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# APPLICATION OF VIRTUAL SENSORS IN THREE DIMENSIONAL, BROADBAND ACTIVE NOISE CONTROL AND THE EFFECTS ON THE QUIET ZONES

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This paper presents various experimental results of a real-time, multiple-channel, broadband Active Noise Control (ANC) system, employing the Remote Microphone Technique (RMT) as virtual sensing algorithm in different settings. The effects of virtual sensing on the shape and size of the quiet zone are experimentally investigated.

To enhance the quiet zone, an acoustic energy density probe can be used as error sensor. Such a sensor not only measures sound pressure, but also the particle velocity in three directions, providing four signals to be minimized by the ANC system. The RMT is used to construct a virtual three dimensional, acoustic energy density probe, which is validated in real-time ANC. In conclusion, advantages, drawbacks and practical considerations of using RMT virtual sensing in active noise control are discussed.

## 1. Introduction

Local active noise control (ANC) systems aim at creating quiet zones in a *primary* noise field by introducing a *secondary* noise field that (partly) cancels the primary noise field at certain locations. This is generally done by minimizing the sound pressure that is measured by one or more *error sensors*. As a result, the *quiet zones*, i.e. the volumes where the noise reduction exceeds 10 dB, are centered on the error sensors. The quiet zones tend to be small, especially when the undesired noise contains higher frequencies. Therefore, the error sensors should be placed in close proximity to the user's ears, to maximize the perceived noise attenuation. This is not always possible or desirable.

To overcome this problem, various virtual sensor techniques have been proposed [2, 3, 4, 5], of which a comprehensive overview is given in [6]. With these techniques, the sound pressure signals at specific locations, referred to as *virtual locations*, e.g. near the user's ears, are estimated using the measurements of sensors that are placed in more convenient locations, referred to as *physical sensors*. The estimated signals are then minimized by the ANC system, resulting in quiet zones centered on the virtual locations. The virtual sensor algorithm used in this paper is the Remote Microphone Technique (RMT), by Roure and Albarrazin [3]. It is implemented in a real-time ANC system and tested in two experimental setups.

Elliott et al. [1] have calculated that the quiet zone in a fully diffuse, pure tone sound field is spherical, with a diameter of approximately one tenth of the wavelength of the tone. This result is often used as a rule of thumb in various other active noise control setups, such as broadband multiple-channel active noise control in enclosures. We will investigate if this rule of thumb can be applied to RMT ANC as well. To enhance the quiet zone, an acoustic energy density probe can be used as error sensor. Such a sensor not only measures sound pressure, but also the particle velocity in three directions, providing four signals to be minimized by the ANC system [9]. Using the RMT, a virtual three dimensional, acoustic energy density probe is constructed and tested in the real-time ANC system.

## 2. The Remote Microphone Technique in Active Noise Control

In a conventional ANC system, an undesired primary noise signal $x(n)$ is to be minimized at certain locations. This is done by introducing actuators (e.g. speakers) and placing sensors (e.g. microphones) at those locations, such that the sound emitted by the actuators minimizes the signals that are captured by the sensors. To calculate the actuation signals, an adaptive feedforward algorithm is often used, where a recording of the source signal (i.e. the *reference signal*) is adaptively filtered, with the *error signals* that are measured by the sensors adapting the filter coefficients in order to minimize the error signals. If it is undesirable or unfeasible to place sensors at the locations where one wishes to minimize the undesired noise, a virtual sensor algorithm, like the RMT can be used. With such an algorithm, *physical sensors* are placed at feasible locations and its measurements are used to reconstruct the signal at the locations where reduction is desired, thus creating *virtual sensors* at those locations.

Figure 1 shows the RMT in an ANC setup, schematically. The undesired signal $x(n)$ travels physical primary paths $\mathbf{G}_{px}$ and virtual primary paths $\mathbf{G}_{vx}$ to $M_p$ physical and $M_v$ virtual sensors positions, respectively. At these locations, the noise is observed as physical and virtual disturbance signals $\mathbf{d}_p(n)$ and $\mathbf{d}_v(n)$, respectively. The $L$ actuation signals $\mathbf{u}(n)$ travel physical and virtual secondary paths $\mathbf{G}_{pu}$ and $\mathbf{G}_{vu}$ to arrive at the physical and virtual sensor positions as $\mathbf{y}_p(n)$ and $\mathbf{y}_v(n)$ respectively. The physical sensors measure $\mathbf{e}_p(n) = \mathbf{d}_p(n) + \mathbf{y}_p(n)$ and the virtual sensors would, if it were real sensors, measure $\mathbf{e}_v(n) = \mathbf{d}_v(n) + \mathbf{y}_v(n)$. Actuation signals $\mathbf{u}(n)$ are calculated using the normalized Filtered-x Least Mean Squares (nFXLMS) algorithm [7, 8]. Note that the inputs of the nFXLMS are the reference signal, which is here assumed to be a perfect source measurement and the reconstructed virtual error signals $\tilde{\mathbf{e}}_v(n)$, which are to be minimized. The RMT calculates signals $\tilde{\mathbf{e}}_v(n) = \tilde{\mathbf{d}}_v(n) + \tilde{\mathbf{y}}_v(n)$, using $\mathbf{u}(n)$, $\mathbf{e}_p(n)$ and estimated transfer functions $\tilde{\mathbf{G}}_{pu}$, $\tilde{\mathbf{G}}_{vu}$ and filter $\tilde{\mathbf{H}}$, which relates the estimated disturbance at the physical locations $\tilde{\mathbf{d}}_p = \mathbf{e}_p(n) - \tilde{\mathbf{y}}_p(n)$ to the estimated disturbance at the virtual locations $\tilde{\mathbf{d}}_v(n)$.

The RMT can be set up in four steps:

1. Sensors are placed at the virtual locations. An input-output data set of $\{\mathbf{u}(n), \mathbf{e}_p(n), \mathbf{e}_v(n)\}$ is recorded.
2. The physical and virtual secondary paths are estimated as $\tilde{\mathbf{G}}_{pu}$ and $\tilde{\mathbf{G}}_{vu}$, respectively. Note that a similar procedure is already carried out in setting up the nFXLMS algorithm, which also uses an estimation of the secondary path.
3. The physical and virtual disturbance signals are estimated according to $\tilde{\mathbf{d}}_p(n) = \mathbf{e}_p(n) - \tilde{\mathbf{y}}_p(n)$ and $\tilde{\mathbf{d}}_v(n) = \mathbf{e}_v(n) - \tilde{\mathbf{y}}_v(n)$ and used to estimate the corresponding transfer function $\tilde{\mathbf{H}}$.
4. The sensors at the virtual locations are removed.

Note that for proper functioning of the RMT, the correlation between $\mathbf{d}_p(n)$ and $\mathbf{d}_v(n)$ should be causal. Otherwise, transfer function $\tilde{\mathbf{H}}$ can not fully model the relationship between them. To ensure causality, at least one physical sensor should be placed between the primary sources and the virtual locations.

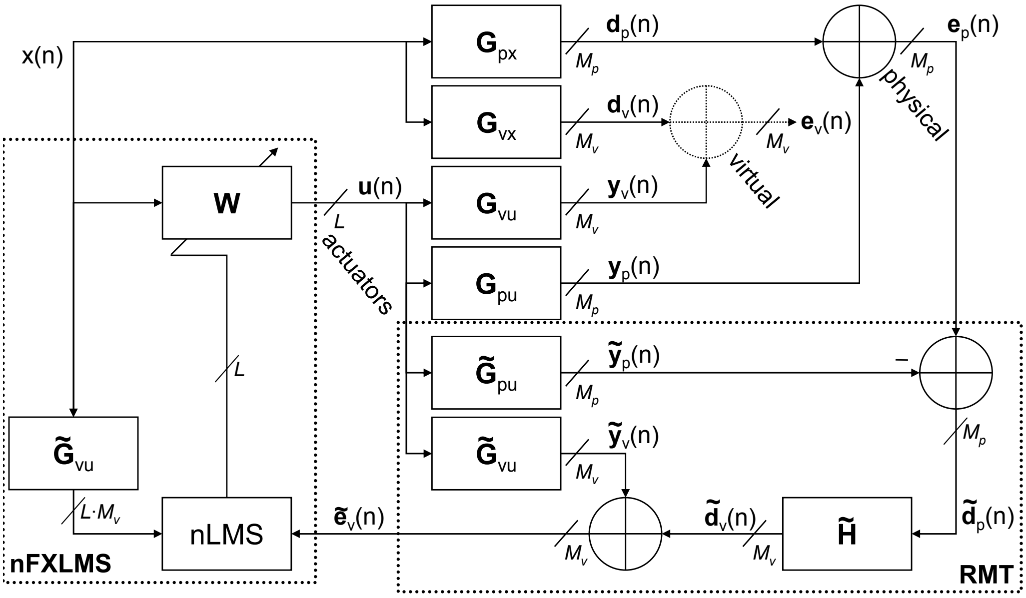


**Figure 1.** Remote Microphone Technique (RMT).

## 3. Experimental Setup: The Silent Chair

Consider the 'Silent Chair' in Figure 2. The speaker in front of the chair is the primary noise source and the two speakers adjacent to the chair are the secondary noise sources. The goal is to minimize the primary noise at the location of the ears of the user. These ear locations will be referred to as the virtual locations, accentuated by the two green circles in Figure 2. The red circles in Figure 2 show the locations of four physical microphones that are symmetrically attached to the chair. In the head area of the chair, around the virtual locations, a three-dimensional grid is placed, holding 26 microphones. Two of these microphones measure the two virtual locations, the other 24 are regularly spaced in all three dimensions and enable measurements of the three dimensional quiet zone.

Three configurations are compared:

1. Measurements from the two physical sensors on the sides of the chair at ear level are used as error signals. These signals are minimized by the conventional ANC system. This would be the best attempt to reduce the noise at the virtual locations without placing error sensors at those locations or using virtual sensing techniques. We will call this the *conventional configuration*.

2. Measurements from two temporary sensors at the virtual locations are used as error signals and are minimized by the conventional ANC system. This will provide the best possible reduction at the virtual locations, but comes with the price of having to place sensors there. We will call this the *optimal configuration*.

3. RMT virtual sensing is used to estimate the error signals at the virtual locations. This way, there is no need for placing microphones at the virtual locations, but estimation errors of the RMT will result in lower reduction than the optimal configuration. We will call this the *virtual configuration*.

### 3.1 Results

Figure 3 shows the reduction at the virtual locations for each configuration spectrally, up to 500 Hz. From the figure, it is clear that the conventional configuration achieves significant ($>$ 10 dB) reduction at the virtual locations between 30 and 90 Hz only. For higher frequencies, the quiet zones get smaller and do not extend to the virtual locations anymore. Lower frequencies are not present in the primary noise. In the optimal configuration, proper reduction at the virtual locations is achieved over the entire bandwidth of interest. The virtual configuration shows comparable behavior to the optimal configuration, although the overall performance is lower. This difference is caused by


**Figure 2.** 'Silent Chair' experimental setup. The red circles show the physical locations, the green circles the virtual locations. The primary source is placed in front of the chair, the two secondary sources on the sides.

estimation errors of the RMT. More specifically, by inaccuracies in the estimated paths $\tilde{\mathbf{G}}_{pu}, \tilde{\mathbf{G}}_{vu}$ and $\tilde{\mathbf{H}}$, as stated by [3, 6]. These inaccuracies are generally higher for higher frequencies, where the room acoustics become more susceptible to disturbances, like temperature changes and moving people. In fact, we have put a person in the chair, after having estimated the paths without the chair empty and the perceivable reduction at the higher frequencies vanished almost completely.

Theoretically, the shape of the quiet zone is spherical in diffuse sound fields [1]. This is not the case for modal sound fields. When observing the quiet zones in the experiment of Figure 2 as function of frequency, we see that these zones are not consistently shaped. For some frequency ranges, where the room exhibits significant modal acoustics, the quiet zones are increasingly ellipsoidal and show irregularities. Truly spherical quiet zones are exception, rather than rule in the performed measurements. The volumes of the quiet zones also develop quite dynamically as a function of frequency. Instead of a continuous decrease of volume for increasing frequencies, it turns out that the system performance (i.e. the reduction of the error signals) plays a much larger role in the quiet zone volumes. This is shown in Figure 4 for the optimal and virtual configurations. Here, the dotted blue line depicts the predicted total volume where reduction exceeds 10 dB, according to the rule of thumb that describes spherical quiet zones with diameters of one tenth of the wavelength, calculated according to [8]. The solid blue line shows the measured volume. The solid red line, belonging to the red axis at the right of the plot, shows the average reduction at the two virtual locations. The results for frequencies lower than 300 Hz are not shown, because the quiet zone exceeded the size of the measurement grid for those frequencies.

The figure clearly shows that the volume of the total quiet zone for a certain frequency depends more significantly on the system's performance at that frequency, than on the frequency itself. Supporting

this statement, we observe that the decrease of system's performance caused by the use of RMT virtual sensing (24.4% in the 300-500 Hz range) translates to a 50.7% decrease of the total quiet zone volume. The measurements also show that the total quiet zone volume always exceeds the predicted volume, even when using RMT virtual sensing, as long as the system's performance exceeds 10 dB reduction. This is the result of the proximity of the two virtual locations, which introduces a certain degree of synergy, especially in the area between the two virtual locations.
More plots and results on the quiet zones can be found in [8].

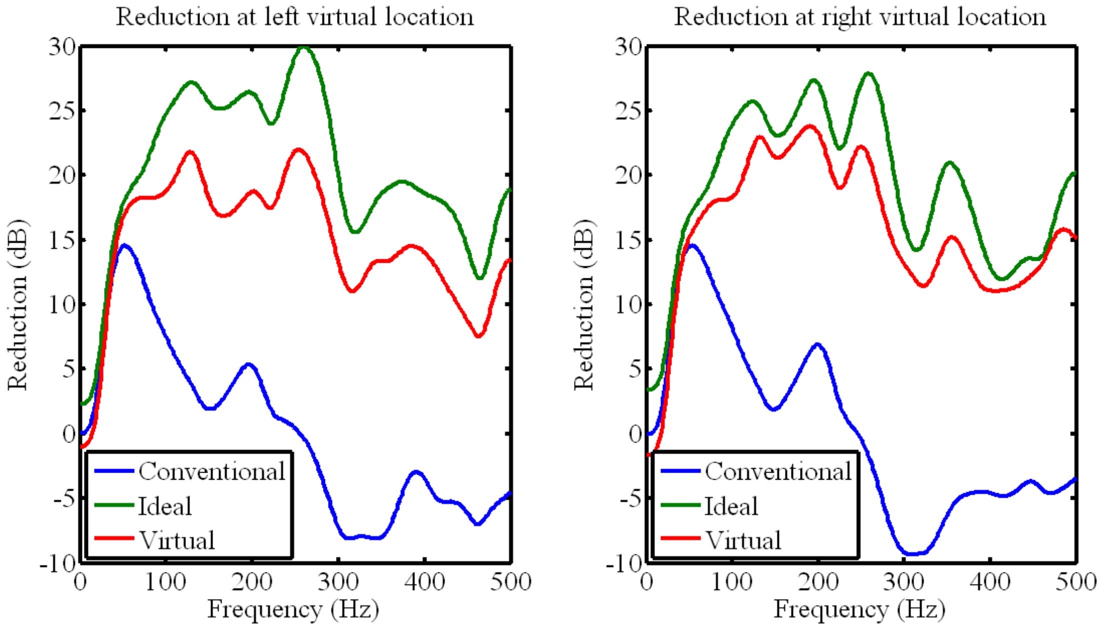


**Figure 3.** Attained spectral reduction as measured at the two virtual locations, for all three 'Silent Chair' configurations.

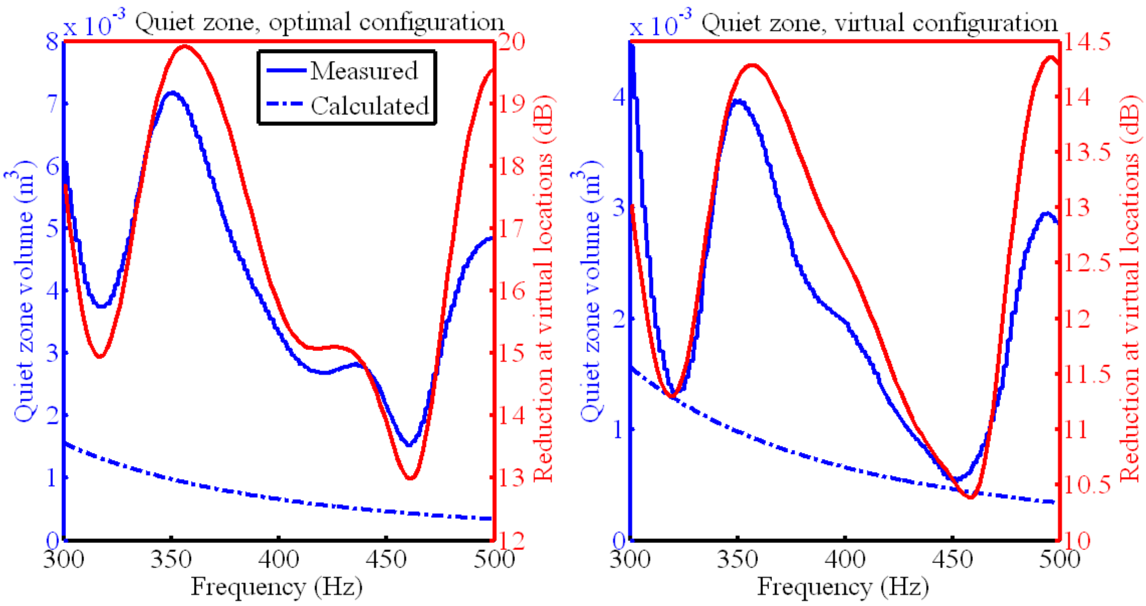


**Figure 4.** The volume of the total 10 dB quiet zone (i.e. the union of the two quiet zones), measured and calculated according to the rule of thumb [1], in relation to the system's performance, expressed by the average reduction at the virtual locations.

## 4. Experimental Setup: The Silent Bed

Figure 5 shows a setup in which the goal is to reduce undesired noise from outside at the head end of a bed. The three secondary sources are placed conveniently in the corners and ideally, there should be no sensors on the bed itself. We again compare three configurations:
1. Measurements from the three physical sensors around the bed are used as error signals. These signals are minimized by the conventional ANC system. We will call this the conventional configuration.
2. A MicroFlown USP [10] is used as an energy density probe at the virtual location. It provides pressure and three dimensional velocity signals that are used as error signals and minimized by the conventional ANC system. We will call this the optimal setup.
3. With RMT virtual sensing, the MicroFlown is virtualized, using the three physical microphones around the bed. The four resulting virtual signals (pressure and velocities) are minimized. We will call this the virtual configuration.

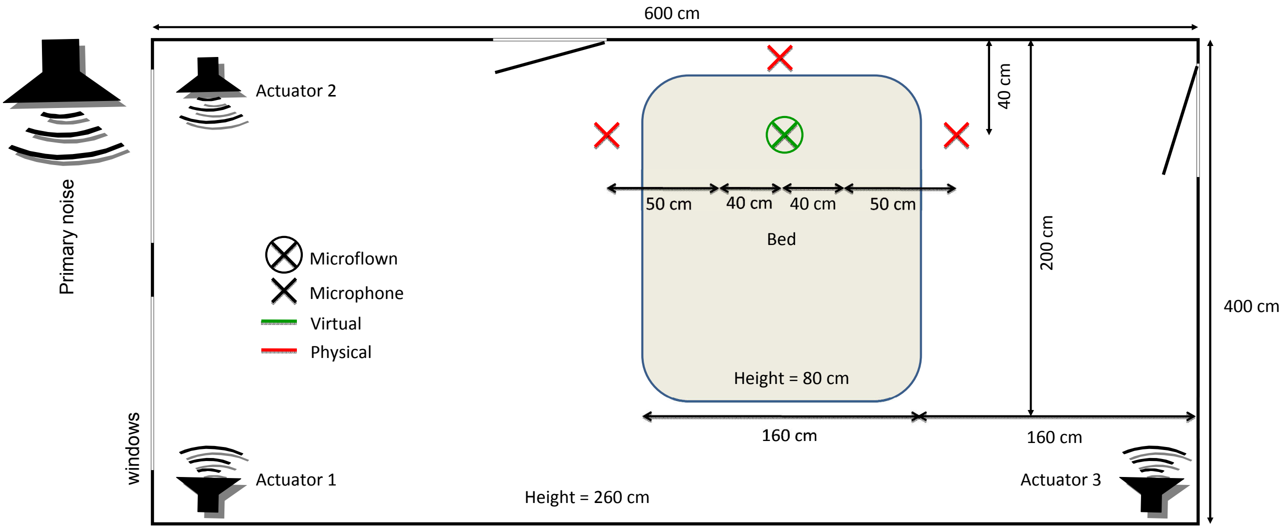


**Figure 5.** 'Silent Bed' experimental setup.

### 4.1 Results

Figure 6 compares the reduction of the pressure and velocities at the virtual location in the three different configurations. The reduction is plotted for frequencies up to 250 Hz, since higher frequencies are sufficiently attenuated by the walls in this setup.

The figure shows that the performance of the virtual configuration is not as high as the performance of the ideal configuration, as is to be expected due to approximation errors in the RMT. In particular, we have seen that filter estimate $\tilde{\mathbf{H}}$ is less accurate when virtualizing velocity signals, compared to virtualizing pressure signals.

More noticably, the figure shows that the conventional configuration perceivably outperforms the ideal configuration. The three actuators are able to cause high pressure reductions at the three physical locations, whereas they have more trouble controlling the combined velocity and pressure signals at the virtual location. In line with the observations on the quiet zone in the previous section, we see that the quiet zone per sensor in the conventional configuration is large enough to encompass the virtual sensor up to 150 Hz, due to the high reductions, whereas the quiet zone in the virtual configuration remains relatively small, due to the limited attained reduction.

It should be noted that the response of the MicroFlown USP is not entirely flat in the lower frequency range. This can be compensated, as described in [9], which could improve the performance of the ideal and virtual configurations in the described experiment.

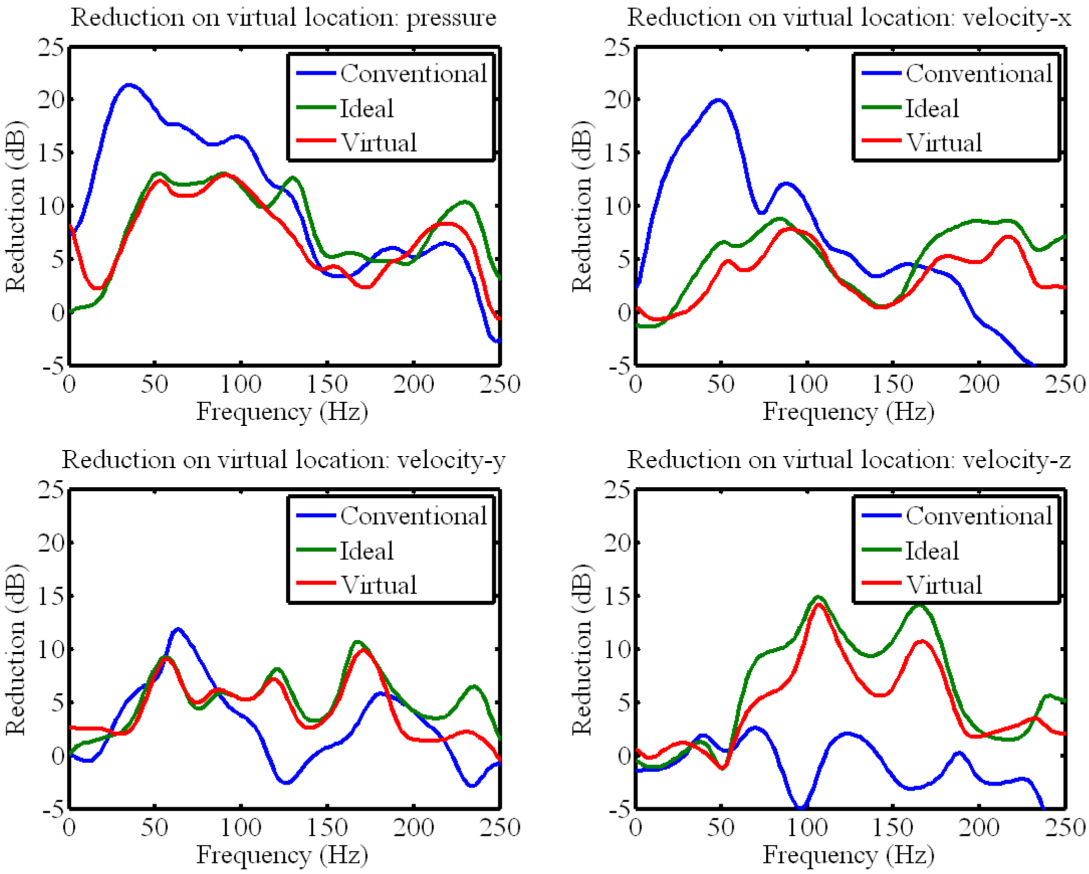


**Figure 6.** Attained spectral reduction of pressure and particle velocity as measured at the virtual location, for all three 'Silent Bed' configurations.

## 5. Conclusions

Basically, the success of RMT virtual sensing in an ANC system depends on the interaction of three variables: The frequency range of the primary disturbance, the distance between physical and virtual sensors and the stationarity of the surroundings. Assuming high system performance, for low frequencies the quiet zone is already large. So a virtual sensor setup will not be successful if the physical-virtual distance is relatively small, since the reduction at the virtual location will inevitably be smaller due to estimation errors of the RMT. From this point of view, RMT is increasingly interesting for higher frequencies. However, the estimation errors will become larger at higher frequencies, as the sensitivity to changes in the surroundings increases. This has been shown in the setup of the silent chair in Figure 2. With no changes in environment, the RMT ANC system is succesful at high frequencies. However, when introducing a person in the chair, the RMT estimation error increases dramatically at these frequencies, destroying perceivable reduction. For the lower frequencies the RMT performs similar to the conventional situation, due to the small physical-virtual distance.

We have shown that the rule of thumb on the quiet zone being a sphere with a diameter of one tenth of the wavelength is not usable in an enclosure with modal acoustic behavior. In these situations, the quiet zone volume for a certain frequency corresponds directly to the achieved reduction at the error sensors for that frequency. As a result, the quiet zone created by an ANC system with virtual sensing is much smaller than the quiet zone created by a conventional ANC system, due to the approximation errors made by the virtual sensing algorithm. This was again demonstrated in the setup of the silent bed with the (virtual) energy density probe in Figure 5. Using an energy density probe can be a good way to expand the quiet zone, since not only the pressure, but also the particle veloctity is minimized at a certain location. However, minimizing the additional velocity signals could suppress the reduction of the sound pressure, which can have a larger negative effect on the quiet zone volume than the intended positive effect of the minimization of the velocity signals.

Overall, we can state that the RMT can be a very valuable means to improve ANC system performance, but tailored to specific situations.

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