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EXTENSION OF TRADITIONAL MEASUREMENT METHODS IN VEHICLE ACOUSTICS TO THE METHOD OF SOURCE LOCALIZATION IN THE VEHICLE INTERIOR

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ABSTRACT

Growing demands on the acoustic comfort of a vehicle and the increase of the importance of lightweight design represent a new challenge in acoustic development tools of an automobile manufacturer. Traditional acoustic measurement techniques offer the opportunity to make statements about structure-borne noise and airborne sound radiation by a vehicle component using accelerometers and microphones. Structure-borne noise and airborne sound sensors thus provide direct information on the accelerations and the sound pressure in the near field. However, single channel methods reach their limits there, where it is important to determine the complex radiation patterns and their superposition into directional radiation. But especially in the interior of the vehicle the direction information of the airborne noise radiation to the occupants is of superior importance. In airborne sound this possibility is given by the microphone array technology (Beamforming). Beyond usual body and airborne sound information, beamforming can thus provide important additional information on the influence of acoustic phenomena on the sound field and the places of occurrence in the vehicle interior. To make the extension to the beamforming suitable and efficient, the evaluation of the results is carried out in multiple stages. The represented work based on a practical example illustrates the methodology of such an advanced, multi-stage approach in the acoustic development of a car manufacturer and will show the potential to improve the sound source localization in the vehicle interior.

1 INTRODUCTION

Intensive investigations in NVH (Noise, Vibration, Harshness) have become an integral part of modern automobile development in the past ten years. This discipline was considered initially in vehicle R&D even with skepticism. It is now an integral part in the early development phase of the product. Thus NVH has become a customer experience and is representative of the overall quality of the product. Strict legal framework conditions and growing demands of the customer set, especially in the premium segment, a challenge for the developers. However, to achieve a continuous improvement of NVH comfort in the vehicle, it requires sophisticated testing methods and advanced tools. One of these tools is beamforming, respectively the acoustic camera. It represents an important extension of conventional methods of investigation and can provide additional knowledge about the secondary sources of airborne sound radiation and localization of such radiation sources in order to achieve significantly improved findings of NVH phenomena.

2 INTEGRATION OF THE BEAMFORMING METHOD

The beamforming as a "stand-alone" method cannot provide significant gains in knowledge regarding development tasks on a modern car in most cases. Therefore, the beamforming is used at Daimler AG as an integral solution. Fig. 1 graphically represents this approach.

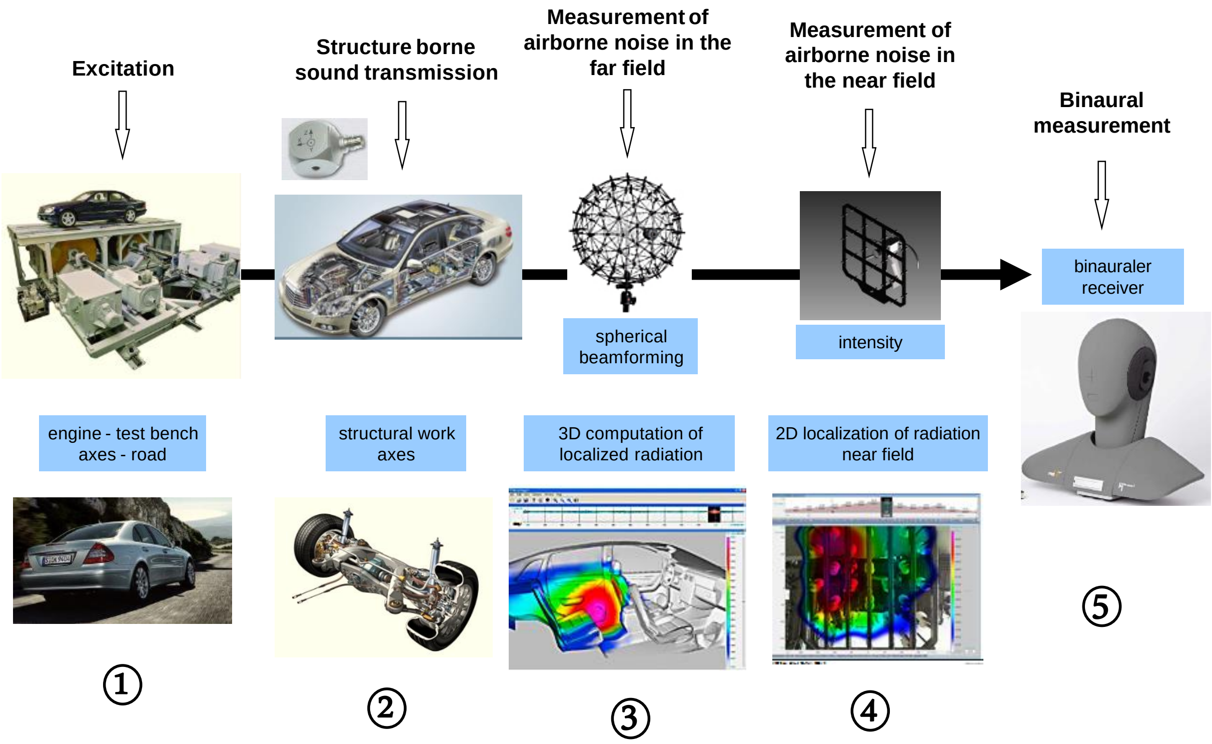

Fig. 1: Integral approach of source localization at Daimler AG

The step 1 and step 2 represent the classical approach of transfer path analysis as an integral part of important information about the state of motion (acceleration, velocity and positional data) provided by the components to be examined. This investigation steps are performed with "traditional" measurement technique as accelerometers, load cells, etc. Thus, in a first step, the accelerations and their derivations at significant points are typically recorded in proximity of the motor bearings or "neuralgic" points of the specific investigation on the vehicle. The sound pressure information of the interior are obtained simultaneously from the beamforming array. In this case, the microphone array provides compared to other procedures a significantly higher number of measurement points which are adjusted by a grid model to the given geometries of the interior and thus allow for the measured accelerations of the structure synchronous, high-resolution sound pressure mapping of the vehicle interior (step 3). Through the merger of the sizes, structure acceleration and the calculated sound pressure information, correlations between excitation, structural movement and radiation can be derived. Since the beamforming below 500 Hz, depending on array geometry, size of the aperture and number of microphones have limitations in the localization of certain phenomena, beamforming is supported and expanded by the intensity method (step 4). For this purpose, an additional microphone array is used, which can detect local airborne sound phenomena between 50 and 2000 Hz. The intensity method used in direct near field of the radiating structure to be examined is largely insensitive to external acoustic disturbances due to a significant back suppression [1]. A use outside of the vehicle is therefore possible even under less than ideal conditions. To ensure a plausibility of the measured sound pressure levels and to allow a binaural auralization, this integrated approach also provides synchronous measurements with at least one artificial head as step 5.

The wide range of applied research methods results in a very high number of channels to be analyzed, depending on the scope of investigation. Given current development status of the measuring system, up to 144 channels can be recorded synchronously at up to a sampling rate of 192 kHz. In the following the sensor groups of a typical measurement scenario are listed below:

- accelerometers
- microphones (optional)
- microphone array (beamforming)
- microphone array (intensity method)
- artificial head(s)
- binaural microphone (optional)

additionally:

- engine speed, drive shaft speed etc.
- CAN signals
- various temperatures

Due to the high number of measured signals, a structured approach to signal analysis is necessary. The structure of this multi-stage approach is shown in Fig. 2. It should first be clarified, how small an additional effort is created in setting up the measurement set-up by the addition of the beamforming- and the intensity array. Taking the maximum set-up time into account, the overhead of setting up the array increases the effort of setting up the conventional sensors by just 25% percent. This slight additional effort definitely justifies the possibility of gaining knowledge regarding the sound radiation through the measurement system “acoustic camera”.

If we now consider the procedure for the subsequent analysis, it has been found in practice that a first assessment of a variant can be worked out only by means of the artificial head measurements. On the one hand, the artificial head as a binaural receiver includes the possibility of a direct assessment by the client, on the other hand variant influences can quickly be verified (stage 1). However, if the result of the artificial head evaluation is considered to be insufficient for assessment or if the transfer paths are to be assessed separately, it is proceeded to the assessment of the conventional sensor data from airborne- and structure-borne sound sensors (stage 2). A completion of the previously interrupted functional chain relationships and an understanding of the propagating sound field inside the cabin or on the vehicle component can be reached only by the evaluation of the radiation through the beamforming and/ or the intensity method (stage 3). Depending on the complexity of the noise complaint on or in the vehicle, the measurement system "acoustic camera" is flexibly applicable.

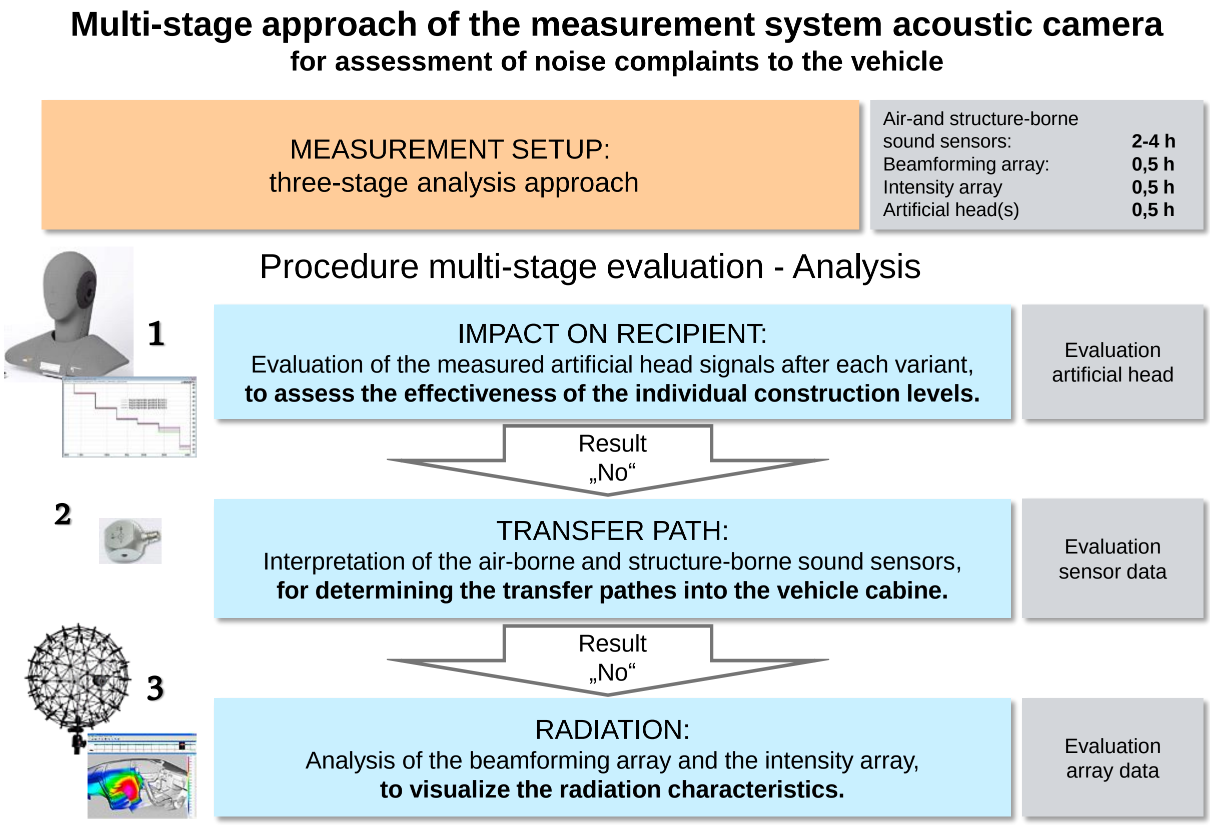

Fig. 2: Multi-stage approach of the measurement system "acoustic camera"

3 STABILITY LIMIT OF THE BEAMFORMING METHOD INSIDE THE VEHICLE CABINE

The classical method of beamforming is based on a decomposition of the incident wave field into plane (or spherical elementary waves). The relative amplitudes and phases across the array's sensors are processed and interpreted into the directions of incidence so that source locations can be identified and classified. A use in reactive sound fields and in "near fields" has not been sufficiently clarified, however. In vehicle interiors, there are both reactive (near field or modal), and pure energy (far field, geometric) sound field components. The dividing line between these areas typically takes the so-called Schroeder frequency; in the range of 700-900 Hz. However, this means that in the interesting frequency range of 200 Hz to about 800 Hz modal effects may be relevant, and therefore purely propagating waves only expected to be above 800 Hz [2]. These conditions provide a special challenge for the use of beamforming in the vehicle interior. A brief insight into current research results is to show the limits of the application.

The investigations were performed inside a Mercedes-Benz S-Class (V221 E55LA) for two measurement positions of the spherical array. Fig. 3 shows the measured positions of the microphone array in the vehicle interior (left: "array position Front", right: "array position Rear"). The Schroeder frequency of the S-Class can be estimated to a good approximation by (1) [2]:

$$f_s \gg \sqrt{\frac{c^3}{4V\langle\delta_{lmn}\rangle}} \approx 1200\sqrt{\frac{T}{V}} \tag{1}$$

with the reverberation time T [s] and the volume V [m3]. Thus, the Schroeder frequency is given for the vehicle under test at a reverberation time of 0,065 s and a volume of 3,244 m^3 geater than 169 Hz.

Fig. 3: Measurement positions of the spherical array in the vehicle cabine

For the investigations of the vehicle interior, a measurement signal (exponential sweep) was individually played in sequence to the 14 built-in speakers of the onboard sound system and recorded simultaneously with the 32-channel microphone array to evaluate the frequency-dependent directional characteristics of the vehicle interior. The application of the spherical beamforming to the described measurement configurations provides the results shown in the following using the plane-wave decomposition by Rafaely [3].

Fig. 4 shows the calculated angles of incidence of plane-wave decomposition in the vehicle interior. The signal to be measured was emitted through the center speaker of the audio system. The center speaker is centrally integrated into the dashboard, and can radiate freely in the direction of the windshield. It is well recognized that in the case of a "free transmission path" between speaker and array, the localization in the vehicle interior is possible in a wide frequency range (300-2000 Hz).

Exemplary for the stability limit of the method in the vehicle interior, the radiation of the passenger doors loudspeaker to the microphone array in the "Rear" is shown in Fig. 5. This demonstrates the influence of shading by the front passenger seat to higher frequencies. The evaluation of the frequency-dependent directional characteristics, excited by the 14 on-board speakers delivers plausible results.

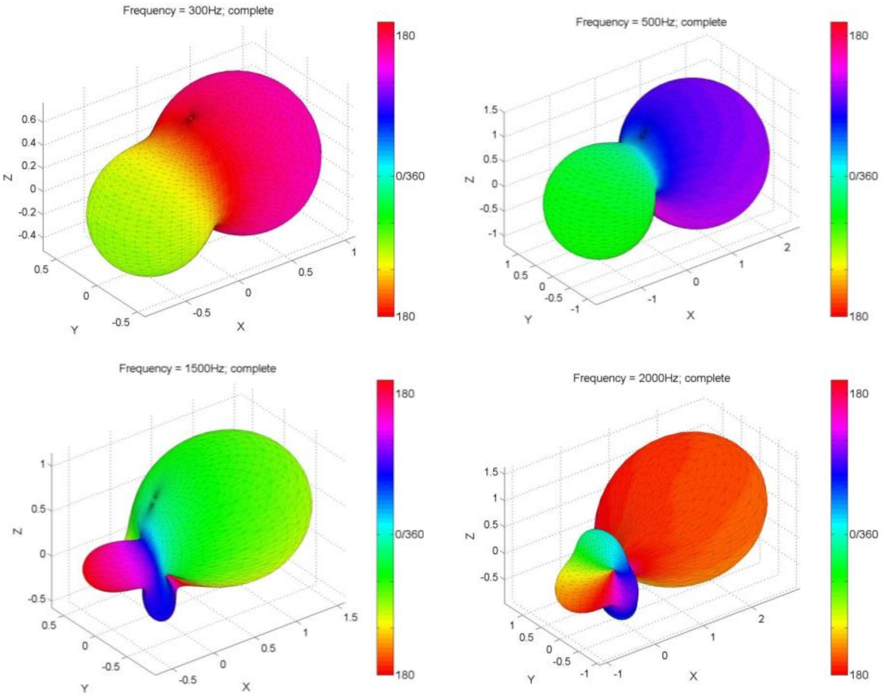

Fig. 4: Result of the plane-wave decomposition for the center speaker in the vehicle interior, Array position "Front"

Depending on the location of the receiving position of the microphone array, the direction of each speaker can be determined reliably by the plane-wave decomposition of the spherical beamforming in a frequency range of about 500-1500 Hz (or for a "free transmission path" 300-2000 Hz). It is assumed that the results are positively influenced in particular by the short reverberation time (T_{60}) for a room of this size. The measurement results confirm the beamforming as a promising approach for the localization of sound sources even under the constraints of a vehicle cabin.

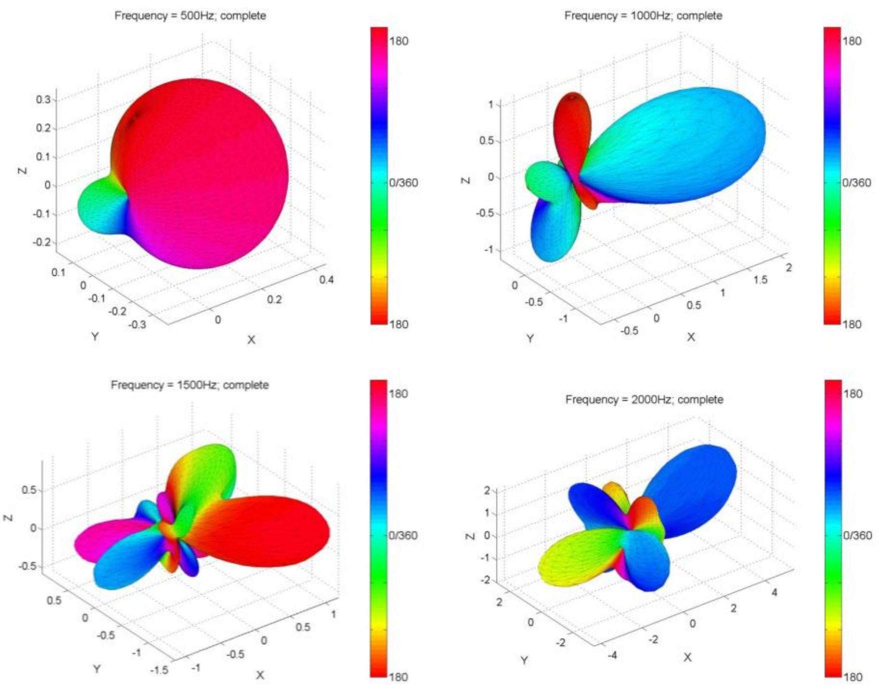

Fig. 5: Result of the plane-wave decomposition for the speaker in the passenger door inside the vehicle, array position "Rear"

4 EXAMPLE OF APPLICATION

The following study gives a brief overview of the application of the described integral use of the source location at Daimler AG.

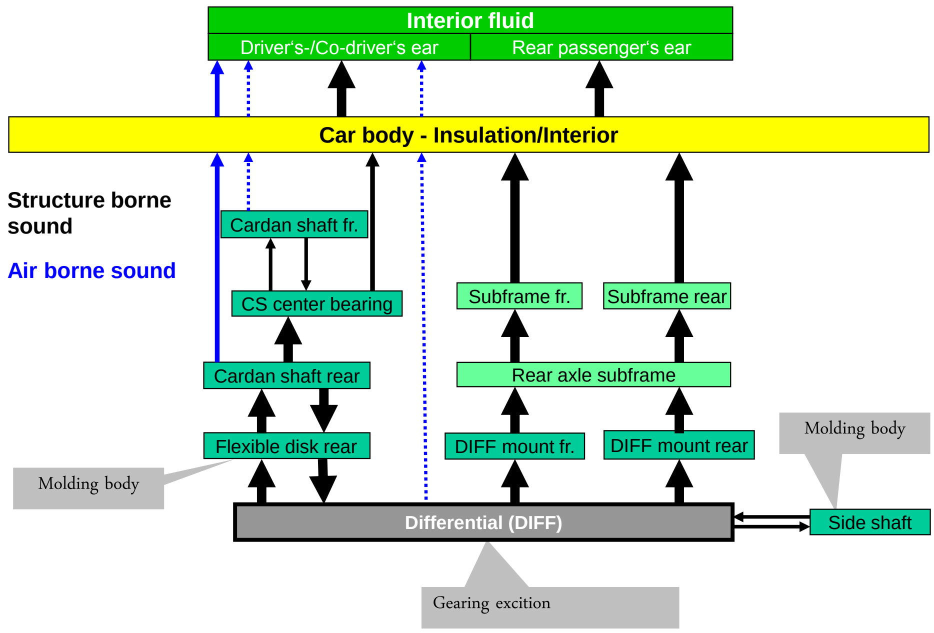

Fig. 6: Functional chain viewed from the rear interior of the vehicle

In the present example, the influence of the cardan shaft on both airborne and structure-borne noise shares to the vehicle interior at defined operating points should be examined. The relevant measuring points for the investigation are derived from the known effect relationships for each component, module or craft. In this case, the effect relationships of the transfer paths are described from chassis and powertrain to the body. The transfer paths are differentiated into airborne and structure-borne paths. Fig. 6 illustrates the so-called functional chain of this specific problem schematically.

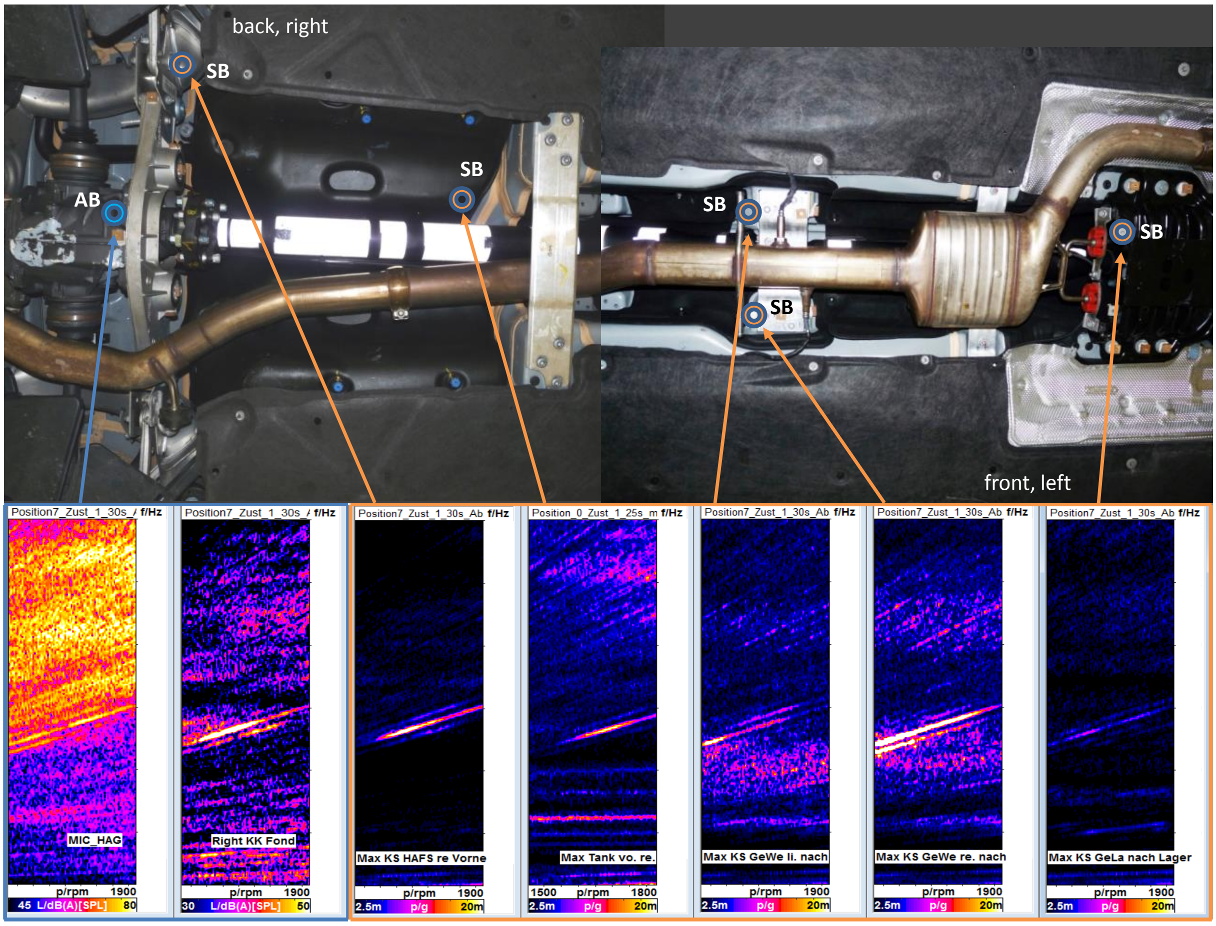

Fig. 7: Analysis of structure-borne sound with reference signals airborne sound

There are possibilities to describe the transmission mechanisms of the impact sound sufficiently accurate in many cases by precise placement of the structure-borne noise paths with acceleration sensors and the use of operational vibration analysis or a Transfer Path Analysis (TPA). The excitation, which in this case is fed by the gear teeth of the rear axle differential (DIFF), can be analyzed at the respective measuring positions by evaluating the acceleration sensors (depending on the direction, magnitude and frequency range). In order to establish a correlation directly between structure-borne sound (SB) and airborne sound (AB), the airborne noise on the differential and the noise at an artificial head channel are considered in parallel. Fig. 7 exemplarily shows the structure of such an analysis.

A major challenge further consists of being able to map and detect the effect / emission of airborne noise locally and in particular its entry into the vehicle interior. An important step towards the full describability of such a functional chain is managed with the beamforming inside the vehicle and the extension to the intensity method.

The direct airborne sound radiation from the cardan shaft between the gearbox output and rear axle differential has therefore been mapped with an intensity array, which has 24 microphone pairs on an area of 30x30 cm. The mapping of the drivetrain is composed of eight individual measurements, which permits a mapping of the entire drivetrain under reproducible conditions. An example of a mapping of the vehicle underbody is shown in Fig. 8. The mapping was performed in a defined frequency range (at a specific engine speed range) and is represented in a dynamic range uniformly selected.

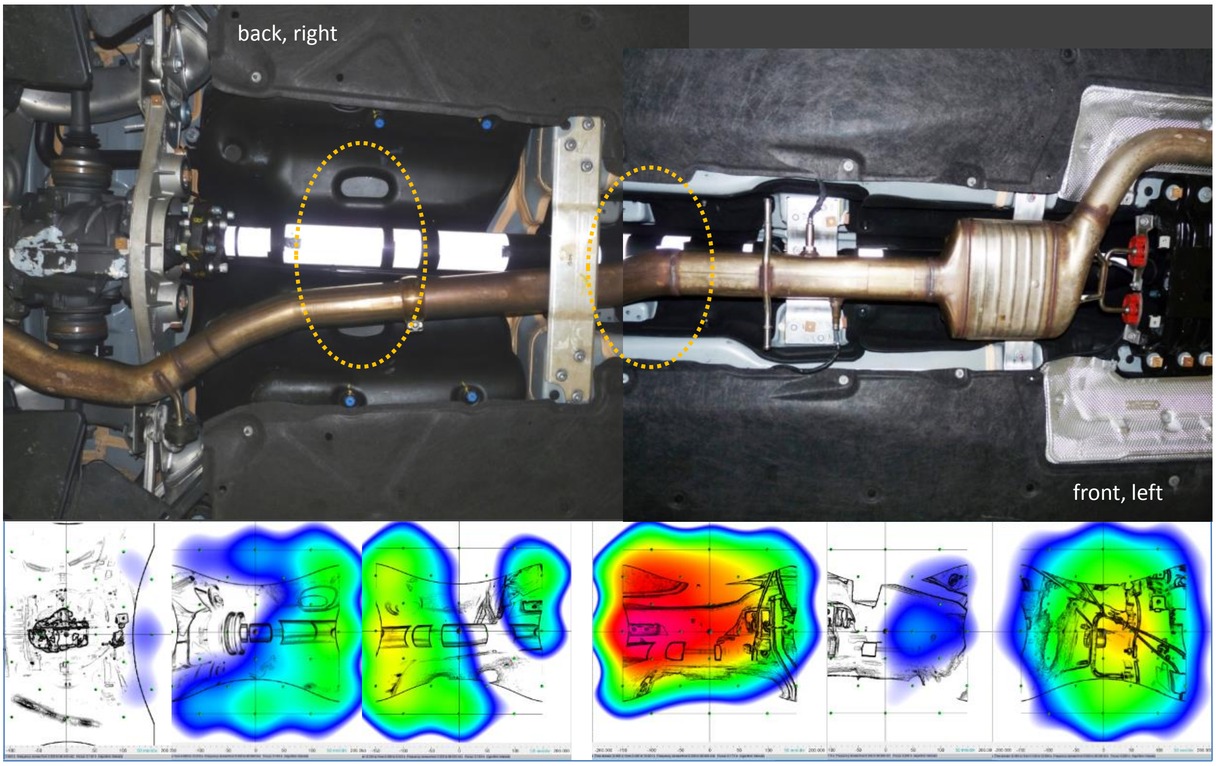

Fig. 8: Airborne noise emission of the cardan shaft detected with the GfaI intensity array

Synchronously ("sample-synchronous") the sound pressure distribution of the vehicle interior has been mapped three-dimensionally with a spherical 48-channel array. Fig. 9 depicts an example of a possible 3D sound pressure mapping in the passenger compartment. In the software NoiseImage there is implemented a classic delay-and-sum beamformer, which can be performed in time domain as well as in frequency domain. As the original beamforming algorithm, it provides "robust results", without being dependent on other boundary conditions [4]. The results therefore require a detailed causal analysis. In addition, there is an extended beamforming algorithm for further evaluation. The so-called high dynamic range algorithm is an iterative procedure to be able to improve the dynamic range of the acoustic pictures significantly. [5]

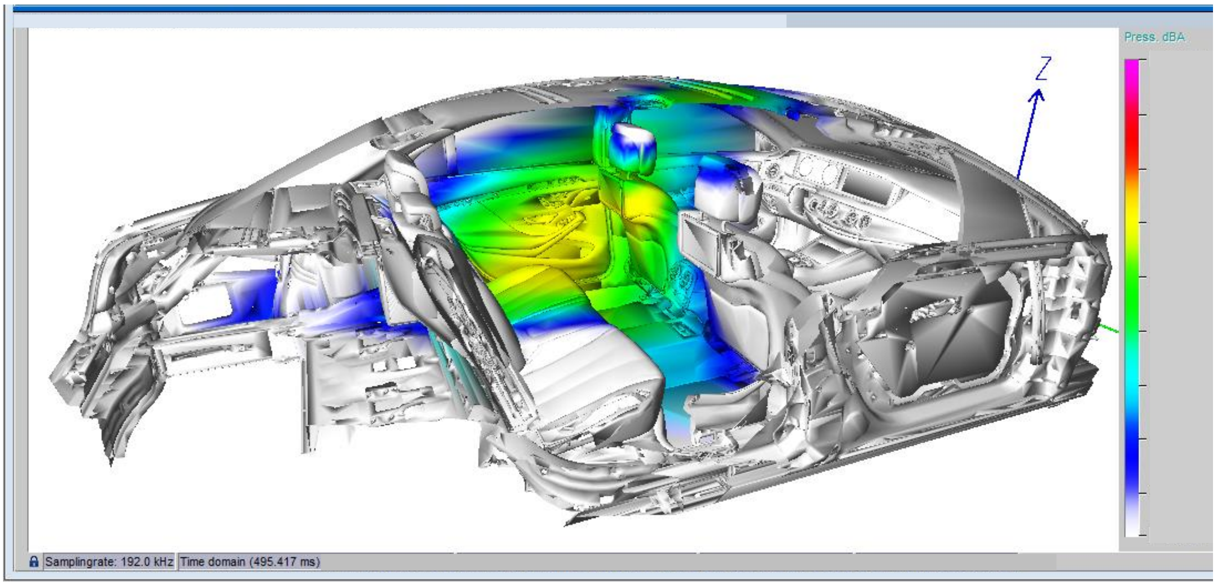

Fig. 9: Exemplary mapping of the sound field in the vehicle interior, SW: NoiseImage,GFaI

By such a mapping, it is possible to locate airborne noise emissions, which lead to peaks inside the vehicle and thus to be able to have a share in resolving acoustic weaknesses of the vehicle directed. Only by applying beamforming in the interior, it is possible to specifically find weaknesses of radiation that are measurable by artificial heads on the inmate's reference positions and rated as annoying by the passengers.

5 CONCLUSIONS

The represented integral approach of NVH evaluation of Daimler AG is providing a significant advancement of the assessment of the entire functional chain from the excitation to the airborne noise inside the vehicle. Due to the complexity of modern vehicle architectures it has become necessary to include new methods for detailed analysis of the entire functional chain in the assessment process. Now, the extension of conventional analytical methods and procedures by the beamforming and the intensity method allow a holistic view of noise problems of the vehicle by:

- Direct evaluation of the structure-borne noise, both near the respective component, and on selected transfer paths
- Localization of the direct airborne sound radiation and intensity of the airborne noise in the near field of the emission
- Thus: Correlation of the structure borne and airborne sound in the near field
- Assessing of local air sound swells and tracking of airborne sound paths through additional individual microphones
- Determination of the sound field respectively the spatial acoustic pressure distribution on the basis of an exact CAD model of the vehicle or individual components

- All information will be recorded synchronously in time and with a high sampling rate of up to 192 kHz
- Resulting: Uniform consideration and assessment of the entire measurement scenarios

The software NoiseImage also has advanced, imaging filter functions, such as a correlation filter or a psycho-acoustic filter that allow to put a combination of the individual measures into relationship more closely. In the future, it is conceivable to integrate adaptive beam-former in the existing measurement environment to improve the mapping under certain boundary conditions. Another promising approach is to consider in the future the acoustic properties of each vehicle's interior to take into account for example modal influences on the sound field in the beamforming process.

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