Benefit of Acoustic Particle Velocity Based Reverberant Room Testing of Spacecraft

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Abstract

The vibro-acoustic load during launch takes a big toll on space structures. In order to simulate the dynamic loading as encountered during launch, both shaker facilities and high sound pressure reverberant rooms are used. Acoustic particle velocity sensors offer interesting new opportunities, for measuring both the applied noise field as well as the structural responses.

Single particle velocity sensors in a so-called U probe can be used for very near field vibration measurements. When they are combined with a microphone in a PU probe the full sound vector can be measured.

The novel perspectives of using PU probes for reverberant room testing comprise:

- The classical control of the noise field and the measurement of the sound pressure level, and of acoustic quantities like the reverberation time may be complemented by making reference to the total acoustic energy.
- The input power of the sound source can be measured directly using PU probes.
- Arrays of U probes can be used to measure contactless surface vibrations at multiple measurement points simultaneously as an alternative to accelerometers or laser vibrometers.
- PU probes can be used to measure local acoustic quantities near the structure like sound radiation, acoustic impedance and energy.
- 3D sound fields around structures can be visualized.
- The degree of diffusion in a reverberation room can be better characterized.

In this paper, the first experience with practical implementation and the results of recent measurements using the PU probe will be presented.

Introduction

Nowadays, particle velocity sensors are used for many applications in industry such as automotive and aerospace, complementing traditional sensor technology, or are even offering entirely novel measurement capabilities. The most important features for some of these applications are the small size of the sensors, their intrinsic directional and broad band behavior, and their low influence to background noise and reflections under certain conditions. Particle velocity sensors are sometimes used alone, to measure structural vibration, or in combination with a sound pressure microphone to measure the sound intensity, impedance and energy.

Here, the perspective of measuring in reverberant chambers under high sound levels is being investigated. Today, typically only two types of sensors are used for the acoustic noise tests for spaceflight: accelerometers are used to measure the vibration; microphones are used to measure the sound pressure.

Accelerometers are relatively cheap, but although they are available in various types their mass can influence the response of the lightweight object under test. Laser vibrometers can be used for non-contact measurements instead, but their application is difficult because their mountings are subjected to vibrations, the number of measurement points is restricted due to the limited test time, and more importantly, it is extremely complicated to reach all outer/inner surfaces or measurement points. Velocity sensors placed close to the surface could be used for non-contact measurements. In the

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(very) near field of a surface the structural vibration almost equals the particle velocity because the air layer can be considered to be almost incompressible [2-5].

Microphones of are used to measure the sound pressure level in the reverberant chamber. But the sound pressure level only represents the potential energy of the reverberant noise field. Using particle velocity sensors, also the kinetic energy could be measured complementing the measurement to record the total acoustic energy at any arbitrary point. Depending on the location in the reverberant chamber the standing waves result in different sound pressure readings from point to point. To reduce this effect, the mean sound pressure of microphone measurements on multiple locations is used.

Sound pressure measured in the vicinity of a structure is also used to estimate the local acoustic load as input for simulation. However, some principles based on sound pressure measurements cannot be used here. E.g. P-P sound intensity probes cannot be used because of the reverberant conditions and because the relation between pressure and velocity cannot be assumed constant at these high sound levels.

This paper will describe the applications of PU probes that are envisaged at the moment. To demonstrate some of these applications the first results of a test on the FRED/ATV solar array wing of Dutch Space [1] will be shown. Many accelerometers and sound pressure microphones were also installed on the panel during this test, and a comparison with these sensors will be made. These activities were made in the frame if the ESA funded project VAATLMDS conducted by Dutch Space and partners. The acoustic test and the measurements were carried out in the reverberant chamber of IABG [6].

1. Applications of PU probes in reverberant conditions at high sound levels

Several applications of PU probes for reverberant room testing of space structures can be envisaged and will be discussed here. The applications involve enhanced or new methods to improve testing on test objects or the performance of the reverberant room.

1.1 Measurement of the full energy density

By measuring the sound pressure only the potential energy is measured. The energy density is approximated with the potential energy alone via [7-10]:

$$E \approx 2 * U = 2 * \frac{p^2}{2\rho c^2}[W] \tag{1}$$

With E being the sound energy, U the potential energy, p pressure, ρ air density and c speed of sound

From the particle velocity vector u the kinetic energy K in one direction can be calculated:

$$\vec{K} = \frac{\rho \vec{v}^2}{2}[W] \tag{2}$$

By measuring both the potential and kinetic energy in three directions the full energy density E can be calculated:

$$E = U + K = U + K_x + K_y + K_z = \frac{p^2}{2\rho c^2} + \rho \frac{u_x^2 + u_y^2 + u_z^2}{2}[W] \tag{3}$$

While the conventional sound pressure based energy measurements by using intensity probes are place dependent, actually the full energy density is a place independent quantity. Accordingly, sound energy measurements could be performed in addition or could even replace all control microphones in a reverberant noise field (typically 5 to 10 control microphones are normally used).

Also for measurements of the acoustic characteristics like the reverberation time and equivalent absorption area, full energy density measurements could be done with fewer probes than with microphones only.

1.2 Direct measurement of the input power

A reverberant room for testing of space structures generally consists of several noise sources to cover a broad frequency range. The noise level inside the reverberation chamber is influenced by the presence of test structures and measurement equipment. The adjustment of the sound level is not so straightforward because the energy is measured indirectly via several control microphones. Because of the long reverberation time it can take a certain amount of time to obtain a stable sound pressure level after adjustment of the sound source level.

A direct measurement of the input power with a PU probe could save time for such an adjustment. The input power could be measured with particle velocity alone at low frequencies, and with sound intensity probes at high frequencies.

In the near field of a sound source almost all direct energy is kinetic energy. The potential energy near the source is much more influenced by the reflections. The assumption here is that the amount of energy being absorbed by the sound source is low. By measuring the kinetic energy with a particle velocity sensor the source can then be characterized at low frequencies [2-5]. This direct measurement of the sound source could also be used as a reference for calculation of the impulse response of all the other sensors, which could be used for measurement of the magnitude and delay of each reflection.

At high frequencies the near field conditions do no not hold anymore. This means the sound intensity should be measured instead [2-5, 11]. However, sound intensity measurements with traditional P-P probes are impossible in these reverberant conditions because of the amount of reflections, or in other terms the p/I (pressure/intensity) index is too high. PU intensity probes are not affected by this p/I index problem.

1.3 Non contact vibration measurements

Close to the surface, in the so called very near field, the particle velocity is almost equal to the surface velocity, due to the almost incompressible characteristic of air. For this relation to become valid two conditions have to be met: the distance r_n to the surface should be much smaller its typical size L, and the wavelength λ should be larger than the vibration surface L [3]:

$$r_n << \frac{L}{2\pi} << \frac{\lambda}{2\pi} \tag{4}$$

Practically the maximum frequency is often 1-2 kHz because it is often not possible to position the sensor very close to the surface and because the typical size of the surface cannot be regarded to be small anymore (at high frequencies there are many material modes).

Accordingly, when placed on a separate mounting, particle velocity sensors can be used for non-contact vibration measurements. Also arrays of particle velocity sensors can be used. Because of the small size of the sensors also measurements inside structures are possible.

1.4 Acoustic quantities near the structure: sound radiation, impedance and energy

Apart from vibration measurements with a velocity sensor only, it also possible to measure other quantities in the vicinity of the structure when these sensors are combined with a sound pressure microphone. Sound intensity, impedance and energy are vector quantities that can be calculated in one or three directions, depending on the number of velocity sensors inside the probe [4-5, 7, 11]. Sound intensity I and impedance Z can be calculated directly with sound pressure p and particle velocity u:

$$I = \frac{1}{2}\hat{p}\hat{u}\cos\varphi\left[W/m^2\right]; \quad (5) \qquad Z = \frac{p}{u}\left[Ns/m^3\right] \quad (6)$$

Where φ is the phase between p and u. The small sensor size allows detailed testing of the surface. Impedance measurements have been done with millimeter accuracy [16]. Many pressure microphone based methods are not valid because of the reverberant conditions and because the relation between pressure and velocity is not linear anymore at high sound levels. Although the measurement of these properties should be possible with PU probes more verifications at high sound levels is still required.

1.5 Visualization of 3D sound fields around structures

The structure under test will influence the sound field inside the reverberant room. Their impact could be measured with 3D sound intensity and energy measurements. In a reverberation chamber, the noise sources are located at a certain part of the chamber. In consequence the noise field may not be ideally homogeneous. Hence it might be useful to measure the distribution of the acoustic load in the empty chamber or around the test object.

1.6 Diffusion

The reverberation time is a scalar quantity for the room absorption and the objects inside chamber. With PU probes it is also possible to characterize the degree of diffusion via the ratio of intensity and energy [8,9]. In [8] a metric called the field index F was developed. Assuming plane waves the following ratio is a metric for the amount of diffusion (ranging from 0 to 1):

$$F = \frac{2|I|}{cE}\left[-\right] \quad (7)$$

Where I is intensity, c is the speed of sound and E is the sound energy. In an anechoic environment the intensity would be high and this ratio would approach unity. In a perfect reverberant room the intensity would be zero.

2. High sound level PU probes

Although it is possible to measure with regular PU probes in reverberant field (figure 1) it was necessary to develop special low sensitive sensors to measure at these high sound levels. The development of these probes is an ongoing business, and previous versions are described in [14-15].

In figure 1d the 3D PU probe is shown that is used for the measurements in this paper. It consists of three low sensitive particle velocity sensors and one pressure transducer. To prevent that there are vibrations via the support the probe is suspended in springs. Some mass was added to the suspension to reduce the resonance frequency to 15-20Hz. The outer dimensions of the probe are 7x7cm, while the sensors themselves are almost at the same spot within a 7x7mm area. The total weight is 17 gram, of which 6 gram is rigidly fixed to the surface, and 11 gram is suspended in spring which can be regarded as dynamic weight that doesn’t influence the structure.

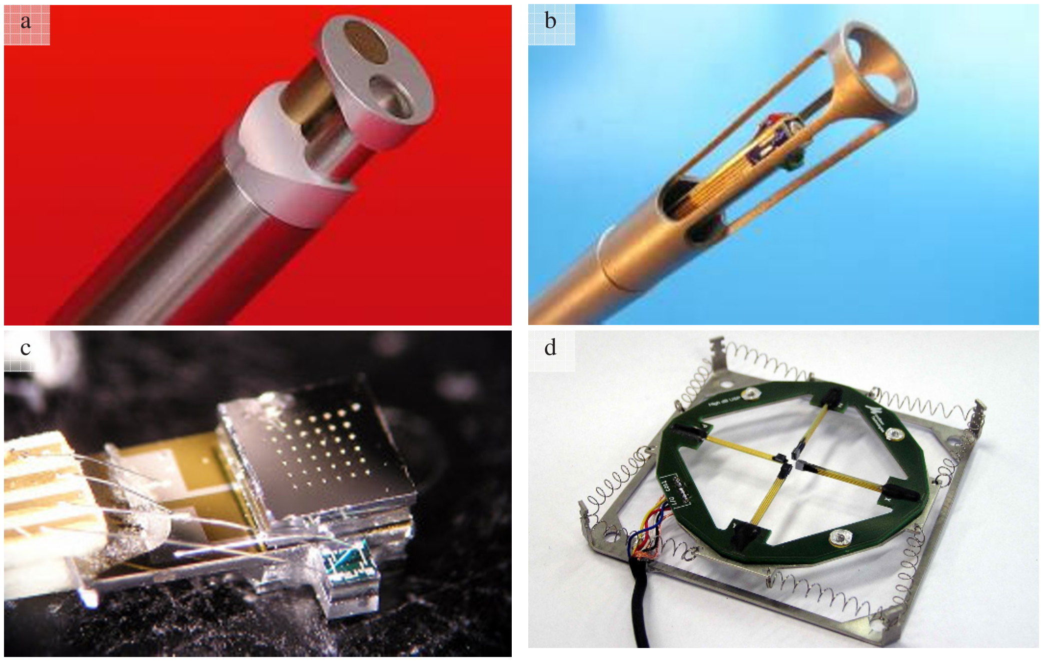

Fig. 1. (a) Regular 1D PU probe, (b) Regular 3D PU probe, (c) High sound level velocity and pressure sensor, (d) The 3D high sound level PU probe that is used here.

3. Description of the test on a folded solar array wing

The objective of Dutch Space and their partners in the VAATMLDS project was to measure the response and acoustic environment characteristics of a bread board wing when exposed to a diffuse sound field [1]. Like during launch, in this test the 4 solar panel layers are folded into a package with outer dimensions of 1805 x 1156mm x139mm, see figure 2 and 3. Most sensors were installed in the 12mm gaps in between the panels.

Fig. 2. Left: Deployed solar array, front view. Right: 3D PU probe next to an accelerometer and a surface microphone. Pictures taken at the premises of Dutch Space.

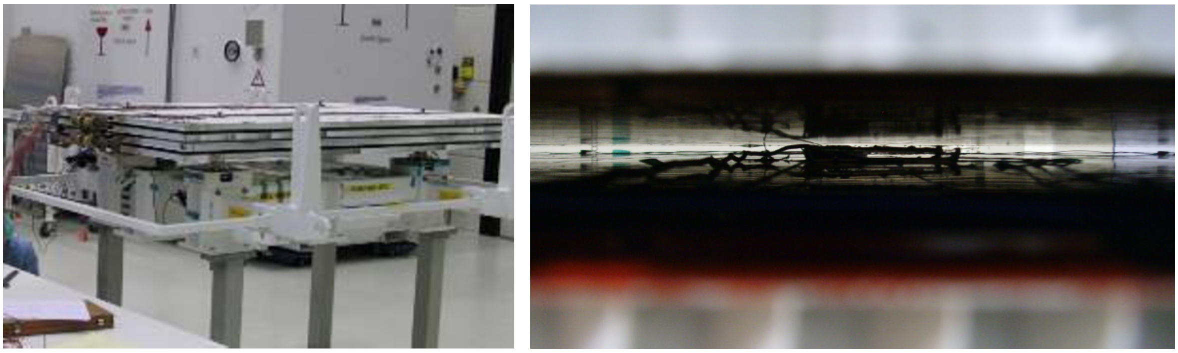

Fig. 3. Right: Stowed solar array (picture taken at Dutch Space). 3D PU probe inside an air gap. (picture taken at IABG).

81 accelerometers and 8 B&K surface microphones were installed on the panel. Also eight 3D velocity probes were installed. A sketch of the sensor arrangement on top and in between the panels is shown in figure 4. Two surface microphones and velocity probes were installed on the top, the bottom panel and on each side of panel number 2. No microphones and velocity sensors were installed on the third panel.

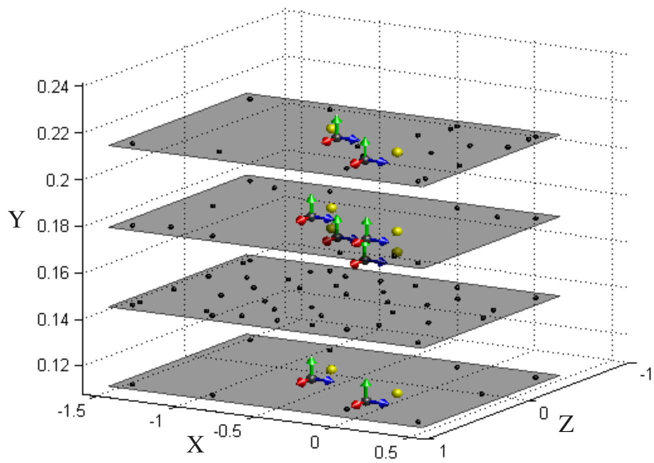

Fig. 4. Exploded 3D view of the sensor arrangement on the solar array wing: 81 accelerometers (small black spheres), eight surface microphones (yellow) and eight 3D velocity probes were installed.

The stowed solar array wing was tested at the reverberant chamber of IABG. This chamber has a volume of 1378m^3 and is capable to generate 156dB OASPL. Five control microphones and 1 monitor microphone were used during the tests. In figure 5 the test set-up is shown.

During this test, first empty chamber calibration runs were performed at 140.2dB, 137.2dB and 133.2dB OASPL. After the integration of the test article, a low level test at 133.5dB was done, followed by an intermediate level test at 137.5dB, an acceptance level test at 140.5dB and finally a post low level test at 133.6dB OASPL.

Unfortunately, something went wrong during the manufacturing process of the 3D PU probes, resulting in the fact that the integrated sound pressure microphones did not work during these measurements. In consequence, the sound pressure signals from the nearby surface microphones were used instead. Also there are several accelerometers relatively close to the probes to compare with. In this paper the sensor names are the same as in [17].

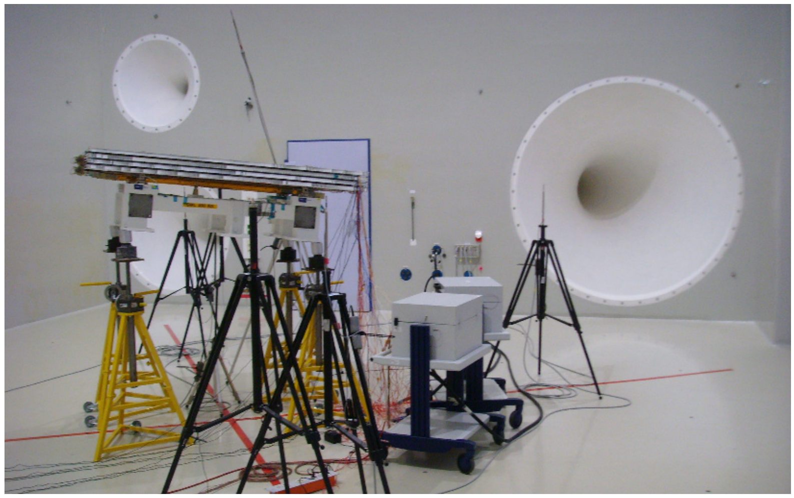

Fig. 5. The stowed FRED/ATV solar array wing surrounded by microphones inside the reverberant chamber. Photo was made at the premises of IABG

4. Measurements Results

Since this was only a first reverberant noise test using the particle velocity sensors, not all the applications that were mentioned in chapter 1 are investigated. In this first step, a comparison could be made with accelerometer and a surface microphone very near to the probe.

4.1 Linearity of the probes

First the linearity of the particle velocity probes is checked. This is done by comparing the spectra of the pre- and the post low level run [1]. There was no visible damage of the probes and the higher level responses are very similar to the lower ones. This means the high level run did not affect the integrity of the probes. As example the responses of probe 4 and the nearby surface microphone are shown:

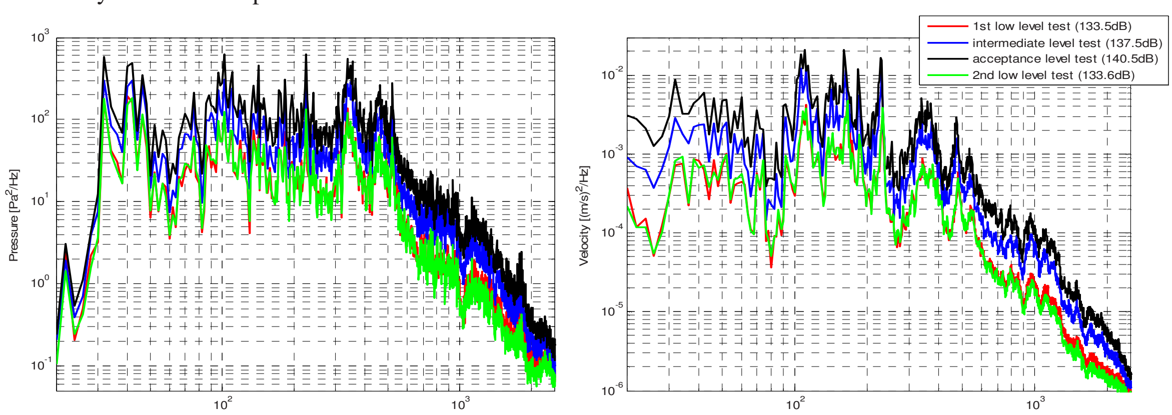

Fig. 6. Power spectral density during several measurement runs. Left: surface microphone SP3-2. Right: velocity element in direction X of PU probe 4. [17]

4.2 Velocity vs. acceleration

The acceleration can be calculated from the velocity sensors that were placed normal to the panels. The results are compared with accelerometers that were positioned nearby. Some results are in reasonable agreement, others not so much. This might be due to the fact that both sensors do not measure at the same position. Two examples are shown in figure 7. In most figures the result of the velocity sensor is higher than the accelerometer. This might be caused by the PU probe suspension system that is used. The resonance frequency of the used suspension spring system is between 15 and 20Hz.

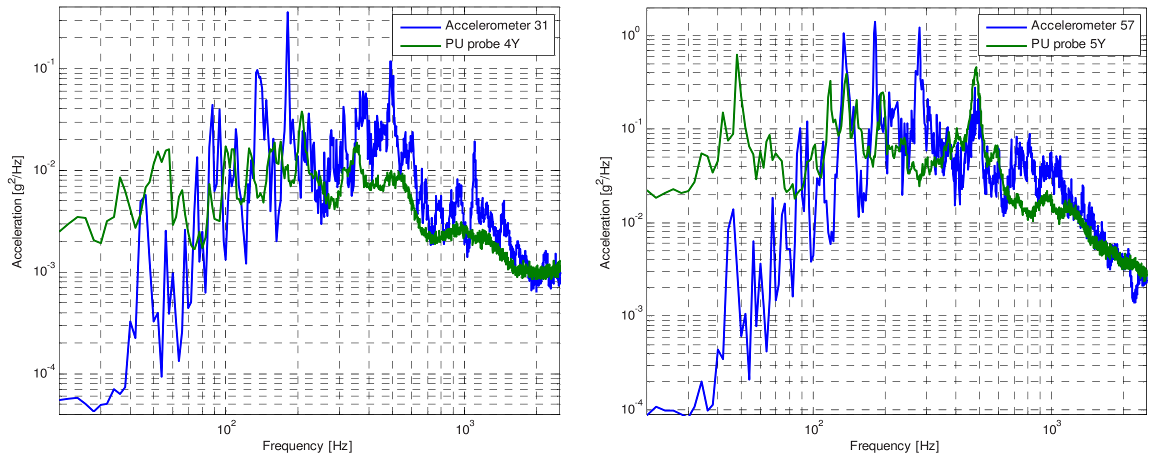

Fig. 7. Acceleration measured with an accelerometer and a velocity sensor. Left: 1st low level run. Right: acceptance level run. [17]

4.3 Energy vs. sound pressure

As mentioned earlier, the potential energy *U* can be calculated from the sound pressure which is often used to estimate the energy density inside the reverberant chamber. The total energy density *E* is the sum of potential energy and the kinetic energy *K* in all three directions. In the following graphs is shown that the 2*the potential energy U is often in quite good agreement with the energy density. In some cases the potential energy is a bit lower and it seems to be affected by standing waves at some frequencies. The kinetic energy component normal to the surface seems to be lowest in all cases.

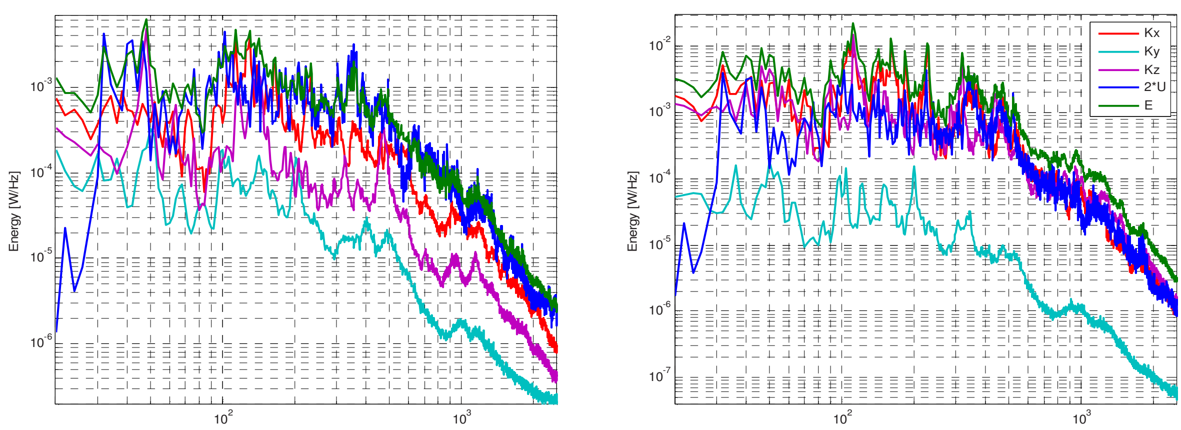

Fig. 8. Kinetic-, potential- and full energy density during acceptance level run. Left: Probe2 and SP1. Right Probe4 and SP3-2. [17]

4.4 Diffusion

From the particle velocity in three directions and the nearby sound pressure the sound intensity and energy can be calculated. In an anechoic environment the field index ratio $2I/cE$ will approach unity. In a reverberant environment this quantity shall approach zero. As expected this value is very near zero here (figure 9, left):

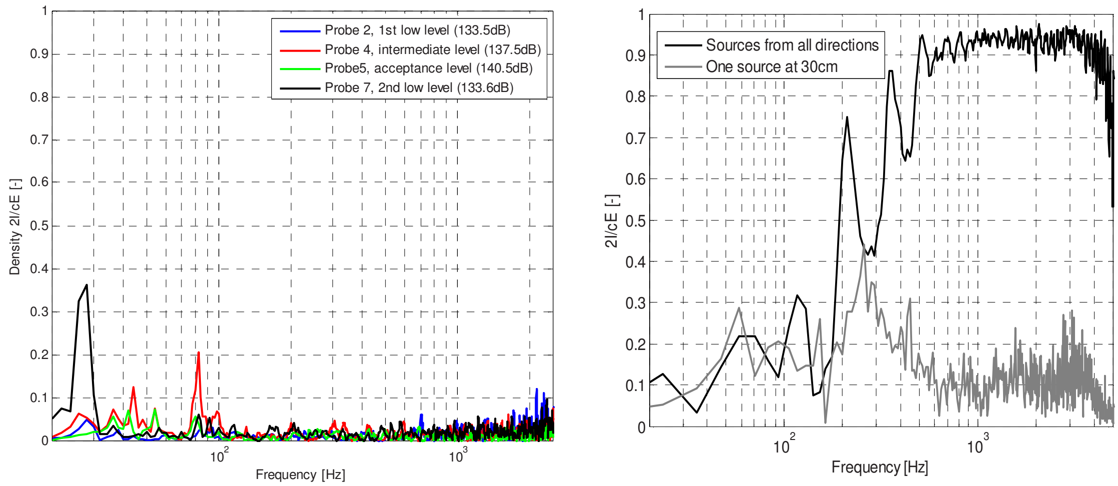

Fig. 9. Left: Diffusion calculated at four different locations and measurement runs. [17]. Right: diffusion in a gym.

A remark has to be made here that for an accurate calculation of the intensity and energy the sensors should be as close as possible to each other (especially at high frequencies). Here the spacing between the surface microphones and the velocity sensors was relatively large (around 15cm in most cases).

In order to demonstrate that the field index is not always near zero the diffusion was also measured in a gym. Two situations were measured; one with sources from all directions, and one with a single source relatively close to the sensor (figure 9, right). With sources from all directions the ratio 2I/cE is low because the intensity is low, while the pressure and energy are high, figure 10 left. The direct signal strength of a single nearby sound source is much stronger than its reflections which have a long path. Therefore the intensity is much higher and 2I is almost equal to the $p^2/\rho c$ and E, figure 10 right.

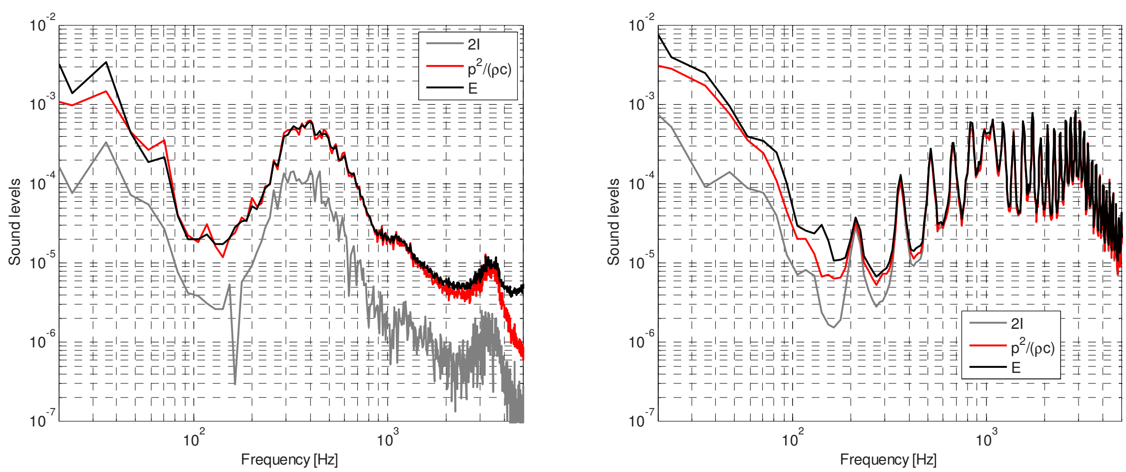

Fig. 10. Scaled intensity, pressure and energy values. Left: Sound sources from all directions. Right: Single sound source at 30cm.

Conclusion & Outlook

PU probes offer interesting opportunities for reverberant room testing of space structures. Here some of these applications were demonstrated with the data obtained from a measurement with a stowed solar array wing. Several sensors were placed on, and inside the array wing. The linearity and structural integrity of the probes have been tested, showing a similar behavior before and after a high level run (140.5dB OASPL). Velocity sensors can be used for non-contact vibration measurements. From the velocity normal to the surface the acceleration is calculated and compared to nearby accelerometers. The results show some differences which might be explained by the variation between different measurement positions and by the suspension system of the velocity sensors. The potential energy (sound pressure based), the kinetic energy (velocity based), and the full energy density (pressure & velocity) are compared. In some cases the potential energy deviates slightly from the full energy as the potential energy can be affected by standing waves. Also the principle of quantifying diffusion is tested with the ratio of intensity and energy. This field index factor shows to be almost zero in the reverberant room while it increases to a maximum of one in an anechoic environment.

There are several ideas that should be tested in the future. Energy, intensity and acoustic impedance could be measured inside, around, or on the surface of structures, or can be used to measure the quality of the reverberant room. With PU probes the input power of the sound sources might be measured directly while being much less affected by reverberations, with the potential of saving time and money.

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