Correlation of parallel car interior and exterior beamforming measurements in a wind tunnel

Stefan NEUGEBAUER[1]; Reinhard RÖSEL[2]; Dirk DÖBLER[3]

[1−3] GFaI e.V., Germany

ABSTRACT

In aeroacoustics, beamforming measurements have become a standard tool for sound source localization. Additionally, correlation methods are applied to determine the contributions of local wind noise to the measurement. We present a series of synchronized measurements of a car in a wind tunnel, all of them using two beamforming arrays at the same time. One is placed outside the wind stream near the shear layer while the other array is located inside the car's cabin. This setup enables us to localize wind noise transmission into the car's cabin. In the next step, leaks will be ranked by their exterior origins, e.g. side mirror, wheel house etc. by correlating interior and exterior acoustic images. In contrast to this method, we additionally used measurement microphones as reference channels, which is the classic approach up to now. The paper will compare those two methods.

Keywords: Correlation, Beamforming, Wind tunnel
I-INCE Classification of Subjects Number(s): 13.2.1, 21.6, 25.4, **74.1**, 74.6, 74.7

1. INTRODUCTION

Vehicle interior noise predominantly consists of noise sources from the powertrain, road and air. At low speeds engine noise is dominating, at low motor load it is road noise. For higher speeds wind noise gains more and more significance. At lower speeds monopole sources are most efficient. Those monopole sources are typically generated by noise propagating past/through seals (1), (2). Traditionally, aeroacoustic development will consist of doing repeated measurements, exchanging/removing/altering exterior components and removing sections of tape across each seal and gap to analyze noise contributions. To find the noise transmission path into the interior, reference microphones are used at assumed source positions and at the driverâĂŹs ear position. Additionally, the classical beamforming approach can be used, either by a beamforming array inside the car or an array outside the shear layer.

We follow a different approach here which completely dispenses with additional taping and reference microphones by a simple multi array setup which will be described in the following. Leading automotive companies are continuing to look for new innovative methods to streamline and improve the accuracy of development techniques, this beamforming-based technique can speed up the acoustic contribution analysis and can be used for correlating CFD based aeroacoustic analysis (as with purpose of using the vehicle in images below).

2. MEASUREMENT SETUP

All measurements described in the following were performed on a car placed in an aeroacoustic wind tunnel at 140 km/h speed with frontal upstream flow. For the acoustic measurements we placed a 120-channel spiral array with a diameter of 2 meters outside the stream (Figure 1) and a 48-channel spherical array with a diameter of 0.35 meters inside the cabin of the car at the driver's position (Figure 2). Additionally, G.R.A.S. reference microphones for comparison were fixed to the side glass inside the car.

Using this setup we were able to take parallel interior-exterior beamforming measurements. For the interior beamforming we fitted a 3D interior model to the array position and calculated the sound pressure levels on the shape of a 3D model as described in (3).

[2]rroesel@gfai.de
[3]doebler@gfai.de

Figure 1 – Spiral array, positioned outside the shear layer.

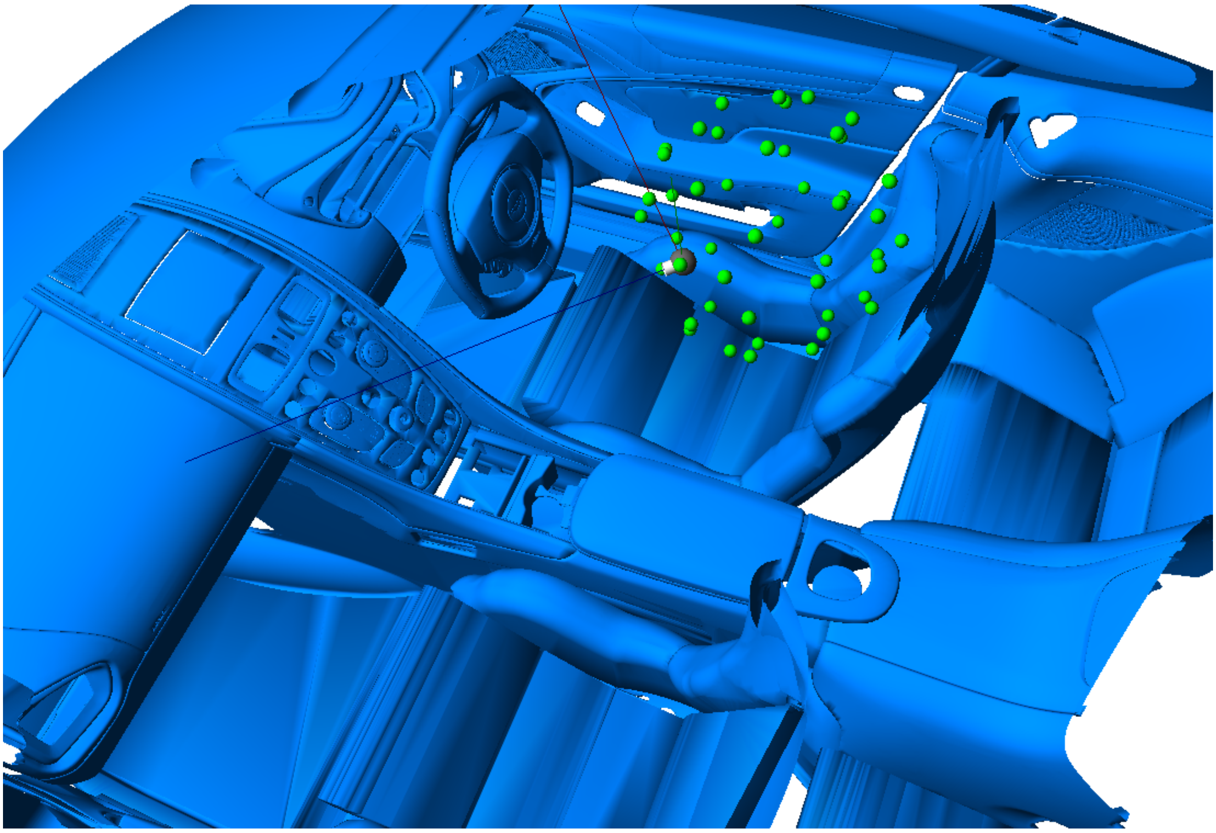

Figure 2 – Spherical array, positioned inside the car.

3. RESULTS

3.1 Interior noise sources

Figure 3 shows the result for the beamforming of the interior spherical array at a frequency range of 0.5 kHz to 3 kHz. Three sources can be identified at the drivers door.

Noise sources: S1 on the side glass near the mirror, S2 at the lower back corner of the side glass, S3 near the middle of the lower edge of the door.

The sources identified inside the car cabin are dominant between 0.5 kHz and 3 kHz for source S1 at the front of the glass and between 1.7 kHz and 3 kHz for source S2 at the back of the front glass and source S3 at the bottom of the door.

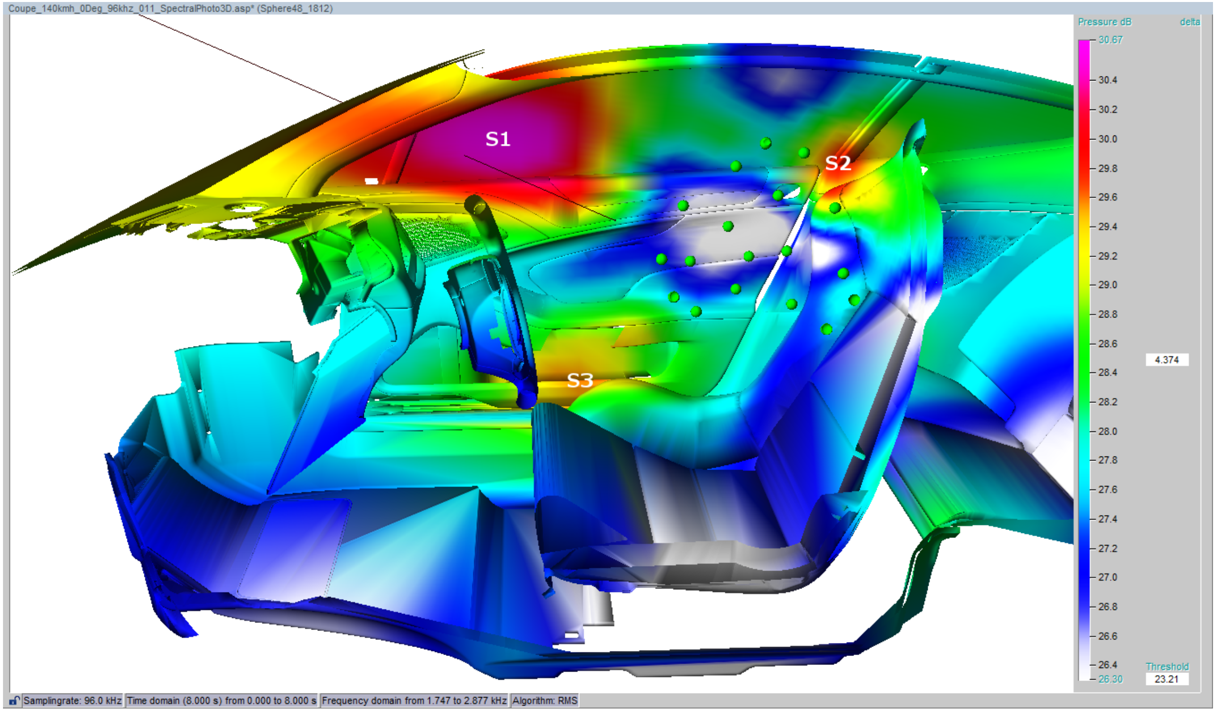

Figure 3 – Acoustic map (SPL) of the three sound sources inside the car in the frequency range of 1.7 kHz to 3 kHz measured by the spherical array.

3.2 Exterior noise sources

For the exterior beamforming analyses we calculated a geometrical correction of the source positions introduced by Amiet (4), (5). This correction takes into account shear layer refraction of the sound waves at the edge of the wind stream. To calculate the exact correlation between the interior and exterior sound sources we apply the same frequency range (0.5 kHz to 3 kHz) used for the interior measurements. The main source (Figure 4) is at the front wheel with an SPL of 57 dB.A secondary source is visible only by its reflection on the floor, suggesting the original source is underneath the car. The reflection shows an SPL of 53.5 dB. A third source is visible at the mirror and measures 53 dB.

3.3 Correlation Analyses

With the help of the beamforming technique we separated the three source components which were found in the interior measurement. The primary purpose of this paper is to investigate the contribution of each exterior source to the interior measurements, and also their positions. In addition, we are looking for evidence of interior sources that do not correlate to outside sources, suggesting leakages due to weak points in the door seal. From the beamforming results obtained from the interior measurement with the sphere array we reconstructed a time function at each of the three positions of the detected sources. These time functions are treated as virtual reference microphone signals recorded at optimal positions. For these interior sources we calculated the normed cross correlation function $C(\tau)$ between the interior source signal $A(t)$ and the microphone signals $B_i(t)$ of the spiral array outside the car.

$$C(\tau) = \frac{\int_{-\infty}^{\infty} A(t) B_i(t+\tau) dt}{\sqrt{\|A(t)\| \cdot \|B_i(t)\|}} \tag{1}$$

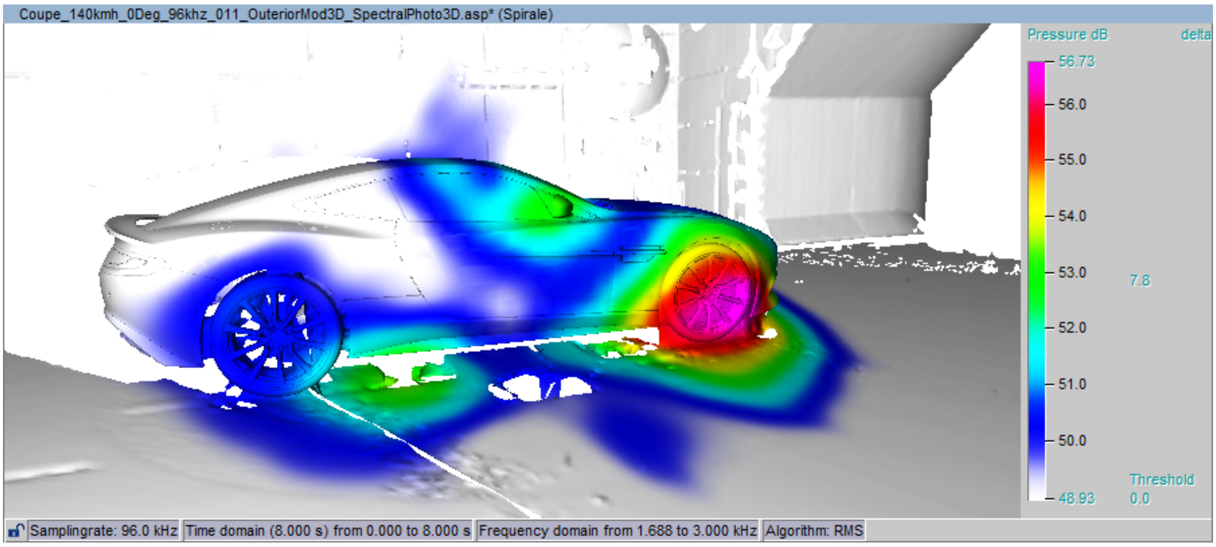

Figure 4 – Acoustic Map (SPL) of the exterior noise sources measured by the spiral array.

where $\|\cdot\|$ is the L2 norm. This means that the correlation function is 100% at $\tau = 0$ if $A(t)$ and $B_i(t)$ are identical.

The sources identified inside the car cabin are dominant between 0.5 kHz to 3 kHz for source S1 at the front corner of the glass and between 1.7 kHz to 3 kHz for source S2 at the lower back corner of the front glass and source S3 near the middle of the bottom edge of the door. Figure 5, 6 and 7 show the resulting correlation function between the inside sources and the outside array signals. To improve signal-to-noise ratio the plots contain the smoothed and averaged cross correlation even if the maximum correlation is decreased by the averaging as the peak positions in the correlation function do not fit perfectly due to the different microphone positions.

With the help of the beamforming technique we now can choose each of the peaks of the correlation function and can localize the origin of the correlated sound components.

3.4 S1

For the source 1 at the front of the side glass the maximum correlation found was 17%. The origin of this signal is the mirror. The second peak in the correlation function on a first glance seems to be localized at the front wheel. The delay between both peaks is about 13 ms, corresponding to a distance of about 4 m. Since the external beamforming results did not expose any source this far from the wing mirror, another explanation was sought out. Figure 5 shows a strong reflection at a glass window and the surrounding walls to the rear of the microphone array. The distance from the array to the wall was a bit over 2 m, which corresponds to the measured peak delay. In conclusion, for S1, our results show that the most dominant source outside the car, i.e. the front wheel, is of less significance to interior measurements than the wing mirror.

3.5 S2

For source 2 at the back of the front glass the correlation is greatest with the source underneath the car, but there are also contributions made by the mirror and the front wheel. Figure 6

3.6 S3

For source S3 at the bottom of the door only the car bottom source is correlated. The noise from the mirror and the front wheel does not appear to contribute to S3. Figure 7

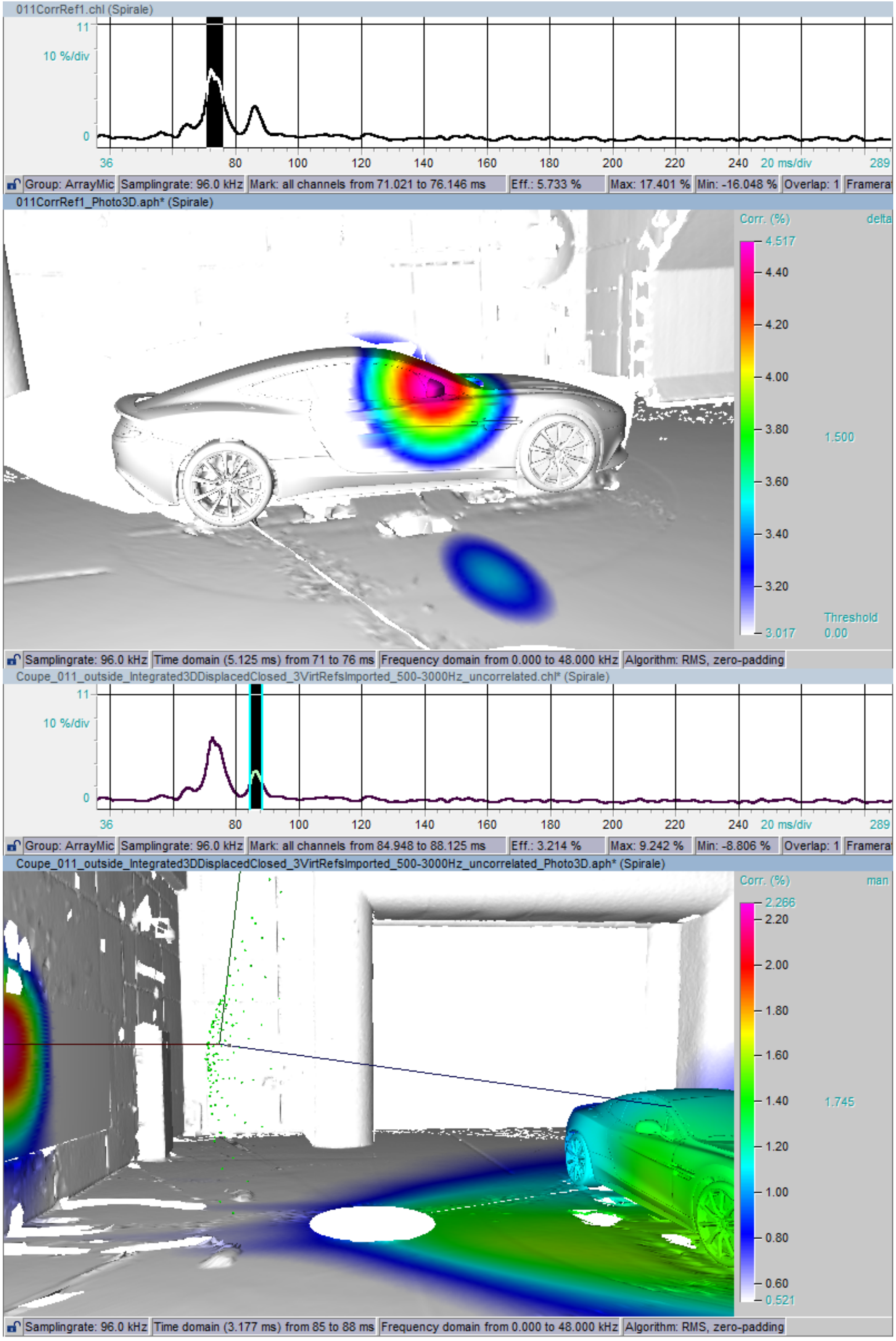

Figure 5 – Cross-correlation between interior source S1 and external microphone signals. Data is smoothed and averaged over all 120 channels. In panel A, the acoustic photo shows the localization of the selected peak of the correlation function. The first peak is clearly located at the side mirror and the reflection on the floor. Panel B shows the second peak which occurs 13 ms after the first; a result of a mirror source on the wall behind the array.

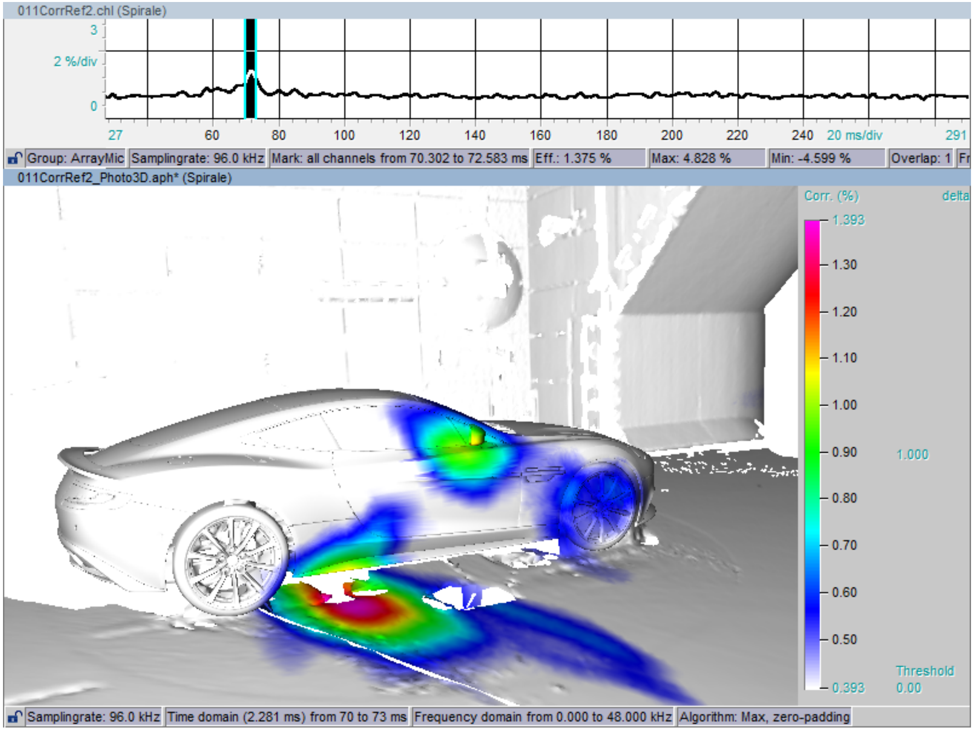

Figure 6 – Cross correlation between interior source S2 and external microphone signals. The peak is located at the source at the bottom of the car with contributions from both the mirror and front wheel.

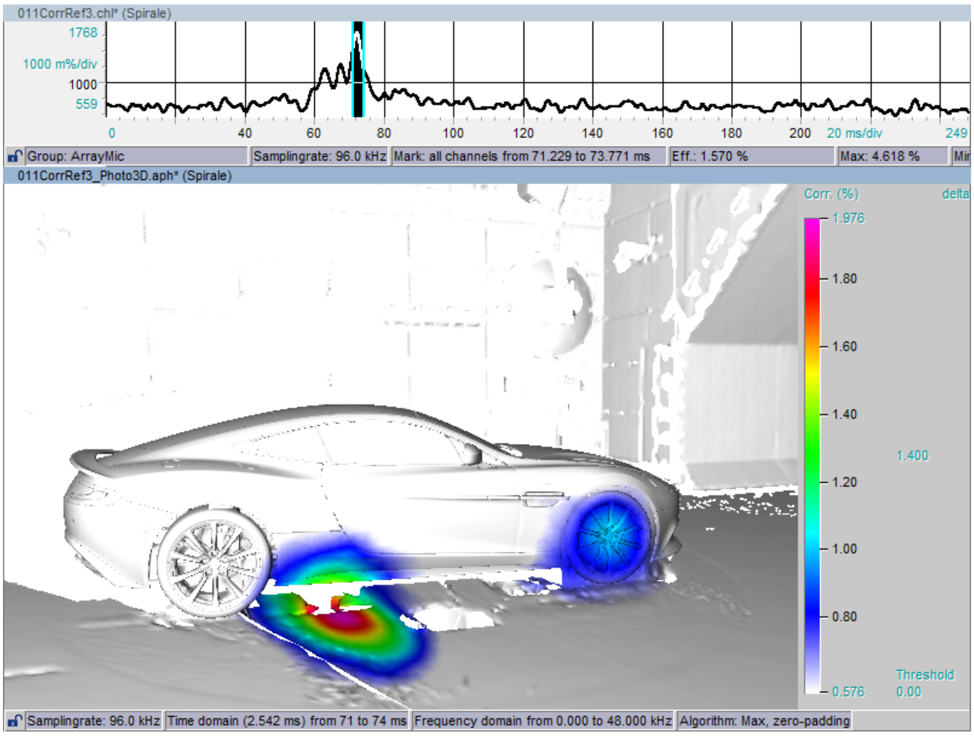

Figure 7 – Cross correlation between interior source S3 and external microphone signals. The peak is located at the source at the bottom of the car, with further contributions from the front wheel. The noise generated by the mirror doesnot appear to contribute to S3.

3.7 Discussion

All mapped interior sources were found to be correlated with mapped sources outside the car. No interior sources were found to represent noise by air streaming into the cabin as a result of a weak door seal. All interior sources are caused by the transmission of externally generated sources from the vehicle in a wind stream.

The most dominant interior source is S1 and the most dominant component of S1 within the selected frequency range is the turbulence caused by the mirror, contrary to expectation as the loudest externally measured source is emmited by the front wheel.

3.8 Comparison: Use of standard reference microphones

Figure 8 – Setup of reference microphones.

When using the reference microphones instead of the virtual reference sources generated by beamforming inside the car the correlation results were similar by quality whereas the amplitude was considerably lower.

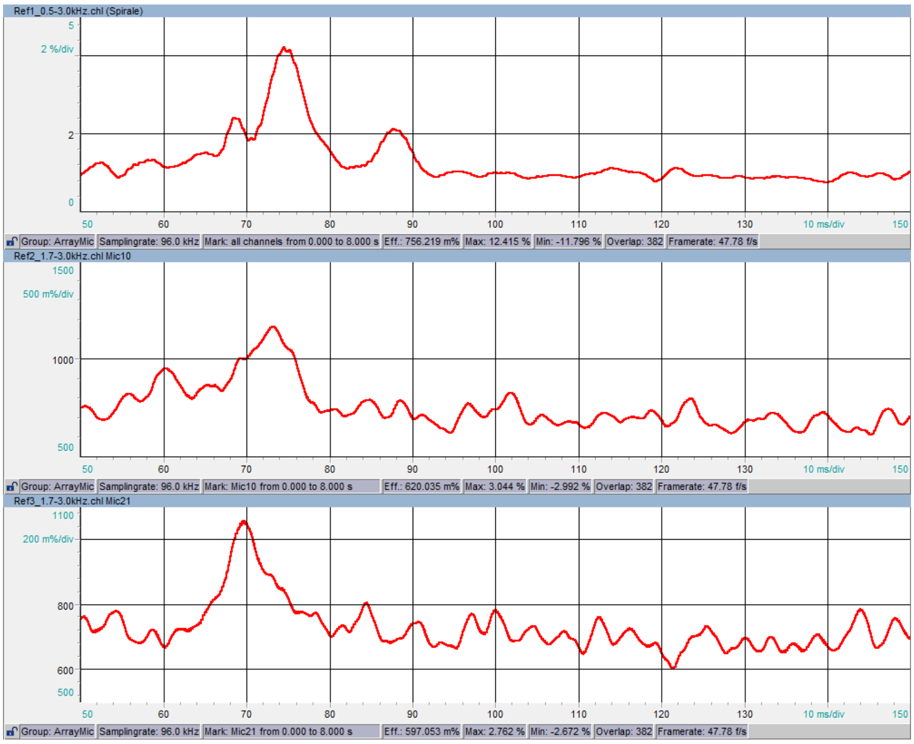

Figure 9 – Cross correlation of reference microphone signals R1-R3 with external microphone array signals.

The reason for the lower correlation results might be found in the microphone placement in the near field of vibrating structures of the door and the window glass. Parts of these signals don't contribute to the far field measured with the beamforming array and perceived by the passengers.

4. CONCLUSIONS

The use of virtual reference sources from interiour beamforming in comparison to fixed reference microphones offers some improvement in the analysis of the individual contributions of multiple external sources to the internal noise signature.

Virtual reference microphones eliminate the need for an exact placement of physical reference microphones—an essential task in correlation measurements, but inefficient since the locations of the sound emissions are not known beforehand. Furthermore, virtual reference sources have the potential to show greater correlation with the external beamforming measurements which enables the tracking of weaker sources in the outside acoustic photo, which might contribute significantly to the interiour sound signature. Further improvements can be expected from longer measurement durations, thus reducing the noise floor.

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