A sub-array beamforming approach to simulated pass-by measurements

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Introduction

Among many other expectations and regulations, automotive manufacturers also have to satisfy increasingly strict legal requirements regarding the acoustical properties of their newly designed vehicles. Above all, the exterior noise is the decisive factor in this context. One conventional approach to the uniform measurement of exterior noise of a vehicle in an operating state is the so-called simulated pass-by measurement. Unfortunately, these measurements result in sound-level profiles of the entire exterior noise only which is sufficient to indicate if the vehicle satisfies the maximal sound level specified by the regulations but not the influence of the individual sound sources.

In this paper, we discuss a method that utilizes two 432-channel microphone arrays in order to create a 3D-beamforming map of both sides of a running car during a simulated pass-by measurement on a test stand. First, we present the steps that led to the design of the multi-purpose microphone array(s) under consideration. We then introduce a sub-array method that directly interfaces a simulated pass-by measurement by projecting its unique microphone trajectory onto the planes of the array. In theory, any multi-channel method could be used to analyze the time data of each of these sub-array measurements. Choosing a suitable frequency-domain beamforming method and composing the resulting maps on the 3D model with some directivity information derived in the process, we finally demonstrate this method in its entirety for a real-world measurement.

Design of the microphone array

The microphone array design had to serve two main purposes, acoustical holography on the one hand and beamforming applications on the other. The former requires a uniform distribution of the microphones arranged in the greatest coverage possible of the measurement object (cf. [1]) while the latter calls for a certain distribution of microphone distances that balances beamwidth and maximal side lobe levels (see [2]). In order to allow for a simultaneous measurement of both driver's and passenger's side, a symmetric approach using two microphone arrays was chosen. Each side consists of 432 microphones arranged in three planar sub-arrays in order to cover a large azimuthal angle but leaving enough room for switching cars (see fig. 1). Each of these sub-arrays is realized as a sunflower spiral (see [2, 3]) with an intended frequency range of application of $50 - 3500$ Hz.

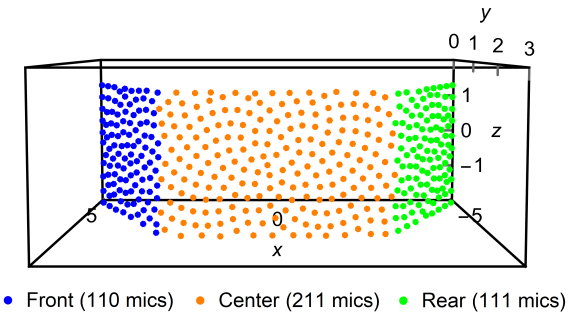

Figure 1: Design used for each of the two microphone arrays.

Implementation

In order to visualize the sources of noise in a way which reflects their relevance for the pass-by level profiles, we assume a virtual observer on each side of the measured vehicle. Given the recorded velocity of the vehicle $v(t)$, we determine the current positions of the virtual observers in driving direction by integration $x(t) = x_0 - \int_{t_0}^{t} \mathrm{d}t\ v(t)$. The positions of the observers are denoted with $\mathbf{r}(t)$ and are set to $\mathbf{r}(t) = (x(t), \pm 7.5\,\mathrm{m}, 1.2\,\mathrm{m})$ for our investigation. In addition, we assume that the observers look directly at a fixed position $\mathbf{r}_\mathrm{d}$ inside the car at any time.

Considering N equidistant time points t_i with a distance Δt during the pass-by, for each t_i the intersection point $\mathbf{r}_\mathrm{i}$ of the array plane and the line of sight from $\mathbf{r}(t_i)$ to $\mathbf{r}_\mathrm{d}$ will be determined. Around this intersection, a vertical cylinder of radius r_c is assumed (see fig. 2).

Every microphone within this cylinder is considered the center of a sub-array (see fig. 3). For each of these sub-arrays, the nearest microphone, then the next nearest etc. from the center microphone is added to the array. This procedure is stopped if either the number of microphones in the current sub-array reaches N_max or there are no more microphones within a distance of r_s around the center microphone. Now, we have determined a subset of microphone sub-arrays which reflects the views of the observers to the car at time t_i. For every sub-array, the visible parts of the 3D model from the view point of the center microphone are determined. Then, the acoustic map for the visible points is calculated for the time interval $(t_i - \Delta t_\mathrm{bf}/2, t_i + \Delta t_\mathrm{bf}/2)$. The size of the interval Δt_bf is a parameter which must be adopted accordingly. It is possible to use any supported beamforming algorithm (e. g. CLEAN-SC [4], power beamforming [5], HDR [6]). This procedure is repeated for every t_i.

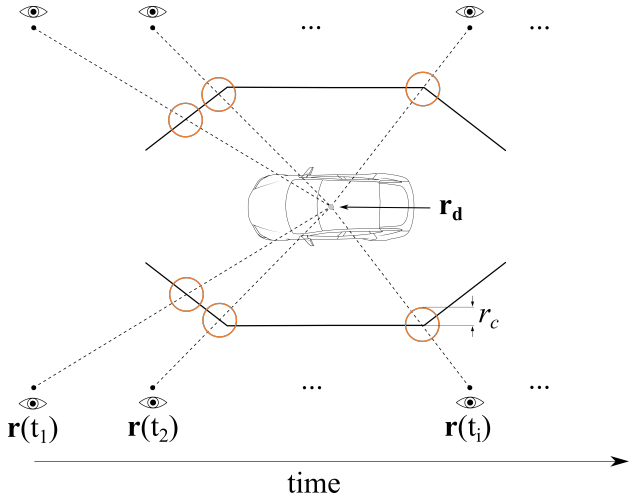

Figure 2: Determination of sub-arrays: On both sides of the vehicle, an observer moves past the car according to the vehicle's virtual position resulting from the RPM channel. These observers are looking at a fixed point on the car at any given time. At the intersection of the line of sight with the array plane, a vertical cylinder of radius r_c is assumed. All microphones within this cylinder will be used as center for a sub-array (see also fig. 3).

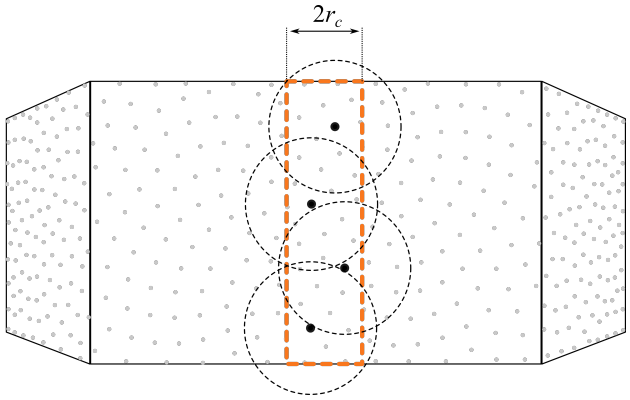

Figure 3: According to the intersection of the line of view of the virtual observers (see fig. 2), all microphones within a cylinder (red dashed line) are considered as sub-array centers. These sub-arrays comprise at most N_s microphones, since only the nearest microphones within a distance of r_s from the center microphone are considered.

Finally, all acoustic maps from the whole set of sub-arrays are averaged. For the average result of any map point, only results from sub-arrays for which the point was visible are considered.

Not only the noise levels, but also the directivities (how they are perceived by the passing observer) of the noise sources are of interest. For every point in the acoustic map, we determine the sub-array that detected the maximal noise level for this point. The direction from the point to the center microphone of this sub-array is considered as the main radiation direction.

Measurement Setup

The measurement was done in a semi-anechoic chamber with the two previously described microphone arrays surrounding the vehicle. The vehicle itself was placed on a chassis dynamometer. In this investigation a vehicle with rear-wheel drive was used, therefore the front wheels were fixed (see figure 4).

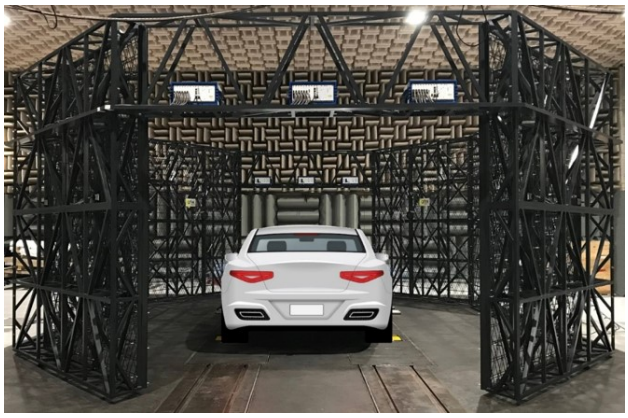

Figure 4: Measurement setup in a semi-anechoic chamber. Two microphone arrays, each consisting of 432 microphones, surround the vehicle to be measured. The vehicle shown is an artificially generated symbol image [7].

The measurement was done with a sample rate of 48 kS/s. Here, the vehicle was initially driving at 50 km/h in the 3rd gear. It then started accelerating at an assumed position of −15 m. The duration of the measurement was chosen such that the vehicle covers at least a distance of 30 m like in a conventional simulated pass-by measurement.

Results

The results shown in this section were calculated with the following parameters:

Table 1: Calculation Parameters

FFT	
Block Size	4096
Window	von Hann
Overlap	at least 50%
Sub-Array Calculation	
Pass-By Segment	from −15 m to +15 m (approx. 1.94 s)
Time Step Δt	0.2 s
Cylinder Radius r_c	0.1 m
Max. Sub-Array Radius r_s	1 m
Max. Sub-Array Mics N_{max}.	60
Lowest Center Mic.	0.2 m above the ground
→ Number of Sub-Arrays	164
Acoustic Map	
Algorithm	CLEAN-SC [4]
Voxel Size	1 cm^3

Furthermore, in the evaluation shown below, the 3D model of the measured vehicle had to be replaced due to legal reasons. The alternative model consists of nearly 2.5 million triangles and was matched so that the wheels, the engine area and the exhaust coincide with the original 3D model since these are the main sources in this case.

Acoustic Maps

In figure 5, the resulting acoustic maps of our approach are exemplarily shown for two third octaves. For the 315 Hz third octave, we can clearly identify the reflections of the engine and the exhaust as main sources while the rear wheels are no relevant source at low frequencies.

At higher frequencies, however, the rear wheels are the dominant sound source. The reflection of the exhaust is still a major source at the 1000 Hz third octave, while only the direct sound emission from the engine is detected in the chosen dynamic range.

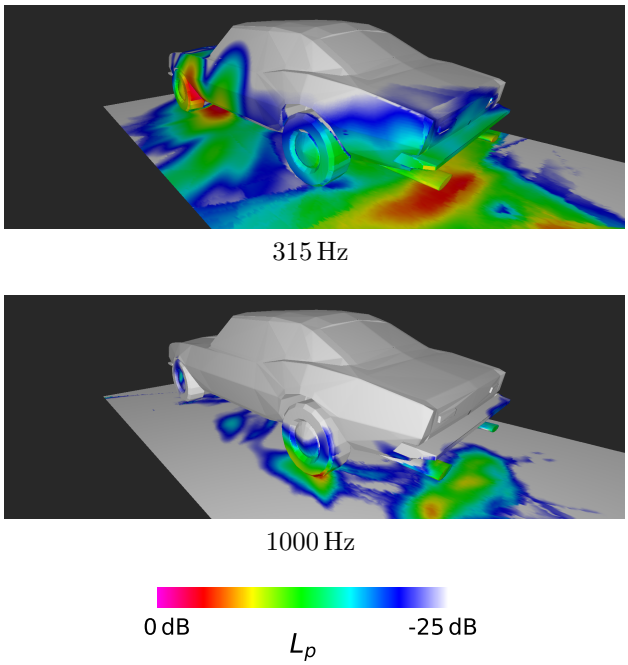

Figure 5: Resulting acoustic maps for the 315 Hz and 1000 Hz third octaves calculated with the sub-array approach using CLEAN-SC [4].

Directivities

By using a multitude of sub-arrays and thus having many different view angles on the measured vehicle, it is possible to determine the main radiation direction of the acoustic sources. In figure 6, the directivities for the engine area at the 315 Hz third octave are shown. It becomes clear that the highest sound pressure levels are detected on the floor by sub-arrays located in the upper half of the microphone array. Thus the dominant measured source in this area is indeed the reflection of the engine noise.

At higher frequencies the rear wheels of the vehicle provide a more complex example for the directional characteristics of a sound source. As expected, the wheels emit noise mainly to the front and the back (see fig. 7). But

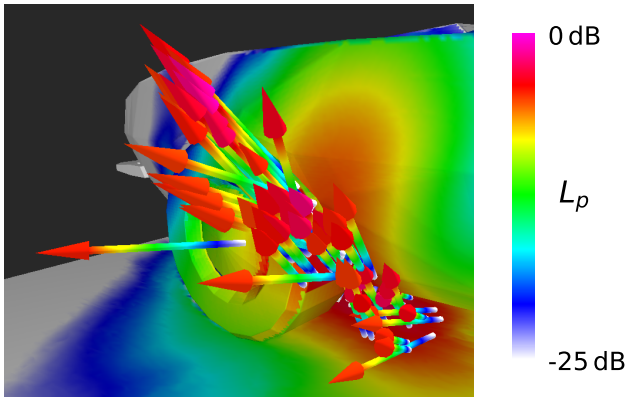

Figure 6: Resulting directivities of the vehicle's engine for the 315 Hz third octave.

since the rear sub-arrays detect higher sound pressure levels in their respective acoustic maps, as indicated by the red and purple arrows, the main direction of emission can be assumed to be the backward direction. The slight shift of the determined directivities to the side is due to the fact that there are no microphones directly in front of the car and behind it.

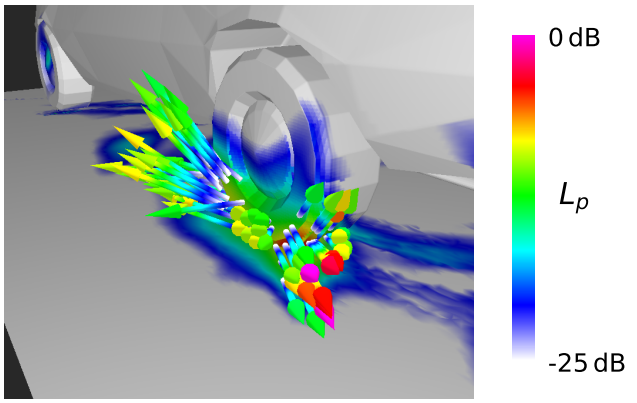

Figure 7: Resulting directivities of the vehicle's left rear wheel for the 1000 Hz third octave.

Conclusion

Our introduced approach accomodates the transient nature of simulated pass-by measurements and thus enables the identification of the relevant sound sources.
In addition to improving the dynamic range of the resulting acoustic map, the use of a multitude of sub-arrays allows for a better understanding of the directional characteristics of the individual sound sources.

Nevertheless the resulting acoustic maps could be further improved by statistically filtering possible outliers as suggested in [8] or [9].

Acknowledgments

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