MEVAT: MICROFLOWN ENABLED VIBRO-ACOUSTIC TESTING

B. Zajamšek [(1)], **E.H.G. Tijs** [(1)], **M. Wagner** [(2)], **A. Grillenbeck** [(3)]

[(1)] *Microflown Technologies, PO Box 2205, 6802 CE Arnhem, The Netherlands, info@microflown.com*
[(2)] *ESA ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, Mark.Wagner@esa.int*
[(3)] *IABG mbH, Einsteinstrasse 20, 85521 Ottobrunn, Germany, Grillenbeck@iabg.de*

ABSTRACT

Although Microflown particle velocity sensors have been around for several years they have never been tested thoroughly for space related vibro-acoustic applications. Within the framework of the ESA funded MEVAT project, Microflown Technologies has been investigating the feasibility of using PU sensors in high sound level environments in cooperation with ESA and IABG.

The full sound vector can be measured with PU probes, which consist of acoustic particle velocity sensors and a conventional microphone. Applications of such probes range from the vibration, total acoustic energy, sound source radiation, acoustic impedance and/or diffusion measurements. For this project special one-dimensional and three-dimensional PU probes have been developed, as well as the required mountings and calibration methods. A large array has been constructed and their functionality has been tested. Test results from this project will be presented.

1. INTRODUCTION

The task was to design, build and test arrays of PU probes for global and local measurements and to assess the TRL of these sensors. For this purpose special PU probes have been developed and arrays consisting of in total forty-eight 1D and twenty-five 3D PU probes have been manufactured. The objective was to demonstrate their applicability in high sound level environments, to compare results with today's measurement techniques and to identify and verify potential advantages.

The following items are investigated:

- Measurement of total acoustic energy, instead of mere potential energy which is measured by microphones.
- Measurement of the total energy distribution and thus the homogeneity of the noise field, with- and without test article in the room
- Contactless measurement of acoustically induced surface vibrations as alternative to accelerometers or laser Doppler vibro-meters.
- Direct measurement of the input velocity or sound power of sound sources
- Accuracy of the sensor responses at high sound levels and its time sustainability

2. SENSOR- AND PROBE DEVELOPMENT

2.1. Regular PU probes

For many acoustic problems both sound pressure and particle velocity are of interest. In 1994 a sensor called the Microflown was invented that can directly measure acoustic particle velocity virtually in one spot [1], see figure 1 left. It consists of two closely spaced wires which are heated. If there is a particle velocity the temperature distribution will asymmetrically alter [2]. As a result a temperature difference will occur which is then measured. The sensor output voltage is a good approximation and up to high acoustic levels proportional to the acoustic particle velocity. These particle velocity sensors are small, directional and operate in a broad band frequency range. Close to vibrating surfaces, they can measure structural vibrations close to a surface. Combined with a pressure microphone acoustic quantities such as total acoustic energy, intensity and impedance can be determined as well.

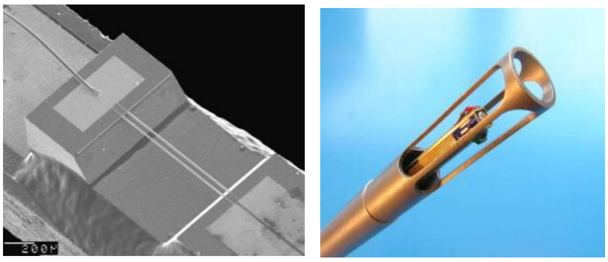

Figure 1. Left: Microflown particle velocity sensor. Right: Regular 3D PU probe

Applications for which they are used include sound source localization (near field & far field), *in situ* characterization of absorption, detection of leakages, and sound source ranking. Compared to classical solutions the most important features of PU probes are their small size, their frequency independent configuration, the high dynamic range of particle velocity measurements in the near field (less influence of background noise and reflections), and the ability to measure intensity in sound fields with a high pressure intensity index (as they are experienced in reverberant fields). A regular three dimensional PU probe for measurements is shown in figure 1 right.

2.2. High sound level sensors

For the intended use in high noise intensity in reverberant rooms and in particular for testing space craft structures conventional PU sensors and mountings have been modified. Several types of 1D and 3D PU probes were designed for measurements at high sound levels as they occur in such reverberant rooms. Also, suitable calibrators have been made. Different low intrusive and robust sensor mountings have been developed with negligible effect on the sound field.

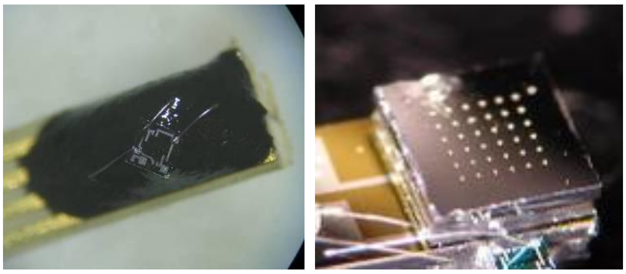

Figure 2. High sound level sensors. Left: sound pressure load cell. Right: particle velocity sensor

One dimensional PU probes consist of one particle velocity sensor combined with a microphone. Three dimensional versions contain two additional velocity sensors which are orthogonally oriented. With this combined sensor pair basic quantities such as vibrations, intensity, impedance and energy can be measured. Load cells are used here for the measurement of sound pressure because of their small size (0.9 x 0.9 x 0.5 mm), see fig. 2 left. For measurements at high levels adapted particle velocity sensors are used. Standard velocity sensors, which normally overload at 135 dB narrow band, are covered by a small protective cap (fig. 2 right). The flow through the sensor is reduced by small perforations in the cap which effectively increases the maximum level and the noise floor of the sensor.

2.3. High sound level PU probes

Several probe versions have been developed for different applications. Separate 1D probes have been manufactured, as well as an array consisting of multiple 1D probes, see fig. 2.

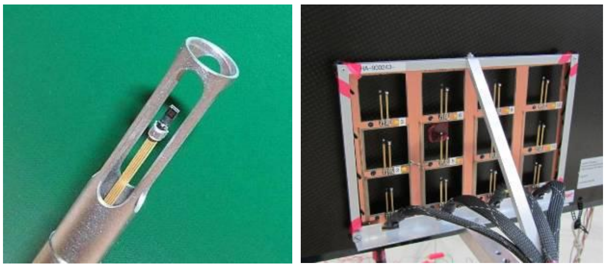

Figure 2. 1D PU probes. Left: ½ inch probe. Right: array of twelve 1D probes

Three dimensional PU probes come in a ½ inch housing (fig. 3, left) or as a surface mounted version which are used for measurements of areas that are difficult to reach, (fig. 3, right). The latter can be installed in front of a surface sensor frame vibrations are decoupled by springs.

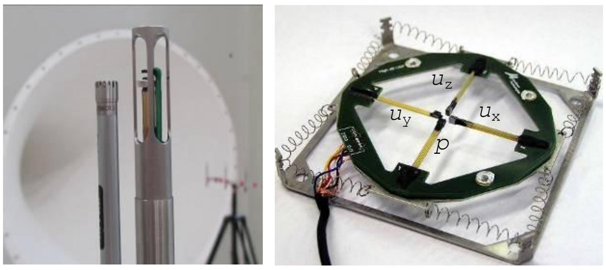

Figure 3. 3D PU probes. Left: ½ inch probe next to a ¼ inch microphone. Right: surface mounted probe

2.4. Calibration

Calibration of particle velocity sensors is important because their amplitude and phase sensitivity varies over the frequency and therefore requires correction.

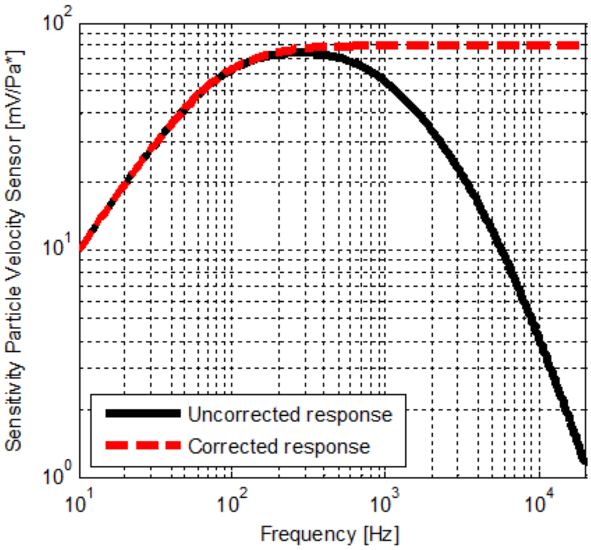

Figure 3. Corrected and un-corrected sensitivity response of a particle velocity sensor.

During the years several techniques have been developed to calibrate particle velocity and sound pressure sensors at low sound levels, e.g. [3]. To calibrate PU probes at high sound levels several methods have been developed within this project for the different probe types and configurations. Each sensor is tested separately. Calibration of the microphone of a PU probe is relatively straightforward; a high sound pressure is generated in a small enclosure and its response is compared to that of a reference microphone that is positioned nearby. Calibration of particle velocity is slightly more elaborate. Existing methods that make use of impedance are not suitable for high sound levels because the sound field becomes non-linear. For this reason a setup consisting of two large speakers is build, see fig. 4. When the speakers are powered in phase there is almost only sound pressure exactly in between the membranes, and no particle velocity. However, when the speakers are powered in anti-phase the opposite is the case. The air can be regarded as incompressible in the small slit in between the loudspeakers and the particle velocity can therefore be compared to the vibration of the membranes which is measured by a reference accelerometer. With these two setups it was possible to calibrate sound pressure up to 160 dB SPL narrow band and particle velocity up to 162 dB PVL narrow band and 167 dB OAPVL.

Figure 4. High sound level particle velocity calibration

Dedicated software for the visualization of all required spectra has been developed in which the frequency dependent sensitivities of the sensors are corrected. Based on the experience of this project it was concluded that for implementation into other software packages an analogue correction by electronics of the probe would be more convenient. Subsequently only one frequency independent sensitivity value, as is common for microphones and accelerometers, might be used then. The aforementioned techniques are available and might be implemented in the future.

3. REVERBERANT ROOM TEST

With a large array of PU probes, (surface) microphones and accelerometers a series of measurements were performed in the reverberant room at IABG. Some of the PU probes were located near sound sources, some distributed throughout the room and some placed near the surface of a test article. In this chapter first the test procedure of the reverberant room will be explained. Next several applications will be introduced and recent measurement results are shown. During or after the reverberant room test no mechanical failures of the probes or its mountings were found. Also responses of the PU probes were consistent during various measurement runs. Their standard deviation is in the order of 5% (0.4 dB).

3.1. Test description

Two test articles were made available by ESA which already were used for other vibroacoustic studies. Hence their dynamic characteristics were well known. The two test articles were a satellite box sized 0.5 m x 1 m x 0.5 m and a plate sized 1 m x 1 m x 0.02 m. The box was bolted on top of a cross-frame, while the panel was suspended below the cross-frame. Measurements were done with- and without these test articles. Fig. 5 shows the full setup with all sensors and test articles.

Figure 5. Setup with all probes, arrays and test articles

The test sequence was as follows:

1. At first only control microphones were installed in an empty room and empty chamber calibration was performed
2. Secondly, sensor arrays distributed throughout the room and near the sound sources were installed to collect PU sensor data of the empty chamber.
3. All test articles and sensors closed to their surface were installed to collect near-field and far field PU sensor data
4. Several measurements at acceptance level were repeated while some PU arrays close to test article surfaces were repositioned for the purpose of obtaining additional spatial information of the noised field

During the tests in total 48 one dimensional PU probes, 25 three dimensional PU probes, 12 microphones, 2 surface microphones and 12 mono-axial accelerometers were used. Several low level, acceptance level and qualification level runs were performed for various configurations. The sound pressure level ranged between 138.9 dB and 146.5 dB OASPL.

3.2. Total energy density

At lower frequencies the sound field has low modal density, especially in small cavities. This means that the results from sound pressure measurements are spatially dependent. Therefore the average value of multiple microphones distributed throughout the room is used in practice. The potential energy density is then calculated and multiplied by two to approximate the full energy density. Direct measurement of the full energy density has the advantage of being more spatially uniform [4]. It can be calculated at any arbitrary point where coherent sound pressure and particle velocity in three orthogonal directions [4-7] are known:

$$\boldsymbol{w} = \underbrace{\frac{\langle p^2 \rangle}{2\rho c^2}}_{w_{\text{potential}}} + \underbrace{\rho \frac{\langle {u_x}^2 \rangle}{2}}_{w_{\text{kinetic dir.x}}} + \underbrace{\rho \frac{\langle {u_y}^2 \rangle}{2}}_{w_{\text{kinetic dir.y}}} + \underbrace{\rho \frac{\langle {u_z}^2 \rangle}{2}}_{w_{\text{kinetic dir.z}}} [W] \quad (2)$$

where p is the sound pressure, u is the particle velocity in each orthogonal direction, ρ is the density of air, c is the speed of sound, and $\langle\ \rangle$ indicates a time average. Figure 6 and 7 show the calculated energies of two probes. For a probe which was positioned far from any reflecting surface the kinetic energy densities in all directions are almost equal to the potential energy density, as would be expected for a perfect diffuse field, see fig. 6. Differences are found for a probe mounted to a panel inside the box (fig. 7), especially the kinetic energy in the direction of the panel is lower (grey line).

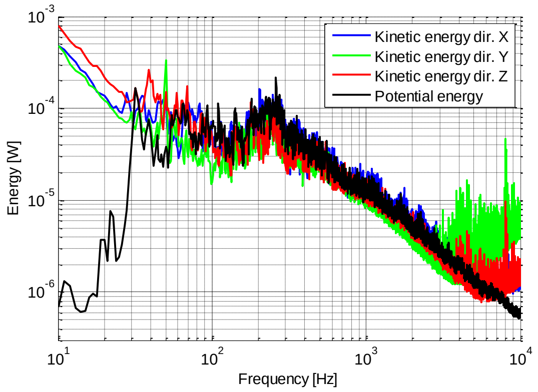

Figure 6. Potential- (blue line) and kinetic energy of a 3D probe positioned away from the test articles

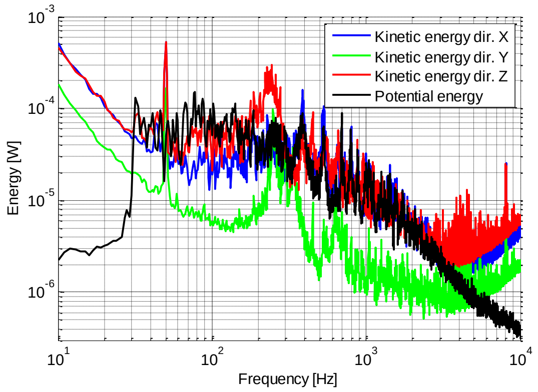

Figure 7. Potential- (blue line) and kinetic energy of a 3D probe which was mounted inside the box.

3.3. Sound field homogeneity

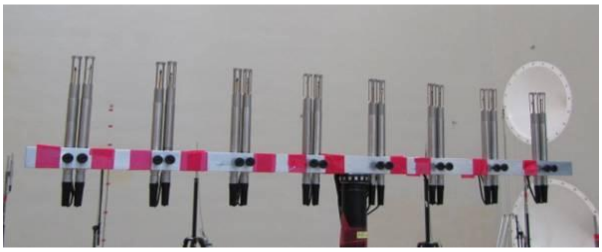

Figure 8. Array with 16 one dimensional PU probes

Sound pressure is a scalar quantity, particle velocity is a vector. The homogeneity of the sound field can therefore be characterized in any particular direction as well. During the measurements in the reverberant room an array of 1D PU probes (see fig. 8) was repositioned 9 times while sound level was kept constant. Three horizontal positions and three vertical directions were measured which resulted in a high number of measurement points. Fig. 9 and Fig. 10 show examples of small pressure and one directional particle velocity variations in the 63 Hz centre frequency 1/3rd octave band over the 2 m (horizontal) × 0.9 m (vertical) large area. The horizontal axis represents the direction towards the horns and the vertical axis the direction towards the roof. Variations in pressure and particle velocity are very small and are in the order of less than 5 dB.

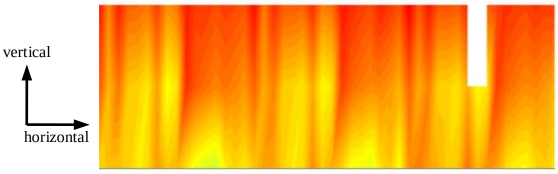

Figure 9. Spatial sound pressure distribution at 63 Hz 1/3 octave band. Due to the failure, one of the sensors was removed therefore white spot in the upper right corner.

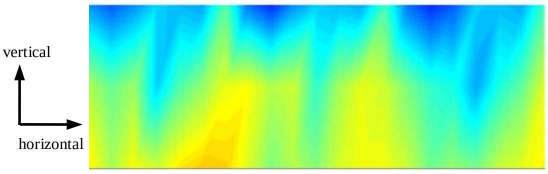

Figure 10. Spatial one directional particle velocity distribution at 63 Hz 1/3 octave frequency band.

Apart from sound pressure and particle velocity also the distribution of quantities such as intensity, impedance and/or energy density might be visualized (results not shown here). In [7] also diffusion measurements have been performed which could be used to characterize the quality of the sound field at arbitrary points in the reverberant room.

3.4. Non-contact vibration measurements

Structural vibrations are commonly measured by accelerometers. The main concern is their influence on the vibrations because they are attached to the surface. Alternatively vibrations might be measured without surface contact by laser Doppler vibrometers, their set-up is not complicated but vibrations of the mounting can cause deviations and laser vibrometers typically are not designed to operate in high level acoustic environment. Microflown sensors measure structural vibrations as well when they are placed very close to a vibrating surface [7-9].

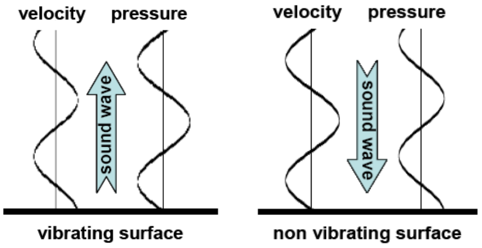

Figure 9. Sound pressure and particle velocity in a near sound field for outgoing and incident sound waves.

Close to the surface, in the so called very near field, the particle velocity of an outgoing wave is almost equal to the surface velocity (Figure 9, left hand side), due to the almost incompressible characteristic of air. The surface velocity for an incoming wave on the other side is almost equal to 0, assuming rigid surface (Figure 2, right hand side). For particle velocity to be directly proportional to vibrating surface velocity the following relationship must hold:

$$r_n \ll \frac{L}{2\pi} \ll \frac{\lambda}{2\pi} \qquad (1)$$

The distance r_n to the surface should be much smaller its typical size: $r > \frac{L}{2\pi}$, and the wavelength λ should be larger than the size of the vibration surface L. Because PU probes are small and light fixtures can be made that suppress the vibrations of its supports.

A surface mounted 3D PU probe and a 1D accelerometer were positioned next to each other inside the box, see fig. 11.

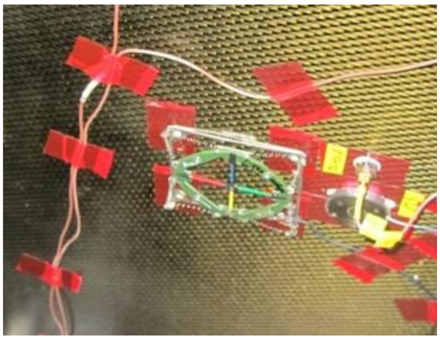

Figure 11. 3D surface mounted PU probe inside the box next to an accelerometer

Figure 12 shows responses of the particle velocity sensor pointed towards the surface (red line) that is compared to that of the accelerometer (black line). Although there are some similarities there is a small offset in the mid frequency range while there are significant deviations at low and high frequencies. In the past measurements have been done with lower levels of background noise where such deviations were not found. Here inaccuracies in the calibration and/or software processing might only have caused small discrepancies since the sensor responses are similar to those of microphones when they are moved further from the panel. Although mean air flow levels are low they might have some influence on low frequencies. Most likely positioning errors are the cause of these differences. Although the matter might be investigated further it is believed that at some distance from the surface (approx. 2-3 cm in most cases) the acoustic (background) noise levels from the reverberant room are high compared to the vibration levels.

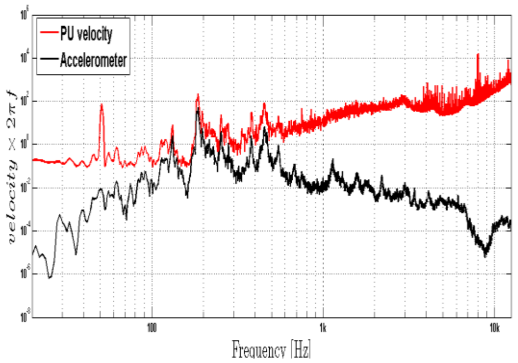

Figure 12. Vibration measured by an accelerometer and a PU probe

3.5. Direct measurement of sound source radiation

With PU probes the radiation of sound sources in reverberant room might be measured directly; either by means of velocity, or by intensity. Close to a sound source acoustic near field conditions apply at low frequencies. In the near field particle velocity is increased more than sound pressure compared to the far field. While sound pressure is influenced by reflections to a large extend, particle velocity is mostly dominated by the direct source. If near field conditions do not apply instead intensity might be used instead. Contrary to intensity probes based on microphones only, PU probes can be used in environments with a high pressure and a low intensity as is the case in a reverberant room [10].

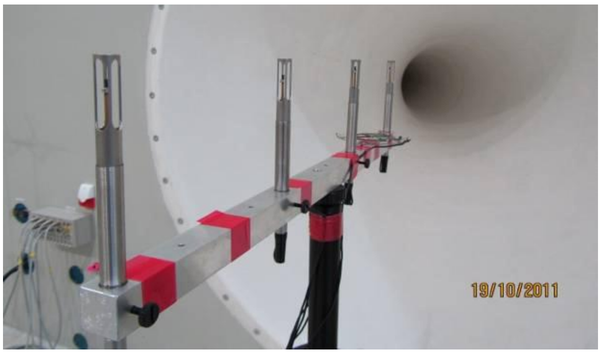

Figure 13. Several PU probes positioned near a horn for determining its radiation

Never before were PU probes used for direct measurement of the radiation of the sound sources in such reverberant rooms. Several probes were positioned near the horns as can be seen in fig. 13. Even though high levels can be expected near the horns, none of the sensors were overloaded. Figure 13 shows the measured velocity and intensity from the probe that was nearest to the horn. Although further validations are necessary both curves are in good agreement. Below 100 Hz there are discrepancies which might be related to flow noise that affects the velocity sensor, or by the high sound source reactivity which increases the error of the intensity calculation.

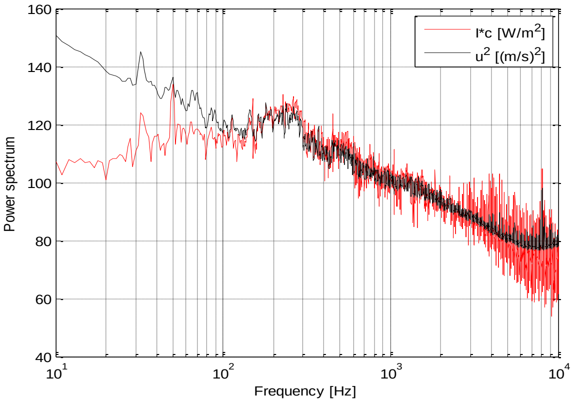

Figure 14. Measurement of sound source radiation

Also the possibility of measuring the impulse response of a sensor in the room has been attempted. In other fields of acoustics impulse responses are e.g. used to isolate (early) reflections. Normally it is not possible to calculate impulse responses because the sound source input signal is not known. Particle velocity sensors near a sound source might be used to capture the direct sound. With this sensor as a reference the impulse response to other sensors in the room can then be calculated. Early measurements show promising results but further investigation is required.

4. CONCLUSIONS

With PU probes sound pressure and acoustic particle velocity can be measured directly in a convenient manner. The feasibility of using PU probes for high sound level reverberant room applications has been investigated within the MEVAT project. For this purpose special probe types, -mountings and -calibrators have been developed. With the calibrators the performance of the sound pressure sensors was tested up to 160 dB SPL narrow band and the particle velocity sensors up to 162 dB PVL narrow band and 167 dB OAPVL. The final reverberant room test involved two test articles and a large amount of 1D and 3D PU probes. The test can be regarded as successful since there were no mechanical defects and none of the particle velocity sensors were overloaded not even those very close to the horns. Their spectra remained constant with time and therefore it can be concluded that probe design is suitable for high SPL environment. Tested features and applications gave very promising results:

- It was found that the kinetic energy in all three directions (which is related to particle velocity) was similar to the potential energy (related to sound pressure) for a probe that was positioned away from the test articles, but near a surface normal components of the kinetic energy are different.
- By repositioning an array of PU probes several times a large virtual array was created and it was shown that directional measurements of the sound field homogeneity can be asses. Obtained results were consistent with theory and previous measurements results.
- Surface vibrations have been measured by particle velocity sensors and accelerometers. However, contrary to earlier measurements significant discrepancies were found in our measurements. It is believed that this is related to the high levels of the acoustic noise at the position of the PU probes compared to the vibration levels.
- Early attempts of measuring the sound source radiation directly were promising and velocity and intensity near the sound source were similar above 100 Hz.

In general can be concluded that quite some interesting results were obtained which promised some potential use in high dB environments. They could be used in high dB testing for estimating sound source input power, for accurate sound field control with fewer sensors, for smaller enclosures where moods are likely to occur, or for non-contact vibrations measurements. Some of the measurements as they are carried out in this project can be viewed as early explorations of the measurement capabilities of high dB PU probes.

5. ACKNOWLEDGEMENTS

We would like to thank HPS GmbH for providing test articles which were used in this project.

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