A novel acoustic pressure-velocity based method to assess acoustic leakages of an acoustic enclosure in non anechoic environments

Emiel Tijs[a]
Steven Steltenpool
Microflown Technologies, Arnhem, the Netherlands

Hans-Elias de Bree
MicroflownTechnologies / HAN University dept. Vehicle Acoustics, Arnhem, the Netherlands

ABSTRACT

Several techniques exist to localize and/or quantify sound sources. However, many techniques have frequency limitations and they often do not work well in an environment with a high level of background noise or reflections.

In practice, there are many cases where anechoic conditions can not be achieved, for instance in an industrial manufacturing environment. Hence, pinpointing the acoustic leakage of an acoustic enclosure used to attenuate a loud noise source becomes difficult.

PU probe based sound intensity measurements capturing both sound pressure and acoustic particle velocity are not affected by background noise. Resolving many industrial noise problems under non anechoic conditions becomes easier then.

The spatial average intensity or sound power can be measured by sweeping a sound intensity probe with a suitably long averaging time over a surface. However, information about the precise sound source location is lost.

By measuring the sound intensity separately at discrete points the sound field can be mapped, but this requires many points to be measured in order to reproduce the true overall intensity or to produce a high resolution image.

In order to assess the quality of a large enclosure in terms of its radiated sound intensity at a very large number of measurement points, a fast method was developed where the position of the acoustic consultant is filmed whilst recording the noise. With the synchronization of the noise and position data, a new and powerful tool has become available to assess large surfaces in a relatively short period of time. The theory of PU based velocity and sound intensity methods will be discussed and the practical case will be demonstrated of a large gas turbine enclosure near Arnhem (the Netherlands).

[a] Email address: tijs@microflown.com

1. INTRODUCTION

Several methods are used to localize and quantify sound sources in various frequency ranges.

At lower frequencies the surface velocity can be measured with accelerometers or via laser vibrometry. However installation is often difficult and airborne leakages through the structure are not measured. At higher frequencies the required spatial resolution becomes a problem [1].

Beamforming or near field holography techniques have limitations both at high and low frequencies, and are susceptible by background noise. Errors can be made by assumptions in the model and because the intensity or the surface velocity is not measured directly the exact sound source level can not be determined [2].

At higher frequencies (typically above 100Hz) sound intensity measurements based upon two phase matched sound pressure transducers can be used. Because of the used spacing between the microphone pair, a finite distance approximation error is introduced at high frequencies. More importantly, the p-p intensity method is affected by the so-called pressure-intensity index that can be overcome by creating more anechoic conditions [3-5].

PU probes have a low susceptibility to background noise and can be used in the entire audible frequency range [1-7]. Both the sound pressure and the acoustic particle velocity are measured simultaneously. Two methods are used for a single measurement: one method for the high frequency range and one low frequency method.

Normally sound source mapping with discrete point measurements take a long time. Especially if the subject of interest is a large machine, while still a high resolution image is requested, as is the case in this study. Here a fast method is introduced that makes use of a PU probe that is swept along the surface. While the sensor signals are being measured, a video is recorded at the same time with a webcam at a certain distance. The position of the probe at a certain time can later on be verified via this webcam video.

2. SOUND SOURCE LOCALISATION WITH PU PROBES

A PU probe captures both the sound pressure and the particle velocity signals simultaneously. With the data that are obtained in one single measurement the whole acoustic behavior at a point can be characterized, using two different types of analysis, each of them intended for a particular frequency range.

A. Low frequency method: Velocity based sound source localization

Close to the vibrating surface of the structure, in the so-called very near field, acoustic particle velocity equals the structural velocity of the structure itself [1,7].

The full behavior of the object can be captured with only the velocity, if two conditions are met:

1) The area of consistent velocity should be small enough compared to the spatial resolution of the sensor. At high frequencies the wavelength becomes smaller, and therefore the number of measurement points that is required is increased. Because of limitation in time and sometimes because of sensor size it is not possible to increase this resolution infinitely.

2) Because the velocity is not measured at the surface, but at a certain distance, the sensor will not be in the very near field of the structure anymore at high frequencies.

From an acoustical point of view the advantage of a measurement with particle velocity sensors compared to a measurement with accelerometers or laser vibrometers, is that not only the vibrations of the structure are measured, but also airborne acoustical leakages are included.

The influence of background noise or reflections on the particle velocity sensor is relatively low because of various reasons [6-7]:

- Many surfaces have a relatively high impedance. Close to such strong reflecting objects the sound pressure will increase. At the surface, most potential energy (pressure) and kinetic energy (velocity) will be converted to potential energy, because the surface itself will not move due to external noise sources.
- In the acoustic near field there is a high particle velocity level due to the vibration of the surface itself, compared to sound pressure. In the far field the relation between the pressure and velocity level is just ρ*c (air density times the speed of sound).
- The directivity pattern of the sensor: The velocity sensor has a figure-of-eight sensitivity, whereas sound pressure transducers are omni-directional. This means external sources from other directions are not measured.

B. High frequency method: sound intensity based sound source localization

At a relative far distance from the surface or at high frequencies, very near field conditions are not valid any more. So the total energy from the surface can not be described with velocity only. Sound intensity has to be measured instead.

Traditionally, sound intensity was measured with PP probes. But sound intensity measurements based upon a pair of phase matched sound pressure transducers do have limitations in practice. Bandwidth is limited by the size of the spacer that is chosen.
Furthermore, PP probes cannot be used in environments where there is a high level of background noise or in strong reactive fields, because of the so-called p-I index.

With the PU probe, the particle velocity is measured directly instead of being derived from two spaced pressure microphones. Because there is no spacer issue, the size of the probe can be smaller and therefore sound intensity can also be measured on smaller objects. As the PU probe error is not affected by p/I index problems, it can also be used in situations with a high level of background noise [3-5].

The PU probe error on the other hand, is more determined by the reactivity of the sound field. The error is high if the reactive part of intensity is much higher than the active part. Or in other words: if the phase between sound pressure and velocity is close to 90 degrees. This is typically the case in the near field of a sound source. Depending on the distance from the surface, the probe will be in the near field at lower frequencies.

C. Combining the velocity and intensity approach

So where the velocity method (paragraph 4A) is limited at higher frequencies, the PU intensity method (paragraph 4B) is limited at low frequencies.

A typical high frequency limit for the velocity method is in the range of 500-2kHz. This depends on the sound source characteristics, on the sound field and on the sensor spacing.

A typical low frequency limit for the intensity method is 80Hz-300Hz. Depending on the spatial resolution, the distance to the material and on the source characteristics.

So, depending on the application, the velocity method and the intensity method should produce similar results in a certain frequency band.

An advantage of using intensity is that not only the strength but also the direction is known. Sound could also go inwards the material. Velocity data from itself only provides amplitude information. It can be necessary to include the phase of velocity, not only for the direction, but also because at lower frequencies acoustic sources can be expected to be coherent. Sources might not just only radiate sound, but they might also interact with each other (partially). For instance, sound might also be being pumped between panels.

To include the phase it is necessary to apply (multiple) reference sensors to correlate with vibration of the overall structure. Another principle is to use the phase of the pressure sensor inside the probe as a reference. However, during this study such a reference sensor was not used.

5. SURFACE MAPPING PRINCIPLE

A novel technique was developed to visualize the surface velocity and intensity data captured with the speed of a sweep. Because not all surfaces are measured simultaneously the sound source should be stationary. The method produces a high resolution sound color map. The procedure is as following:

1) With a two channel sound card the particle velocity sensor and the sound pressure microphone signals are measured. Because of the Windows drivers normally the reference voltage of a sound card is unknown. To calibrate the absolute value of the sound card input a signal with a known amplitude value is applied. During these measurements the sensor signals are also measured with an analyzer as backup.

2) Before the measurement was started a webcam was installed on a stand with a view that covers the whole area of interest. At the same time as the sound is recorded also the video from the webcam is captured.
At the beginning and end of each session a person clapped his hands in front of the camera. This is to verify that the video and sound recording are synchronized.

3) After this the data are post-processed. From the video data all images are observed with certain intervals. In this study frames are used each 0.2 seconds. From each frame the location of the sensor can be seen in the screen and the position of the sensor at that time frame is documented by selecting the position in the screen.

4) A certain period of time is needed for the calculation of the acoustic data. At each measurement point the velocity and intensity are calculated from a time period before and after this moment.
Because of this reason the operator should not scan the surface too quickly. Otherwise an acoustic event might also be included at other positions. Depending on the required frequency range this time period might be changed.
Here a time window of 0.75 seconds is used and the probe is moved with roughly 0.3m/s. To measure very low frequencies a longer time window would be required. To increase the spatial resolution the probe should be moved slower.

5) The value of the nearest measurement point is assigned for each pixel in the image and is plotted.

6. PU SOUND MAPPING MEASUREMENTS ON A LARGE ENCLOSURE

A. Measurements description

The first object under test is a large outdoor machine enclosure around a gas turbine near Arnhem, the Netherlands. The outer dimensions of the housing are 12 x 6.3 x 3.8m, without the chimney. This turbine is used for generation of electricity and heat for the nearby green house. The total measurement time to scan the acoustic behavior of the housing was roughly 5 hours.

Despite of the fact that acoustic damping material was applied in the enclosure, there were still complaints from neighbors about the noise level. Multiple sound pressure measurements at some distance from the housing show that there are high levels at low frequencies and at 6300-8000Hz. The high frequency component is caused by the turbo on the gas turbine.

With a single PU probe on a pole the surface is scanned. The probe is mounted in a vibration free suspension to protect against vibration of the sensor support. To shield against wind a Rycote wind cap is used.

A. Measurements on the left chimney of the gas turbine enclosure

The front part of the chimney is measured first. The surface is covered by the probe and the measurement points with the corresponding time are selected, see figure 1.

Figure 1: Webcam image of the front part of the left chimney with a selection of measurement points

Now the measurement time and measurement location are selected, the velocity and sound intensity can be calculated. Several things can be concluded:

- The color map requires a rectangular array as input, but this is not necessarily the case for the measurement area. The value of the nearest measurement point is assigned to each pixel. The areas far from any measurement point should not be considered.
- At some frequencies the mode of the panel can be recognized (figure 2 left).
- Because of the high spatial resolution of the measurement points, the velocity image can in some case give a result similar to the intensity color map (figure 2 middle and right).
- At many frequencies there is sound leakage at the chimney opening at the top, but high frequency components from the turbo are much more pronounced at the bottom.

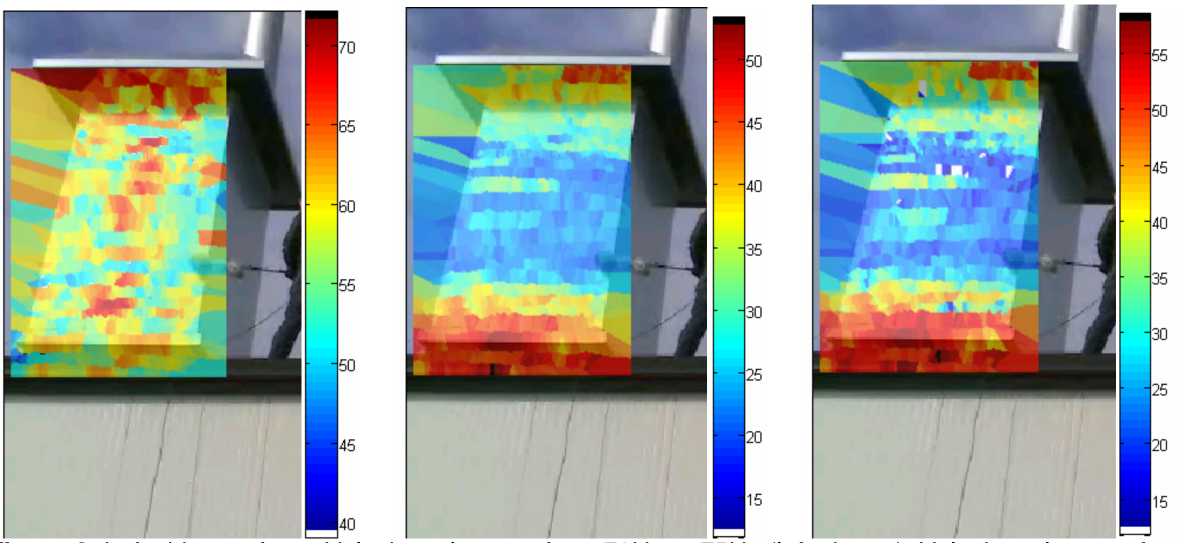

Figure 2: Left chimney front. Velocity color map from 70Hz to 75Hz (left picture). Velocity color map from 7063 Hz to 7095Hz (middle picture). Intensity color map from 7063 Hz to 7095Hz (right picture)

B. Measurements on the backside of the gas turbine enclosure

At the backside of the gas turbine enclosure there is another installation. For this reason the webcam had to be installed at an angle (figure 3).

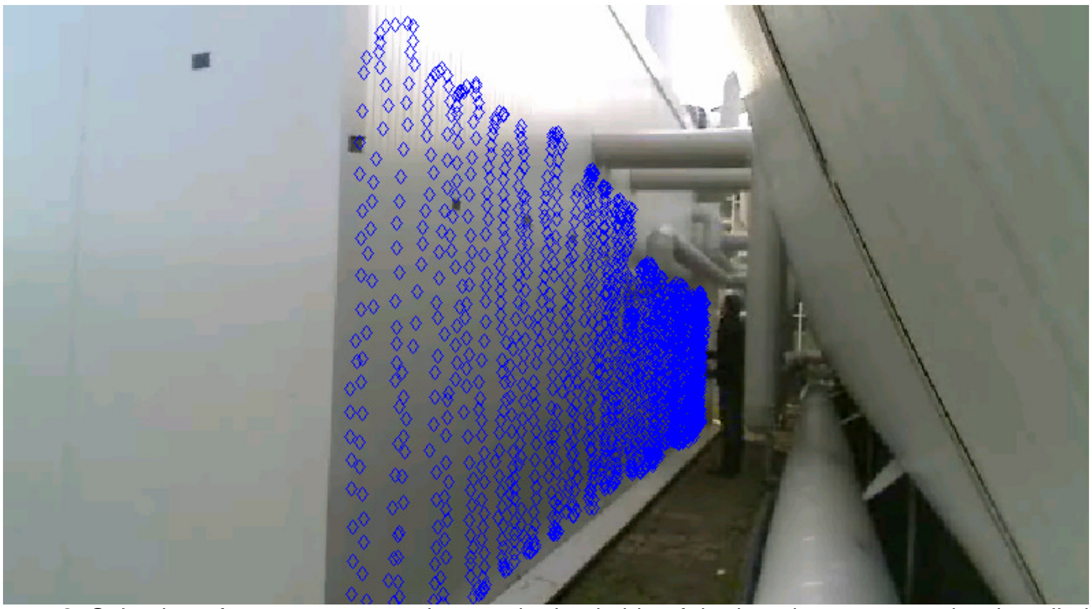

Figure 3: Selection of measurement points on the backside of the housing, near another installation

- For sound source localization purposes it is often necessary to look at narrow band information instead of looking at (1/3) octave bands. As can be seen in figure 4 sometimes a slight increase in frequency can show a very different sound radiation pattern.

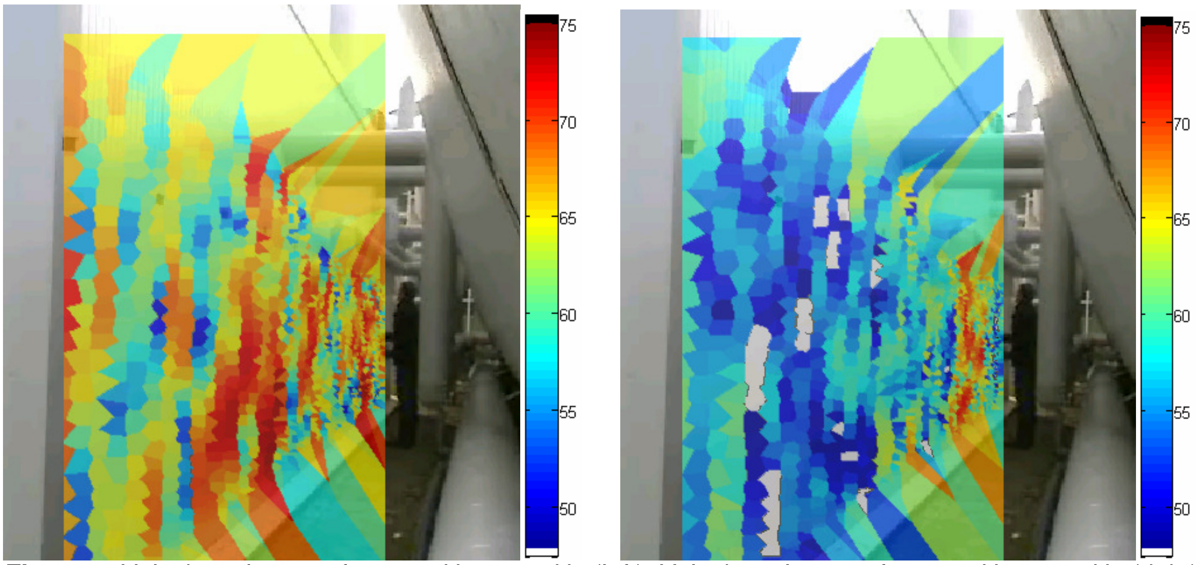

Figure 4: Velocity color map from 124Hz to 129Hz (left). Velocity color map from 162Hz to 167Hz (right)

C. Measurements on the front of the gas turbine enclosure

- The same frequency dependent behavior can be seen at the front part of the enclosure (figure 5 and 6).
- At for instance 124Hz to 129Hz the modes of the panels can be recognized. At the location of the vertical girders (figure 5, red dotted lines) there is less sound radiation than in the middle of the panels.
- There is little sound radiation from the right section of the enclosure. Behind this section there is a separate room without machinery, with extra layers of damping material.

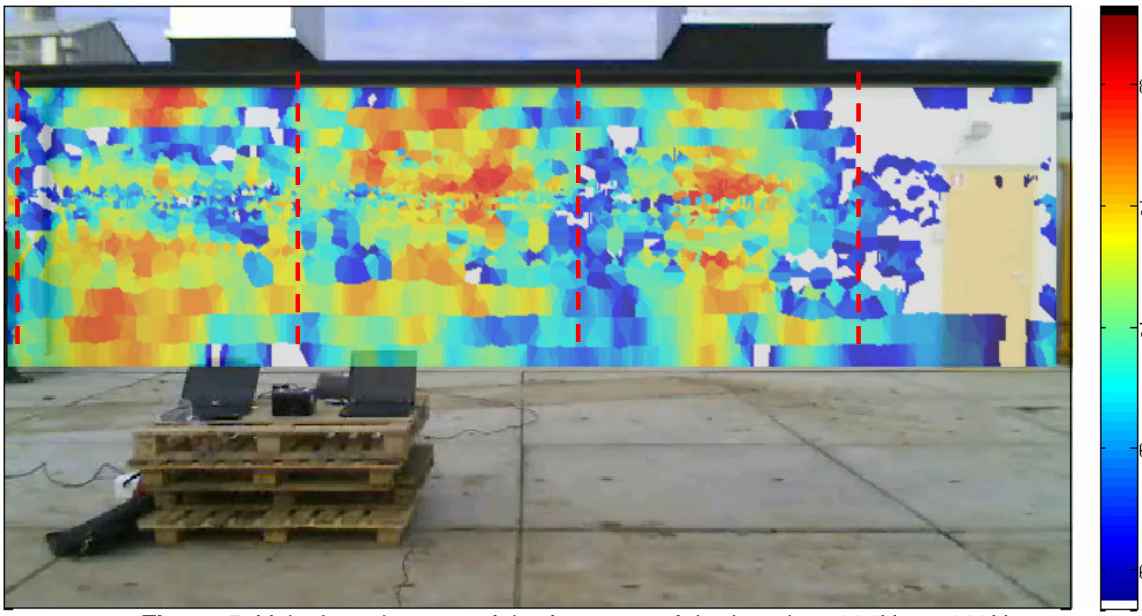

Figure 5: Velocity color map of the front part of the housing: 124Hz to 129Hz

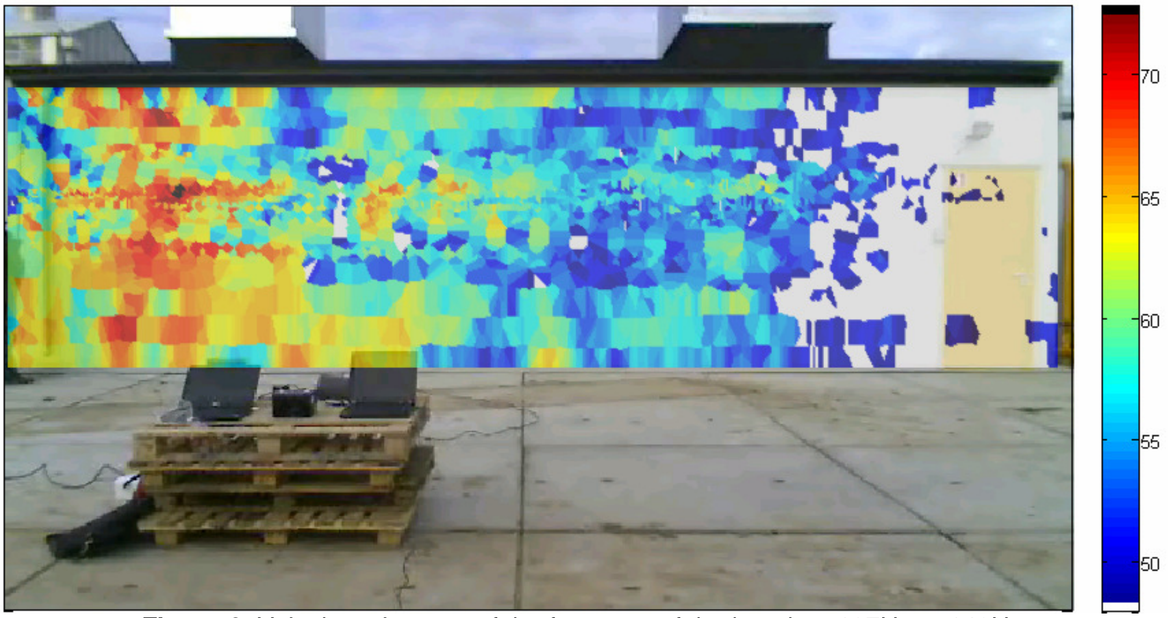

Figure 6: Velocity color map of the front part of the housing: 137Hz to 140Hz

4. CONCLUSIONS

Existing techniques to measure sound sound sources have limitations and a PU probe based scanning method may offer an alternative, capturing both acoustic particle velocity and sound pressure.
In the low frequency range, non contact acoustic particle velocity based measurements can be an alternative for accelerometers or scanning lasers which do not measure airborne sound.
In the higher frequency range, PU probes overcome the limitations of PP probes in terms of bandwidth, spacers, small size when required and use in non anechoic conditions.

With a PU probe a large bandwidth can be measured in one time, using two different types of analysis. At low frequencies the velocity data of the sensor is used and at higher frequencies the intensity data.

A new concept is presented to scan the acoustic performance of large surfaces with a PU probe, while maintaining a high spatial resolution that is needed for sound source localization. The scanning procedure is recorded with a webcam, and in a post processing step the audio and video data are synchronized. After the measurement, the location of the probe is selected at each time frame, by selections with a mouse click in the program. As an end result, an acoustic color map of velocity and sound intensity can be visualized with high resolution.

The method was successfully demonstrated on a gas turbine enclosure on an industrial site in the presence of background noise.

4. FUTURE WORK

Especially for outdoor applications a protection against wind and vibration is needed. The vibration free support is sufficient for most vibrations, but not when the probe hits the surface. During post processing it is difficult to exclude the measurement locations that are affected by this. An idea is to mount an accelerometer on the probe as well to detect any strong vibration of the probe support.

The selection of each measurement point is still time consuming. Especially when the required resolution is high and the measurement area is big. An automatic detection might be useful. The software should be able to recognize the measurement location. To make this possible the wind shield might for instance be intensely colored or be supplied with a (infra red) led light.

REFERENCES

1. Panel contribution analysis, an alternative window method, O. Wolff and R. Sottek, SAE 2005

2. Near Field Acoustic Holography with particle velocity transducers, F. Jacobsen and Y. Liu, JASA, 2005

3. Verification of PU intensity calculation, E. Tijs, A. Nejade and H.E. de Bree, Novem, 2009

4. A Comparison of two different sound intensity measurement principles, F. Jacobsen and H.E. de Bree, JASA, 2005

5. Intensity based sound power determination under adverse sound field conditions : P-P probes versus P-U probes, F. Jacobsen and H.E. de Bree, ICSV, 2005

6. A particle velocity sensor to measure the sound from a structure in the presence of background noise, H-E. de Bree and W.F. Druyvesteyn, Forum Acousticum, 2005

7. The very near field; theory, simulations and measurements, H-E de Bree, V. Svetovoy, R. Raangs, R. Visser, ICSV, 2004