# Transient acoustic analysis of a run-up of a car using a modular 4096 channel MEMS microphone array

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**Summary**
NVH research is important in the automotive industry to analyze the acoustic characteristics of vehicles. Microphone arrays are used as measurement devices, with both near and far-field acoustic algorithms to analyze the acoustic characteristics of vehicles. However, these measurements are typically costly, inaccurate or time-consuming. This paper presents a relatively low-costs rectangular modular 4096 channel MEMS microphone array, currently the largest microphone array available. This array is demonstrated on a run-up of a electric car, using beamforming and Planar Near-field Acoustic Holography (PNAH). Both the accuracy and measurement time is improved greatly. Using PNAH and Beamforming it is possible to analyze vibration paths in the whole car with a single measurement, helping an NVH engineer to improve the charateristics of vehicles.

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## 1. Introduction

Recent research by the World Health Organization [4] pointed out that environmental noise negatively effects humans health. They estimate that one million healthy life years in west Europe are lost every year from traffic related noise. Therefore, it is important to reduce noise and vibrations caused by the automotive industry. To achieve quieter and more comfortable cars, good measurement hardware and techniques are required to gain insight in the acoustic (transient) behavior of vehicles.

In automotive Noise, Vibration, and Harshness (NVH) research is an important area to understand the noise and vibration characteristics of vehicles. R&D labs are using small microphone arrays to analyze the acoustic characteristics of vehicles, typically by using far-field beamforming techniques or near-field acoustic holography techniques. However, using these techniques are either time-consuming (multiple measurements are required), expensive (large amount of hardware is required) or inaccurate (especially low frequent behavior).

An important limiting factor for such measurements systems is the microphone array itself. The frequency range of measurement systems is limited by the microphone array size and the sensor spacing. Analyzing other frequency ranges requires changing the measurement setup. Traditional microphone arrays use expensive high-end analog microphones, limiting the amount of microphones in a system and thus limiting the frequency range and accuracy. Recent technology advancements in digital MEMS technology presents alternatives for these microphone. Instead of using a few expensive high-end microphone, it is possible to use many digital MEMS microphones. This paper presents a modular 4096 channel microphone array, developed by Sorama, a spin-off of the University of Technology Eindhoven. The presented microphone array (see Figure 1) consists of low-cost digital MEMS microphones uniformly spaced with a inter-sensor distance of two centimeters. In this paper, the microphone array is demonstrated on typical NVH areas, such as transient vibration analysis in vehicles. Currently, to the best of the authors knowledge, Sorama has built is the largest functioning microphone array currently available. This fact is also recognized by the Guiness Book of Records [5] , beating the previous record of LOUD [8], a 1020 channel microphone array.

The hardware and design philosophy of the microphone array are described in detail in the next section (2). Based on the hardware setup, the effects of the novel 4096 channel microphone array on both far and near-field algorithms are explained (3). Finally, the microphone array is demonstrated on a run-up of a vehicle on a roller bench (4).

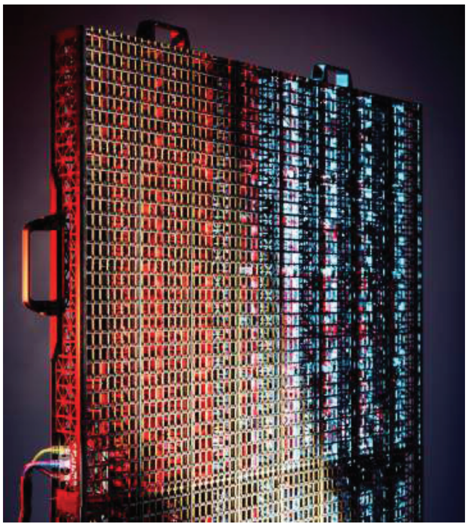


Figure 1: The Sorama 4096 channel microphone array in a square 64 by 64 setup.

## 2. Hardware

The goal of Sorama was to design a low-cost modular microphone array, containing an arbitrary number of microphones (depending on the source and application). This principle of using a huge amount of low-costs microphones has already been demonstrated by MIT during their LOUD project [8]. They presented a 1020 channel microphone array in 2004, containing relative low-end microphones with local AD converters. They demonstrated that spatial filtering using delay-and-sum beamform techniques benefits greatly of the large amount of closely spaced microphones. However, due to its size, the measurement setup was not practical and it was only used as a proof-of-concept, while the array presented in this paper is commercially available.

The microphone array presented in this paper consists of 64 smaller modules, each consisting of 64 microphones. These modules are square and uniformly spaced MEMS microphone arrays of size eight by eight with a spacing of two centimeters. Each array has local processing, storage and interconnect capabilities, such that all microphones in the system are synchronized. Using this basic building block, a variety arbitrarily sized microphone arrays can be built.

The uniform spacing in the square array has both practical and academical reasons. The primary application in mind when designing the microphone array was using Planar Near-field Acoustic Holography (PNAH). An important property of the algorithm is the fact that it is Fourier based, resulting in the requirement of equally distributed microphones. More in-depth analysis of the algorithm can be found in section 3.2. The practical reason is the production of the array; square arrays are easier and cheaper to produce compared to circular or semi-random distributed microphone arrays.

The most important part of the microphone array is the microphone itself. Classic microphone arrays contain a small amount of high-end analog microphones. While the acoustic properties of these microphones are excellent, a drawback is the cost of a single microphone, the required amplifiers and Analog-Digital (AD) converters. Due to the recent rise of digital MEMS microphones in consumer electronics (e.g. smart phones and laptops), both the quality and costs of these microphones has improved considerably. The maturity of these MEMS microphones enables it to be used in microphone arrays as well, for only a fraction of the cost compared to traditional microphones. A typical digital MEMS microphone is a small package, containing a MEMS transducer, an onboard amplifier and a sigma-delta AD converter. The output of the package is a Pulse-Duration Modulation (PDM) bit stream running between 1 and 3 MHZ. Due to the onboard AD converter, the complexity of the system is reduced considerably compared to analog microphones (no extra amplifiers and AD converters are required). The presented microphone array contains Akustica AKU240 microphones, with a 63 dB SNR ratio, 2 dB sensitivity matched and guaranteed phase matching of ten degrees. These microphones are clocked at 1.5 MHz, resulting in a sampling rate (with onboard decimation filter) of 46875 Hz.

## 3. Algorithms

An important technique in NVH is finding the source of the vibrations in the vehicle and analyzing the resulting vibration paths in the vehicle itself. Based on the analysis, the vehicle is adapted to reduce the sound and vibrations in the system. The most used technique is the far-field beamforming technique, offering a global overview of the vehicle with a limited frequency range. Another technique often used is near-field acoustic holography, offering local detailed source reconstructions of the vehicle. A good approach is to use both techniques, to analyze the vehicle in the fastest way. The first step is using far-field techniques to acquire a global overview of the system, while near-field techniques are used to analyze hot-spots of the system in-depth. The effect of the microphone array for both types of algorithms is explained in this section.

### 3.1. Far-field Beamforming

Beamforming assumes that there are only propagating waves present in the measurement, which is only true for far-field measurements. In this paper basic delay-and-sum beamforming is used since it is easy to apply and can be used on large microphone arrays without any computational issues. Delay-and-sum beamforming has already been demonstrated with a 1020 channel microphone array [8], resulting in considerably better results compared to smaller microphone arrays.

The spatial response for a delay-and-sum beamformer given a narrow-band signal with a center frequency $f$ is as follows:

$$S_{bf}(\theta, \phi, f) = \left| \sum_i s_i[f] e^{-i2\pi f d_i(\theta,\phi)/c} \right|, \qquad (1)$$

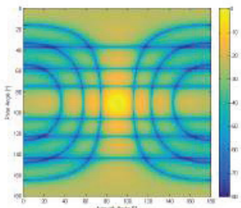
where $\theta$ and $\phi$ are the azimuth and polar angles respectively, $c$ the propagation speed of sound, $d_i(\theta, \phi) = x_i cos(\theta) sin(\phi) + y_i cos(\phi)$ and $s_i[f]$ is the narrowband signal at frequency $f$ measured by sensor $i$. Assumed is a sensor-array of arbitrary size in $x$ and $y$ direction and size 1 in the $z$ (propagation) direction. Figure 2 shows the beampatterns for a number of different microphone array configurations for 1000 Hz. A very clear observation that is made from the beampatterns is that the accuracy of the beamformer (the size of the main-lobe) is greatly influenced by the size of the microphone array. Patterns (a) through (c) where made with arrays that span an area of or close to 1.26 m by 1.26 m, while (d) was made using an circular array with a diameter of 0.62 m. Assuming a one dimensional case, two functions are important [1]. The first indicates the spatial resolution $\theta_{res} \approx \frac{c}{L*f}$ (with $L$ the length of the microphone array) and the second indicates the guaranteed alias free result $d < \frac{\lambda}{1+|sin\theta|}$, with $d$ the inter-sensor distance. The spatial resolution corresponds with the presented beampatterns, that a larger microphone array greatly improves the accuracy.

The beampatterns show the effects of a finitely sized and spaced array. The shape of the array also has a clear influence on the beampattern. These effects should be taken into account when using delay-and-sum beamforming for sound imaging, the first step in analyzing images obtained by delay-and-sum beamforming should therefore be an inspection of the beampattern. Especially when using non-uniform or arbitrarily shaped arrays this inspection is critical.

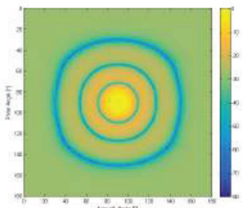
### 3.2. Planar Near-field Acoustic Holography

Planar Near-field Acoustic Holography (PNAH) is a Fourier based method, used to analyze the high resolution dynamic behavior of sources. This near-field technique uses both the evanescent and propagating waves, resulting in detailed source reconstructions. The algorithm used for this measurement setup is based on the research of Scholte [6], using (spatial) filtering and finite aperture extrapolation techniques to reduce the reconstruction error.

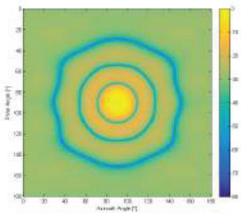
When using an infinite large microphone array with an infinite small microphone spacing and perfect microphones, the result of PNAH is exactly the same as the Rayleigh integral. However a truncated microphone array, with non-ideal microphones and a spacing between the microphones results in errors in the system. Due to the measurement noise and the microphone spacing, the resulting resolution is limited compared to the ideal case. In the perfect case scenario when there is no noise in the system, the minimum distance between two sources for which the sound image results in two unique sources, the Spatial Sound Image Resolution (SSIR), is minimal the wavelength



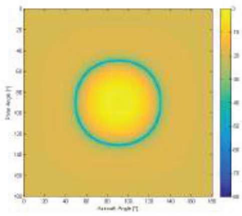
(a) 64 by 64 channel 2 cm spaced square array.



(b) 64 by 64 channel 2 cm spaced circular array.



(c) 32 by 32 channel 4 cm spaced square array.



(d) 32 by 32 channel 2 cm spaced square array.

Figure 2: Spatial impulse responses or *beampatterns* for a variety of microphone array setups at a narrowband singal frequency of f = 1000 Hz.

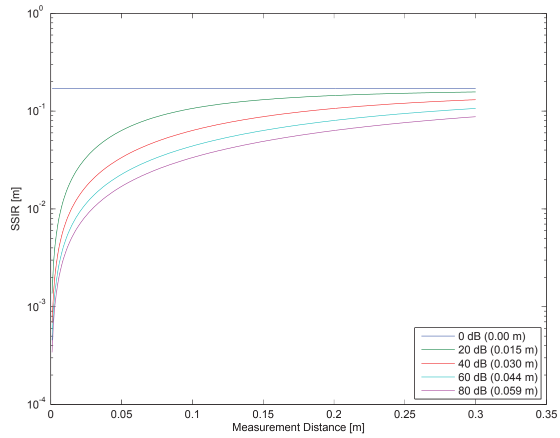



Figure 3: The SSIR versus the measurement distance, for multiple SNR. The frequency is 1 kHz. The distance in the legend displays the minimal standoff distance, to prevent aliasing.

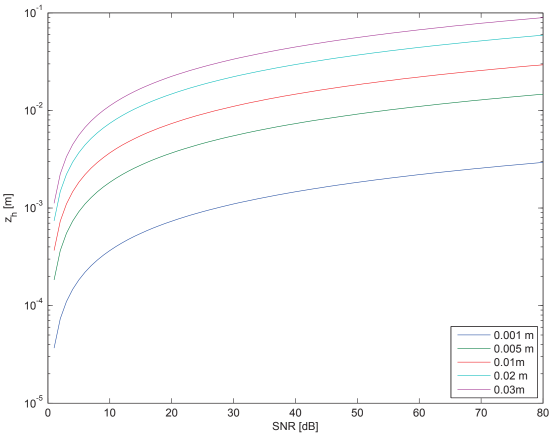



Figure 4: Minimal measurement distance versus the SNR, for multiple sensor spacings. The frequency is 1 kHz.

of the wave and maximum limited by Nyquist criterium [6]:

$$\lambda/2 \leq SSIR \leq 2\delta_s \; [m], \tag{2}$$

where $\delta_s$ is the microphone spacing and $\lambda$the wavelength of the wave. Introducing noise in the system results in a SSIR, typically lowers than the maximum achievable resolution. This is primarily due to the potential blow-up of noise in the system. Regularization is needed to achieve good results [7]. Maynard [3]determined the maximum achievable resolution, based on the SNR in the system:

$$SSIR = \frac{\pi}{\sqrt{k^2 + (\frac{SNR\,ln10}{20(z_h - z_s)})^2}} \; [m], \tag{3}$$

with $z_h$the measurement distance,$z_s$the propagation distance, $k = 2\pi * f/c$. Note that it is assumed that the power on the source of both the propagating and evanescent waves are equal. An example for a source at 1 kHz is given in Figure 3. Based on this figure, the microphone array should be placed as close as possible to the source as possible to achieve the highest SSIR. However, aliasing due to evanescent waves is not taken into account in these formulas. Scholte [6] derived a formula taking this into account:

$$z_h > \frac{SNRln10}{20\sqrt{\frac{1}{4}k_s^2 - k^2}} \; [m], \tag{4}$$

where $k_s = \frac{2\pi}{\lambda_s}$is the sampling wavenumber and $\lambda_s$the sampling wavelength. This response is plotted in Figure 4 and is indicating that a better SNR should result in a larger measurement distance. Since the SNR of the source in the system is generally unknown, the rule of thumb in that the minimal distance should be at least 1.5 times the inter sensor distance, while the maximum distance should be the wavelength of the highest frequency.

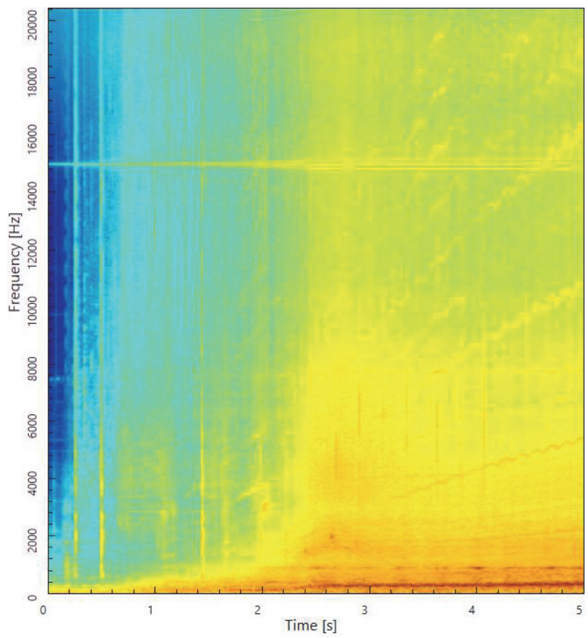



Figure 5: Normalized spectrogram of the car accelerating during 5 seconds. The spectrum was obtained by averaging the spectra of all the individual microphones.

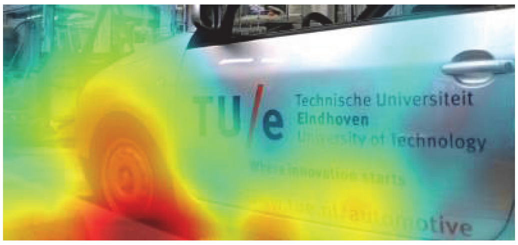
## 4. Measurements & Analysis

Due to the recent advancement in electric cars, the motor is not the most powerful acoustic source in the car. The next step is analyzing the car in depth, what the current hot-spots are and how they are influencing the dynamics of the car. For this purpose, a customized electric Volkswagen Lupo EL is used to demonstrate the microphone array. This electric car is build by the Dynamics and Control group of the University of Technology Eindhoven and is a converted diesel Volkswagen Lupo. The car is tested on a front wheel roller bench setup at the University of Eindhoven. A short movie of the measurement setup and results is found at https://www.youtube.com/watch?v=WrTOuM5LHn4.

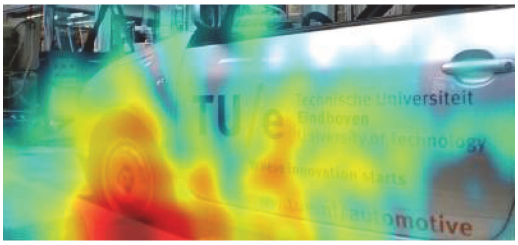
The car is analyzed in two steps. The first step is using the far-field technique beamforming. This results in a global overview of the acoustic behavior of the car. Based on this measurement, the global hotspots are found. Based on this overview, a region of interest is defined and analyzed using PNAH. A spectrogram of one of the measurements is shown in Figure 5.

### 4.1. Far-field Beamforming

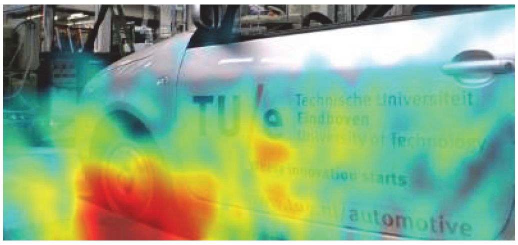
For the far-field measurements, a 64 by 64 microphone array setup is built. Beamforming benefits from a square array, as the resolution in the vertical and horizontal direction is the same. The 1.24 by 1.24 meter area with a spacing of two centimeters results in an effective frequency range between 1 kHz and 10




(a) f = 1500 Hz - 2000 Hz

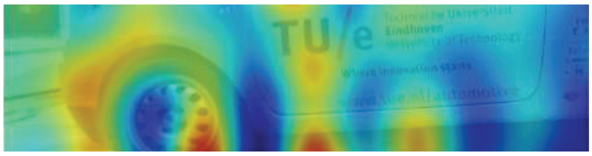


(b) f = 4500 Hz - 5000 Hz

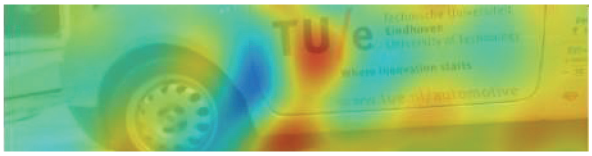


(c) f = 6500 Hz - 7000 Hz

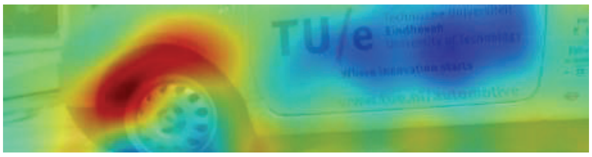
Figure 6: Beamforming results around 4 seconds after the start of the measurement, colormaps are in dB values.



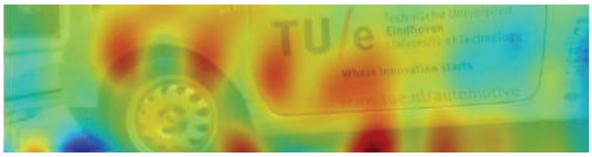
(a) Normal Velocity at f = 20 Hz Hz, t = 0.8-1.0 s and 0 degrees phase



(b) Normal Velocity at f = 20 Hz, t = 0.8-1.0 s and 90 degrees phase



(c) Normal Velocity at f = 37 Hz, t = 4.8-5.0 s



(d) Normal Velocity at f = 185 Hz Hz, t=1.8-2.0 s

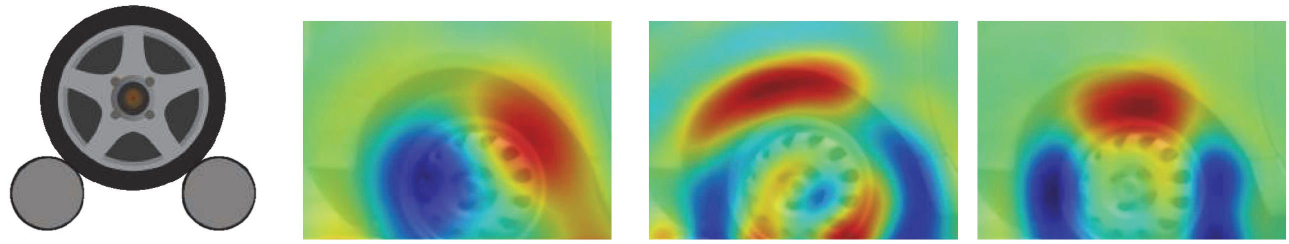
Figure 7: Normalized PNAH normal velocities. Scale is linear.

kHz. Figure 6 depicts the beamforming results. The array was placed at a distance of at 3 meters to the front-tire of the car. It is clearly visible that the main source of noise in this setup is the contact surface of the tire to the roller bench or even the roller bench itself. In the lower frequency ranges (Figure 6a and 6b) the tire and possibly some parts of the wheel casing can be seen vibrating. There also appear to be some effects on the frame of the car (mainly the door), it is possible however that these effects are caused by the beampattern of the delay-and-sum beamformer. Based on these results, the hotspots of the vehicle are the wheels and the frame around the wheel. It should also be noted that most activity is low frequent and it is impossible with this array and beamforming to analyze.

### 4.2. Planar Near-field Acoustic Holography

The beamforming results demonstrates that the primary (acoustic) sources are the tires and the frame around the tires. The next step is analyzing the tires and the effect on the car in detail, using PNAH. Therefore, the PNAH measurement uses a 128 by 32 channel microphone array instead of a 64 by 64 channel array, covering an area containing a wheel of the car and the door. The reconstructing covers the wheel and how the vibrations are influencing the frame of the vehicle. Based on the spectrogram (see Figure 5), the most interesting parts are in the area lower than 3000 Hz and especially below 1 kHz. Based on Section 3.2, this results in a measurement distance of ten centimeters. It should be noted that animated reconstructions are easier to analyze (see provided video link).

The results in Figure 7 depicts contribution of the three largest frequency peaks in the spectrum and demonstrate the the same basic hot-spots compared to beamforming. Figure 7a and 7b demonstrates two different phases of the same frequency of 20 Hz. It shows a vibration starting in the tire and propagating in the frame and below the car. Figure 7c shows an umbrella mode in the door and a vibration around the tire itself. This information can be used to counteract the mode in the frame, by adding extra material in the door. It is also possible to see (see Figure 7a and 7b) that there is a transfer path around the wheel to the frame itself. Based on the PNAH results, further in-depth analysis of the characteristics of the car can be made. More extensive analysis is required to find possible solutions to reduce the vibrations.



(a) A schematic overview of the tire on the roller bench.

(b) Normalized normal velocity at f = 64 Hz and t = 2.0-2.2 s revealing a (1,0) mode in the tire.

(c) Normalized normal velocity at f = 119 Hz and t = 2.0-2.2 s revealing a (2,0) mode in the tire.

(d) Normalized normal velocity at f = 106 Hz and t = 2.9-3.2 s revealing a (2.0) mode in the tire.

Figure 8: Normal velocity of the tire at different frequencies and time intervals. All visualizations are linear scale.

Another important contributor is the wheel itself. Multiple research papers are available researching the (acoustic) behavior of tires. Therefore, the presented measurements are compared to earlier research on this topic. Figure 8a contains an overview of the setup for the tires, as used during the measurement. It should be noted that the test setup has two contact points with the tire, influencing the behavior compared to a single contact point. Figure 8b till 8c shows the normal velocity on the tire for two modes, during the start of he run with a relative low vehicle velocity. Figure 8dshows the same mode as Figure 8c, however during a higher tire velocity. In earlier research [2], their results present similar behavior compared to the presented results. During 17 km/h, comparable to the speed presented in this paper, demonstrate (1,0) mode around 80 Hz and (2,0) mode around 113 Hz. These modes are also visible in the presented measurements, around 64 Hz and 119 Hz. Increasing the speed of the tire, the (2,0) mode is still visible, however now around 106 Hz. A dedicated test setup is required to analyze the vibration in a tire in-depth.

## 5. Conclusion

This paper presented a modular 4096 channel digital MEMS microphone array, currently the largest microphone array available. Due to the modularity of the system, the array is easily adapted for different algorithms and sources. Besides, the large amount of microphones in the system greatly improves accuracy and reduces costly measurement time. The capabilities were demonstrated on a run up of a electric car. Far field technique beamforming demonstrates a global overview of the system, but the frequency range is still limited. However, PNAH demonstrates detailed reconstruction over a large area, even for low frequent behavior. Based on PNAH, the tires and the frame of an electric car is analyzed, demonstrating the wheel as the entry point of the vibrations and visualizes vibration paths in the vehicle. Further research is required to analyze of vehicles in-depth and trying to understand and improve the current design of vehicles. In the end the presented microphone array presents new possibilities to analyze the acoustic behavior of objects, with reduced measurement time and improved accuracy.

## Acknowledgments

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