Scaling of the simulated pass-by measurement based on the vehicle's acoustic centre

Yannik Weber[1]
IPEK - Institute of Product Engineering, Karlsruhe Institute of Technology, Kaiserstr. 10, 76131 Karlsruhe, Germany

Albert Albers[2]
IPEK - Institute of Product Engineering, Karlsruhe Institute of Technology, Kaiserstr. 10, 76131 Karlsruhe, Germany

ABSTRACT

Previous work by the IPEK has shown that the simulated pass-by measurement for exterior noise homologation of vehicles has relevant optimization potential: the measurement can be carried out in smaller halls and with a smaller measurement setup than required by the standard DIN ISO 362-3 and thus with less building construction cost and measurement effort. A prerequisite for this, however, is the scaling of the entire setup. For the scaling to work correctly, the sound sources of the vehicle must be combined to a single point sound source - the acoustic centre. Therefore, in a previous work, the IPEK developed a method, with the help of which the dominant sound sources of a vehicle can be localized and combined to an acoustic centre. In this work, the method is applied exemplarily on a test vehicle and its acoustic centre is determined. Afterwards, the measurement setup is scaled based on the acoustic centre. Finally, the simulated pass-by measurement with the scaled measurement setup is performed on an acoustic roller test bench and the scaled sound pressure levels are determined. To verify the overall method, the results of the scaled pass-by measurements are compared with the unscaled one.

1. INTRODUCTION – SCALING OF THE SIMULATED PASS-BY MEASUREMENT

The simulated pass-by measurement on acoustic roller test benches for exterior noise homologation of vehicles has various advantages compared to the outdoor measurement, such as the independence from weather and disturbing noise, less measurement effort and better reproducibility. This can significantly reduce the development time of vehicles. Previous work at the IPEK [1] has shown that the efficiency of the simulated pass-by measurement can be increased even further: the measurement can be carried out in smaller halls and with a smaller measurement setup than required by the standard DIN ISO 362-3 [2] and thus with less construction cost and measurement effort. One approach to this is to set the microphone array closer than the required 7.5 m from the longitudinal axis of the vehicle, in order to scale the whole measurement setup und thus, virtually extend the measurement distance for measurements in smaller halls (see Figure 1) [1].

For the scaling of the measurement setup however, the sound sources of the vehicle must be combined to a single point sound source - the acoustic centre. Thus, the position of the acoustic centre in vehicle

[1]yannik.weber@kit.edu
[2] albert.albers@kit.edu

longitudinal and transverse direction as well as in vehicle height must be known. This allows to determine both the microphone height and the microphone position in the longitudinal direction for correct scaling. [3]

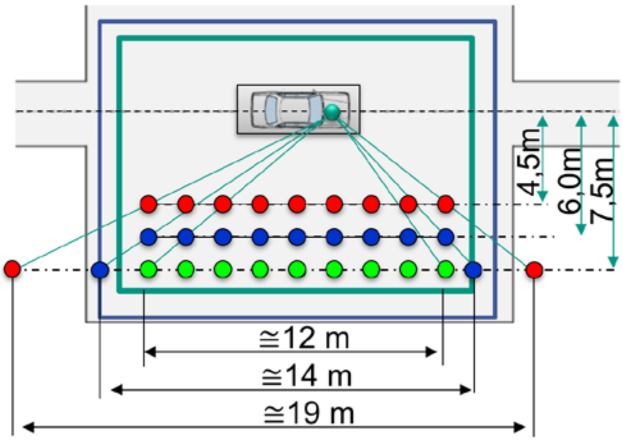

Figure 1: Virtual extension of the measurement distance by setting up the microphone array at a shortened measurement distance [3]

2. ACOUSTIC CENTRE – STATE OF THE ART

The basis for the theory of the acoustic centre is that, in sufficient distance, the vehicle may be assumed as a point sound source [3]. The acoustic centre, composed of its partial sound sources, is to be considered analogically to the centre of mass with its partial masses.

In [4] we introduced a method to localize the dominant sound sources of a vehicle using an acoustic camera and to aggregate the sources to an acoustic centre. The developed method *"AcCent"* (**Ac**oustic **Cent**re) is able to take into account the real noise proportions of the partial sound sources in the calculation, as well as stationary (e.g. constant drive), transient (e.g. acceleration) and erratic (e.g. combustion engine start-up) events. Figure 2 shows the sequence diagram of the method.

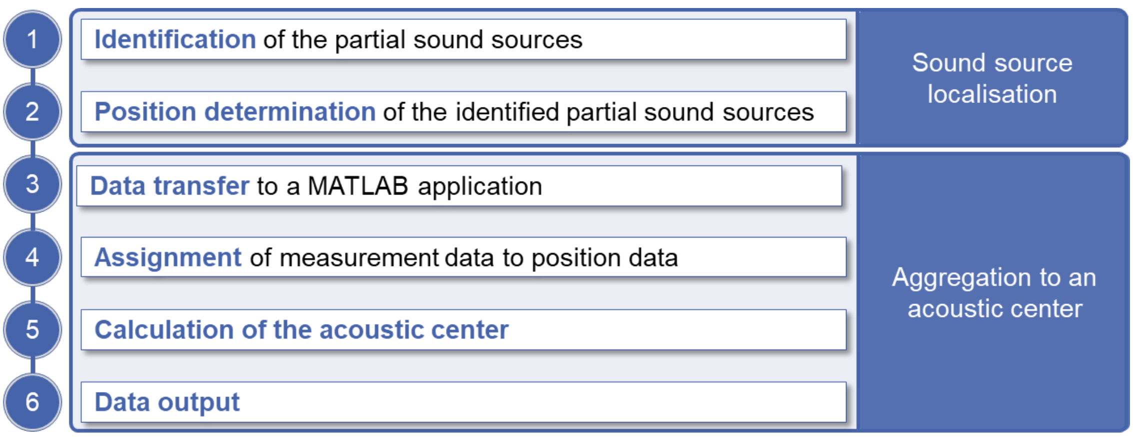

Figure 2: Sequence diagram of the developed method AcCent [4]

The procedure of the method can be divided into two separate processes with a total of 6 steps. In the first step, using the acoustic camera, the dominant partial sound sources of the system under investigation are identified and their sound pressure levels are determined. Afterwards, the individual positions of the identified partial sound sources have to be determined on the physical vehicle or with CAD data. In the second category, the data produced during the measurements is loaded into a MATLAB® application. Within the app, the sound pressure levels of identified sources are assigned to their corresponding position data. Afterwards, the acoustic centre is calculated with the sound pressure and position data. [4]

As mentioned, the calculation of the acoustic centre with the partial sound sources is analogous to the calculation of the centre of mass with its partial masses. In [4] we derived a formula for the calculation of the acoustic centre from incoherent sound sources for the three spatial directions:

$$\begin{pmatrix} x_{AC} \\ y_{AC} \\ z_{AC} \end{pmatrix} = \frac{\sum_{i=1}^{n} \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} * 10^{\frac{L_i}{10}}}{\sum_{i=1}^{n} 10^{\frac{L_i}{10}}} \tag{1}$$

where x_{AC}, y_{AC}, z_{AC} are the positions of the acoustic centre in the three spatial directions, n is the number of partial sound sources, x_i, y_i, z_i are the positions of the partial sound sources and L_i is the sound pressure level of the partial sound sources.

In [4], the method was applied to a hybrid test vehicle for two exemplary operating conditions (hybrid and electric drive mode) and its acoustic centres were calculated. Figure 3 shows the partial sound sources detected with the acoustic camera in hybrid drive mode and the calculated acoustic centres for the hybrid and electric drive mode.

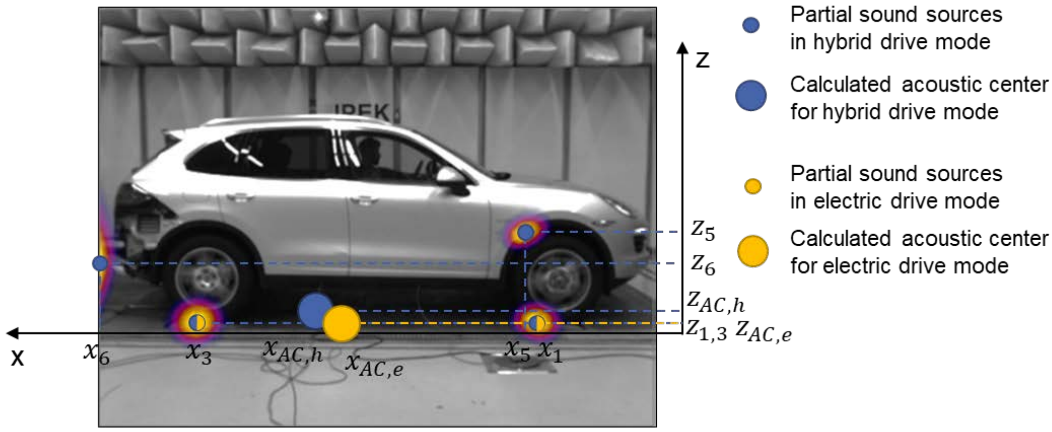

Figure 3: Identified partial sound sources of the hybrid test vehicle in hybrid drive mode and illustration of the calculated acoustic centre in the x-z-plane for hybrid drive mode and electric drive mode [4]

3. SCALING OF THE SIMULATED PASS-BY BASED ON THE ACOUSTIC CENTRE

In this work, the introduced method *AcCent* is used to scale the measurement setup of the simulated pass-by measurement. For this, the method is applied on a fuel cell test vehicle (Toyota Mirai) and its acoustic centre is determined. Afterwards, the measurement setup is scaled based on the acoustic centre. Finally, the simulated pass-by with the scaled measurement setup is performed on an acoustic roller test bench and the sound pressure levels are determined. To verify the overall procedure, the results of the scaled pass-by measurements are compared with the unscaled one in chapter 4.

Figure 4 shows the sequence diagram for the scaling of the simulated pass-by based on the acoustic centre. Step 1 and 2 correspond to the method introduced in chapter 2.

In the following, the individual steps of the procedure are described in detail using the Toyota Mirai on the IPEK acoustic roller test bench as an example.

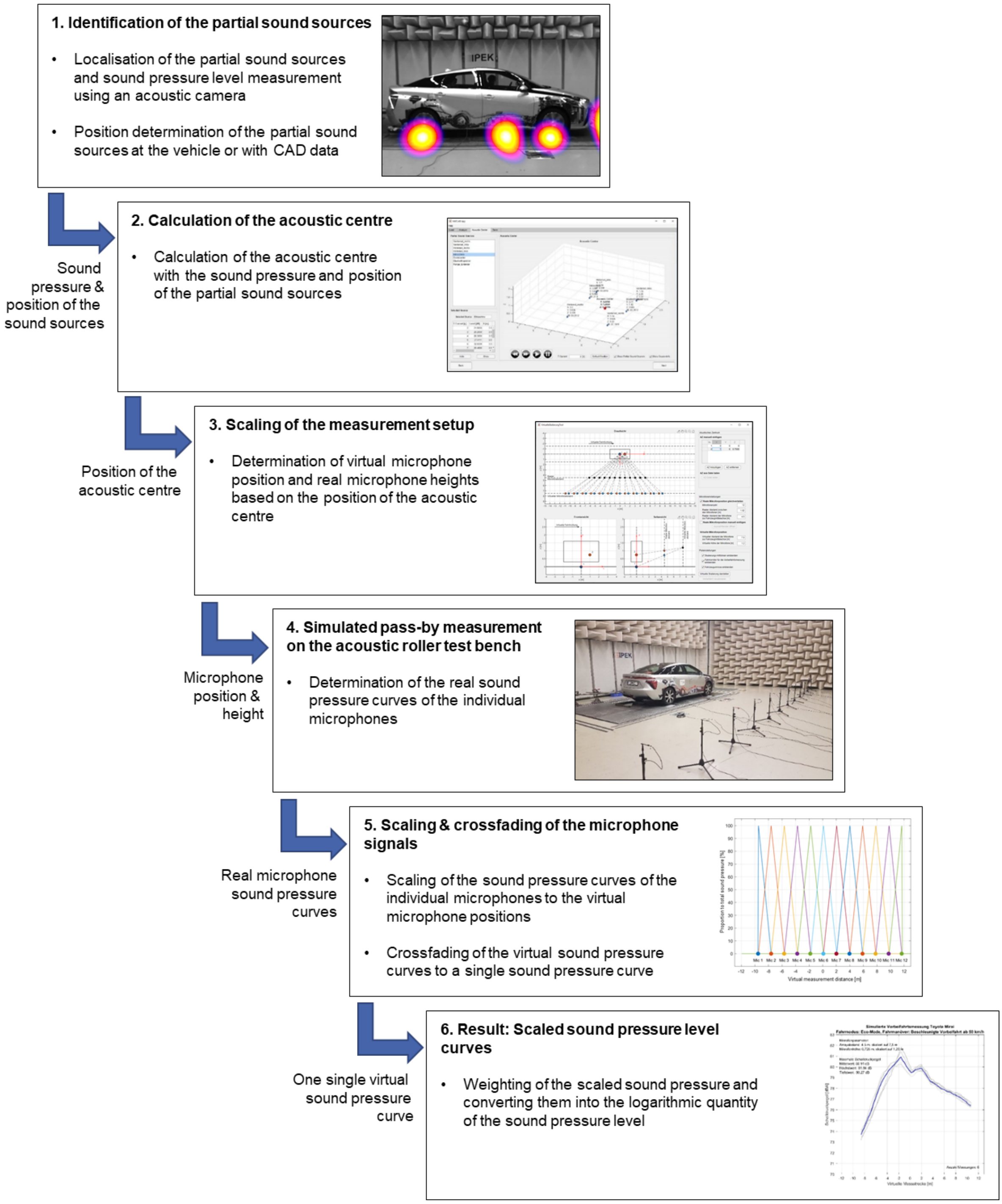

Figure 4: Sequence diagram for the scaling of the simulated pass-by measurement based on the acoustic centre

Step 1: Identification of the partial sound sources

Figure 5 shows the experimental setup for the test vehicle on the IPEK acoustic roller test bench and the partial sound sources detected during a ramp up manoeuvre using the acoustic camera. The following four sources can be identified in this camera shot: the front and rear tire, the fuel cell system under the driver seat and the electro motor/air compressor compound in the engine compartment. Since there are four tires, this results in six partial sound sources of the vehicle. Other possible sound sources of the powertrain are too quiet to be localised amongst the other louder sound sources (especially tire noise).

After the partial sound sources have been identified and their sound pressure levels are measured, the positions of the sources must now be determined as accurately as possible. The positions can either be measured on the vehicle or determined with CAD data.

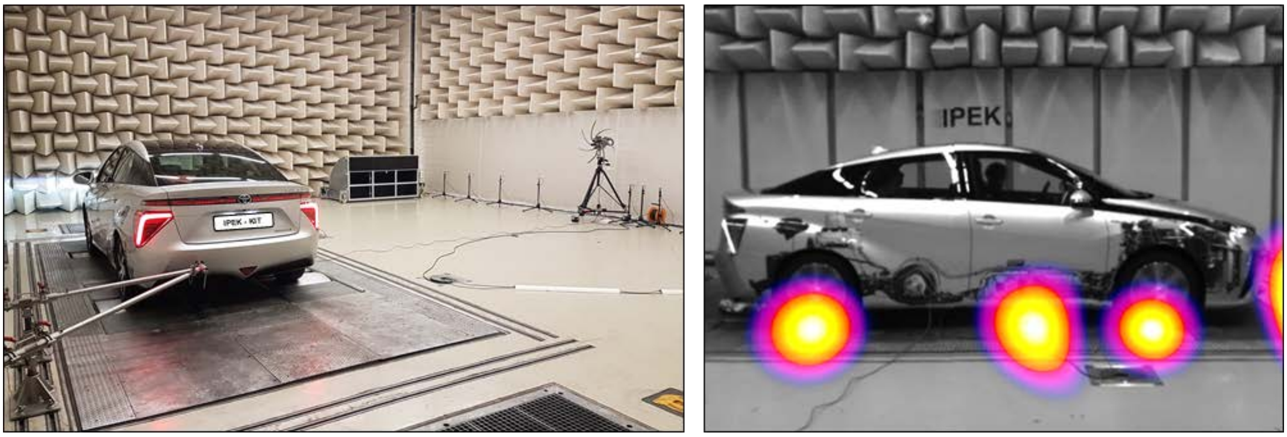

Figure 5: Experimental setup on the IPEK acoustic roller test bench for the test vehicle (left) and identified partial sound sources during a ramp up manoeuvre using an acoustic camera (right)

Step 2: Calculation of the acoustic centre

Once the sound pressure levels and positions of the partial sound sources have been successfully determined, they are manually assigned to each other in a MATLAB® application (which we developed in [4]). Afterwards, the acoustic centre can be calculated using Equation 1. In the app, the acoustic centre can be displayed for any time stamp of a given driving manoeuvre and for different operating states of the vehicle. This makes it possible, for example, to observe a continuous or abrupt shift of the acoustic centre during transient driving conditions (e.g. acceleration manoeuvres). Figure 6 shows the three-dimensional illustration of an exemplarily acoustic centre within the app.

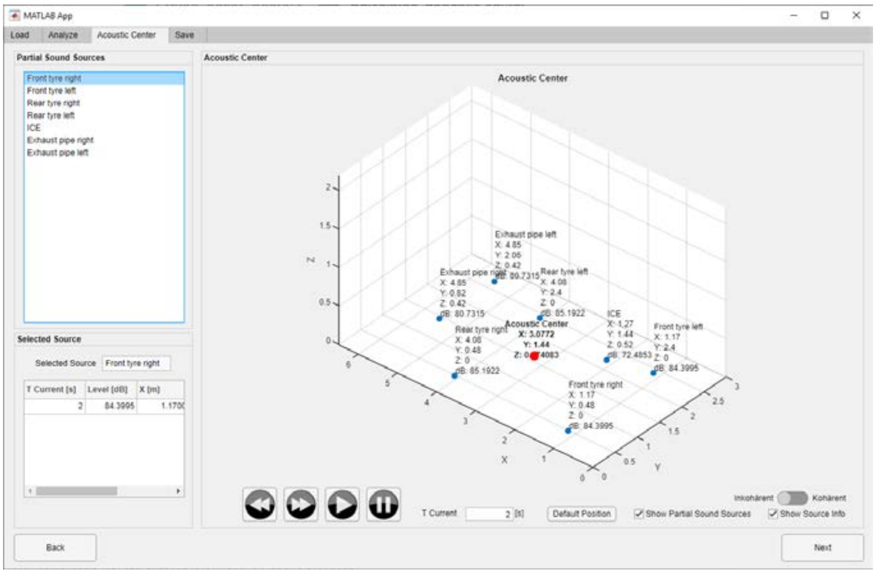

Figure 6: Three-dimensional illustration of an exemplarily acoustic centre in the MATLAB® application

Step 3: Scaling of the simulated pass-by measurement setup

As described in chapter 1 and in [3], the simulated pass-by can be carried out in smaller halls than required by the standard DIN ISO 362-3. For this purpose, the microphone array is placed closer to the vehicle than the required 7.5 m to virtually extend the measurement distance in the vehicle's longitudinal direction.

Due to the hall size of the IPEK acoustic roller test bench, a maximum distance of 12 m can be achieved. In order to realize the virtual measurement distance of 20 m defined by the standard, the microphone array must be set up at a distance of 4.5 m from the longitudinal axis of the vehicle. For correct scaling, the microphone heights must also be converted from the standard height 1.2 m in 7.5 m distance to the height in 4.5 m distance, also depending on the acoustic centre. Figure 7 shows the scaling of the measurement setup based on an exemplarily acoustic centre for measurements in small halls.

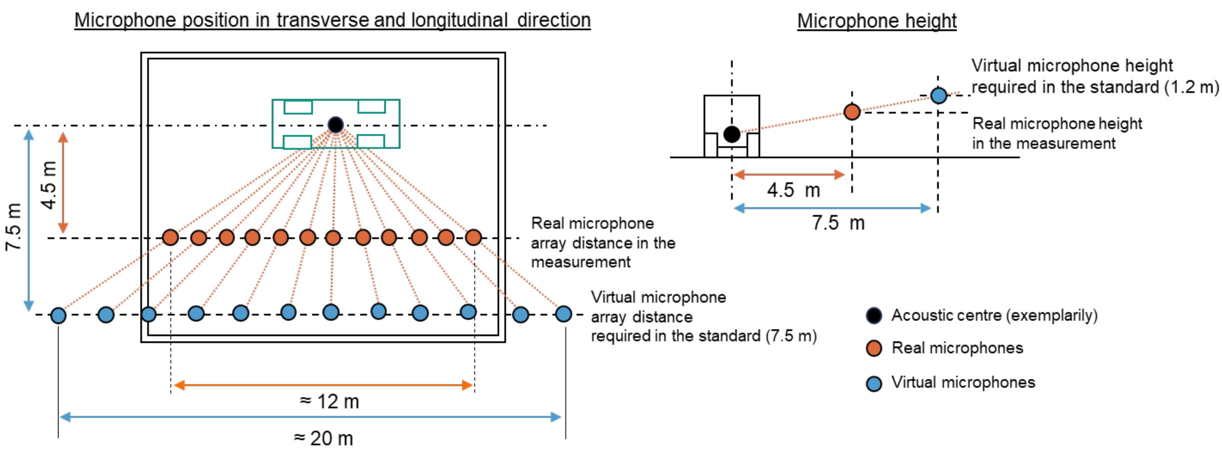

Figure 7: Scaling of the simulated pass-by measurement based on the acoustic centre in small halls: determination of the microphone position in longitudinal direction (left) and of the microphone heights (right) (based on [3])

With the position data of the acoustic centre obtained in step 2, the positions and height of the microphones can now be calculated. With an array distance of 4.5 m, this results in a microphone height of 0.68 m for the acoustic centre of the test vehicle.

For an automated calculation, we also developed an app in MATLAB® (see Figure 8). The position data of the acoustic centre can either be transferred directly from the app in step 2 or entered manually in the graphical user interface. It is possible to display several acoustic centres simultaneously in the app and therefore to examine and compare their influence on the experimental setup.

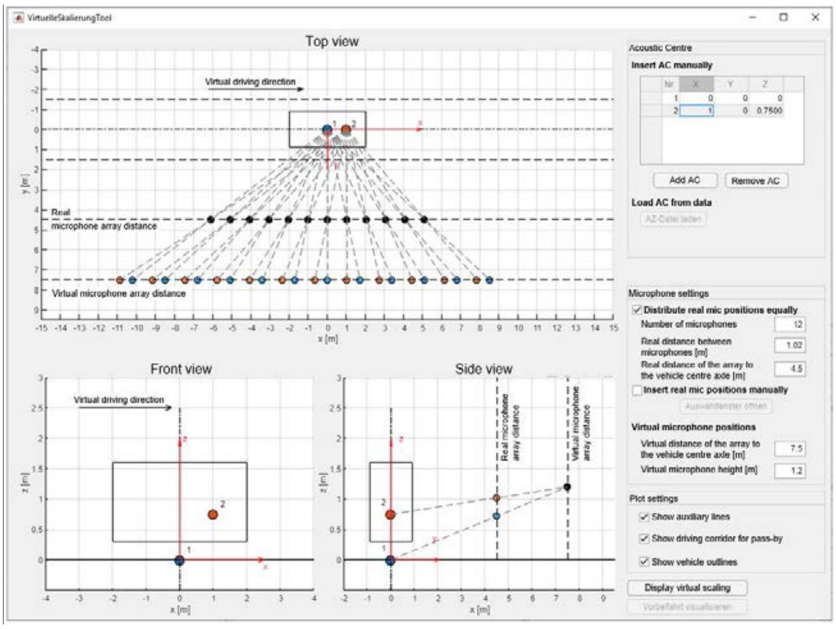

Figure 8: Scaling of the simulated pass-by measurement in the MATLAB® application for two exemplarily acoustic centres

Step 4: Conducting of the simulated pass-by measurement on the acoustic roller test bench

After calculating the position and the height of the microphones, the simulated pass-by measurements can be carried out on the acoustic roller test bench. In this work, the measurements are performed with two different setups. First, measurements are carried out according to the standard with an array distance of 7.5 m and a microphone height of 1.2 m. Afterwards, the experimental setup is scaled down to the array distance of 4.5 m and the microphone height of 0.68 m. For the verification of the entire procedure in chapter 4, the measurement results of the scaled test setup are compared with the results of the unscaled setup according to the standard.

Figure 9 shows the experimental setup on the IPEK acoustic roller test bench for both array distances and microphone heights.

According to the standard, the driving manoeuvres conducted in this work are the pass-by with 50 km/h constant speed and with full-load acceleration from 50 km/h.

To simulate the relative movement of the vehicle on the test bench, the sound pressure signals of all microphones are recorded time-synchronously. In the post-processing, depending on the virtual vehicle position, the individual signals are then combined into a single sound pressure curve in a process called crossfading.

Figure 9: Experimental setup on the IPEK acoustic roller test bench for the simulated pass-by measurement, left: 7.5 m array distance & 1.2 m microphone height, right: 4.5 m array distance & 0.68 m microphone height

Step 5: Scaling of the sound pressure curves & crossfading

In the post-processing, the measured sound pressure of the microphones at 4.5 m are virtually converted to the standard distance at 7.5 m. For this purpose, the sound pressure of each individual microphone is converted to its virtual position in 7.5 m distance, which was calculated in step 3. For the conversion, we use the reciprocal distance law for sound pressure, which states that the sound pressure is inversely proportional to the distance of the source. For the conversion, a varying acoustic centre can also be taken into account, whose position changes during unsteady driving manoeuvres and conditions.

After the conversion, the sound pressure signals are combined into a single signal using the crossfading process. First, the virtual distance travelled by the vehicle is calculated by integrating the speed profile. From this, the virtual position of the vehicle can be determined at any time of the pass-by manoeuvre. Depending on the vehicle position or the position of the acoustic centre, the microphone signals are then added together. If the vehicle is in a position between two microphones, the microphone data is mixed on a percentage basis. In the linear crossfading, the proportion between two microphones of the array are linearly interpolated. Figure 10 shows the contribution of the microphones to the overall signal in relation to the virtual measurement distance.

The crossfading of the microphone recordings results in a single, monaural signal. [2]

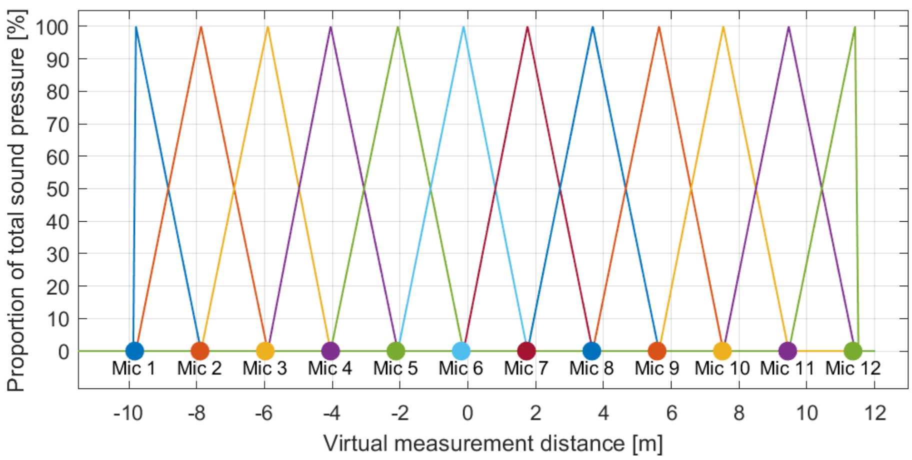

Figure 10: Proportion of the microphones to the total sound pressure signal in relation to the virtual measurement distance for linear crossfading

Step 6: Scaled sound pressure level curves

After scaling and crossfading the sound pressure, the resulting signal is weighted with the frequency-dependent A-factor (according to [2]), which takes into account the human noise perception. Finally, by converting the scaled and weighted sound pressure into the logarithmic quantity, the scaled sound pressure level can be determined and displayed in relation to the virtual measurement distance.

Figure 11 shows the sound pressure curves scaled from an array distance of 4.5 m to 7.5 m for the pass-by manoeuvre with 50 km/h constant speed. Figure 12 shows the scaled curves for the pass-by with full load acceleration from 50 km/h. In both diagrams, the sound pressure levels of the individual measurements are plotted in grey and the mean value curve calculated from them is plotted in blue.

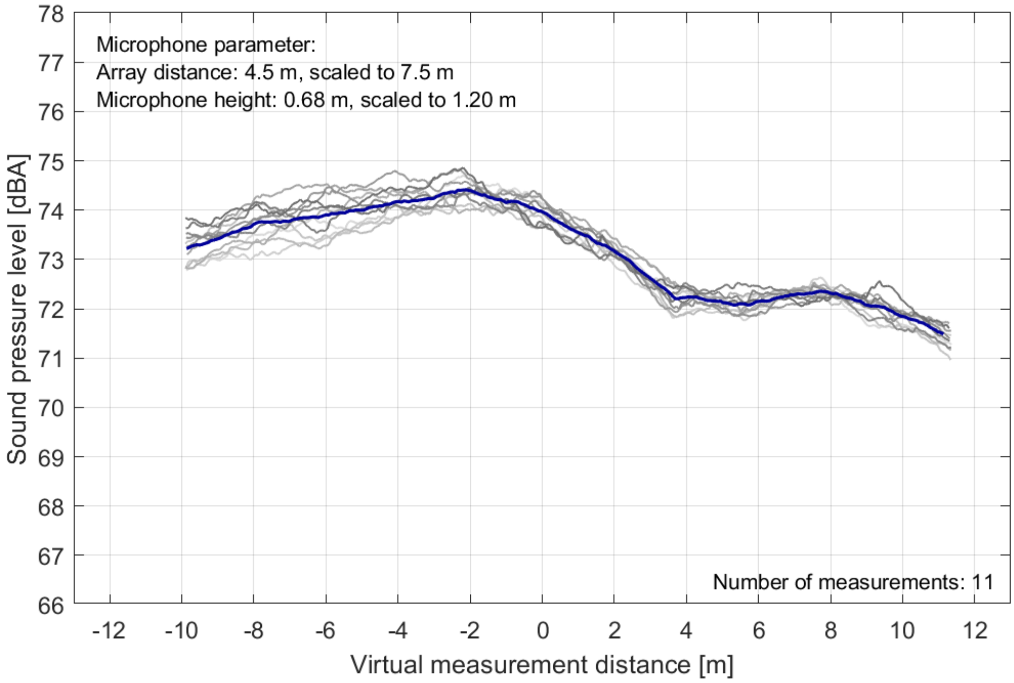

Figure 11: Scaled sound pressure level curves of the simulated pass-by with 50 km/h constant speed, grey lines: curves of the individual measurements, blue line: mean value curve

The measurements show a very good reproducibility, which demonstrates the advantage of measurements on a test bench compared to a test track. In particular, the measurements with constant speed show a low scatter. Slightly higher deviations between the individual measurements can be observed with the full-load accelerations. This can be explained by the fact that the operating strategy of the fuel cell test vehicle depends on many parameters. Especially in transient driving conditions such as full-load acceleration, deviations in the parameters between the individual measurements become noticeable. An example of this would be the battery state of charge (SOC). When the SOC is full, the electric motor can access sufficient electrical energy and the maximum acceleration of the vehicle can be achieved. If, on the contrast, the SOC is partially discharged, the electric motor no longer has enough energy available. Since the battery was only designed as a small intermediate storage unit, the SOC is already sufficiently depleted after 2-3 full-load accelerations, so that maximum acceleration is no longer possible. The fuel cell system delivers too little energy per unit of time to cover the energy demand during full-load acceleration. During the test, the battery therefore had to be regularly conditioned so that the same SOC start values are present at the beginning of the pass-by.

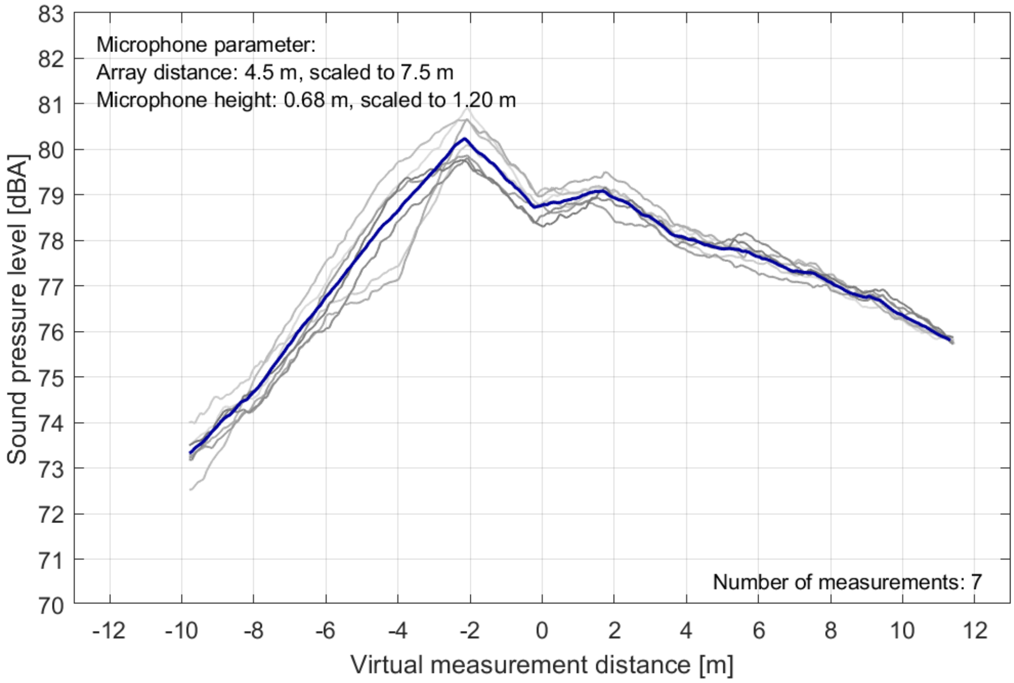

Figure 12: Scaled sound pressure level curves of the simulated pass-by with full-load acceleration from 50 km/h, grey lines: curves of the individual measurements, blue line: mean value curve

As can be seen in the diagrams, the vehicle virtually travels from a measurement distance at -10 m to around +11.5 m. Therefore, the required 20 m measuring distance can be achieved with the scaling. Now it must be ensured that the results of the scaled measurement procedure also correspond to the procedure according to the standard.

4. VERIFICATION OF THE SCALING PROCEDURE

For the verification of the procedure introduced in chapter 3, the results of the scaled measurement are compared with the unscaled one. The procedure is suitable for scaling the simulated pass-by if the results at 4.5 m virtually converted to 7.5 m match the results of the real measurements at 7.5 m.

Figure 13 shows the mean value curves of the scaled and unscaled simulated pass-by at full load acceleration from 50 km/h. As mentioned, due to the hall size of the IPEK acoustic roller test bench, the maximum virtual measurement distance at 7.5 m is 12 m. Therefore, the 20 m distance required in the standard cannot be fully covered with the real measurements at 7.5 m. Nevertheless, the results of the scaled and unscaled setups can still be compared within the realizable area. In contrast, as already mentioned, the entire measurement distance of 20 m can be covered with a distance of 4.5 m.

The comparison shows that the results match very well. Both the position and the height of the maximum sound pressure level are close to each other. The difference between the maximum level is approx. 0.3 dB(A) and thus lies within the variation range of the individual measurements in Figure 12. The allowed tolerance for the maxima according to the standard [2] is 0.5 dB(A) from run to run, 0.9 dB(A) from day to day and even 1.4 dB(A) from place to place. Thus, the tolerance for these measurements is well within the permitted range. It is particularly important that the values of the maximum sound pressure level match here, because this is ultimately decisive for the vehicle's exterior noise certification according to the standard.

The comparison can therefore confirm that the presented procedure is very well suited for scaling the measurement setup.

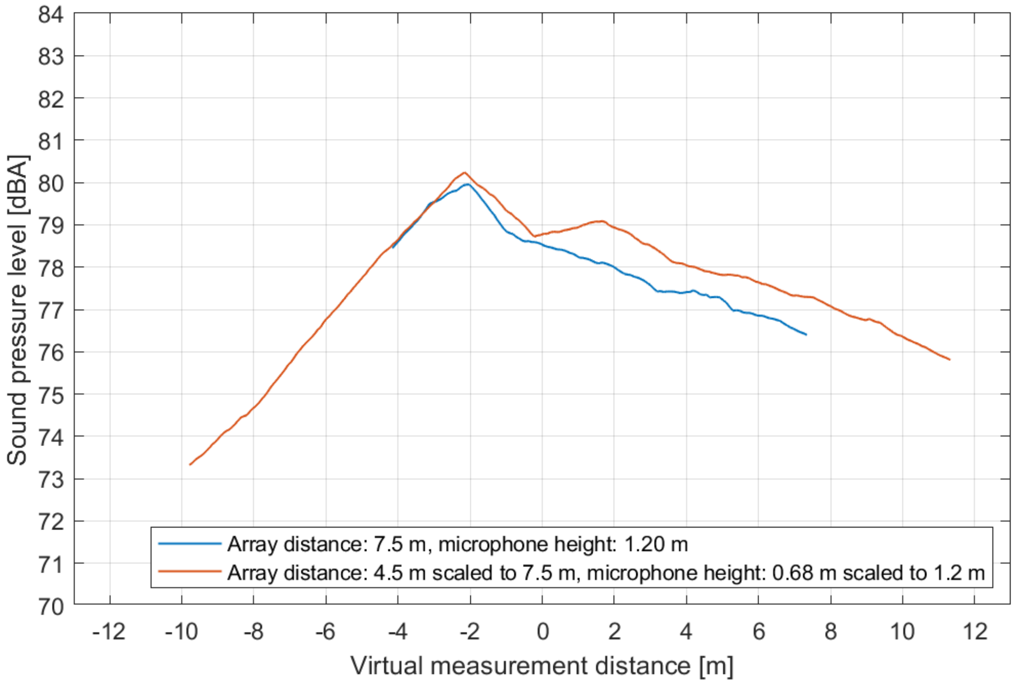

Figure 13: Comparison of the mean value curves for the scaled (red) and unscaled (blue) sound pressure level of the pass-by with full-load acceleration from 50 km/h

5. SUMMARY AND CONCLUSION

In this paper, a procedure was presented with the help of which the simulated pass-by measurement can be carried out in smaller halls than required by the standard. The basis for this is the calculation of the vehicle's acoustic centre from its partial sound sources. The individual steps of the procedure were explained using the example of a fuel cell vehicle and the IPEK acoustic roller test bench.

By comparing the measurement results of the scaled and unscaled measurement procedure, it was shown that the method is suitable for scaling the pass-by measurement.

To ensure that the method is generally applicable, the method can be applied to other vehicles with other drive topologies in the next step.

6. ACKNOWLEDGMENTS

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