no mass load is added to the object. There is also the possibility of listening to the signal and thus the vibration pattern and modes.

**Quality Control.** Microflown probes are suitable for quality control measurements on the production line. They do not require the use of an anechoic room, and products can be tested in the production environment.

**Space Research.** The vibroacoustic loads that space structures are subjected to during launch are potentially damaging. Both the European Space Agency and Netherlands Space Office are sponsoring the development of new, Microflown sensor-enabled methods for reverberant room testing. Three concepts are being evaluated.

In order to assess the uniformity of the sound field created, the total acoustic energy will be measured based on the acoustic potential- and kinetic-energy. Secondly, the acoustic absorption of a structure will be tested using the in-situ absorption method. Third, in order to achieve a very high spatial resolution, direct near field acoustic camera measurements as shown in Figure 14 can implement PU-based holography routines that can be used in extreme reverberant conditions.

## References

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The author can be contacted at: [verbeek@microflown.com](mailto:verbeek@microflown.com).