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Partial sound source estimation with Helmholtz inverse beamforming as a part of pass-by noise virtualization

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ABSTRACT

Noise has an impact on human health. Therefore, pass-by noise of motor vehicles is legally regulated. The latest norm of the Economic Commission for Europe is ECE R51.03. According to this norm, pass-by noise of motor vehicles must be reduced to a sound pressure level of less or equal 68 dB(A). This poses a challenge for original equipment manufacturers. Firstly, they need a detailed analysis on the influence of contributing vehicle components such as engine, exhaust system and tires to the over-all pass-by noise. Secondly, original equipment manufacturers strive to shorten development cycles and lower production costs. Therefore, predictions of the expected physical behaviour of future cars have gained increasing importance. This leads to the emergence of new technological concepts like digital twins. This paper presents an extension of our latest approach to partial sound source analysis of simulated pass-by noise, i.e. Helmholtz Inverse Beamforming. Moreover, we present the embedding of the results of Helmholtz Inverse Beamforming in a comprehensive virtualization concept of pass-by noise engineering. By combining Helmholtz Inverse Beamforming with machine learning predictions of future cars, this concept enables us to derive target values of acoustic components regarding their pass-by noise.

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1. INTRODUCTION

Economic conditions lead to the need for faster development cycles and lower production costs in automotive manufacturing. Thus, original equipment manufacturers (OEMs) increase their activities in the early, digital stages of the development process. Noise causes impact on human health. Therefore, the exterior noise of motor vehicles, also called pass-by noise, is legally regulated. The development of the latest Economic Commission for Europe (ECE) regulation on pass-by noise, the ECE R51.03 test [1], is based on ISO 362-1 [2]. The thresholds of the maximum allowed sound pressure levels (SPL) emitted by cars will be reduced to a value of 68 dB(A) in the next years [1]. For that reason, precise predictions of the expected pass-by noise in the digital stages of the vehicle development process are becoming highly important. Using such predictions OEMs try to ensure that future cars will pass the rising legal requirements before any hardware of the vehicle is available. The need for such predictions leads to new technological concepts, like the digital twin. OEMs are using distinct methods to ensure the sufficiency of form and behavior of future products [3]. Aggregating these methods leads to the concept of the so-called digital twin. The idea of digital twins is no congruent concept within the literature [4]. The definition, we use in this paper, is inspired by [4], where a digital twin is defined as a digital representation of an active product, describing the characteristics and the behavior of the product by information and data. Finite element method (FEM) and boundary element method (BEM) as classical physical simulation methods are also used for pass-by noise predictions [5]. However, these methods do not show sufficient precision in the complete relevant frequency range [5]. Thus, machine learning (ML) predictions of future products have gained high importance in the context of digital twins. One can also find ML approaches targeting the prediction of pass-by noise in the literature [6, 7]. The feature set in [6] is limited to very general attributes as speed, distance to microphone etc., i.e., engine power, applied components like tires and exhaust system are missing. In [7], the authors used multilayer perceptrons and a more extensive feature set to predict pass-by noise. Nevertheless, the predictions in [7] are limited to a single value, the sound pressure level representing the pass-by noise test result. This leads to a significant lack of information, e.g., the position of the car on the test track, needed for further analyses and post processing.

In addition to forecasting pass-by noise based on ML models, there is a need for detailed analysis of the vehicle components', e.g., engine and tires, influence to the over-all pass-by noise. OEMs also measure pass-by indoors at test benches in so-called hemi-anechoic chambers. This process is called simulated pass-by. Transfer path analysis (TPA) is a widely used technique among noise, vibration, harshness (NVH) engineers to identify partial sound sources and their contribution to the over-all noise [8-11]. TPA requires time-consuming measurements and shows some significant disadvantages, e.g., the representation of the acoustic sources as monopoles, which do not represent the real directivity of vehicle components such as the tires. Therefore, we have presented a new algorithm for partial sound source analysis of simulated pass-by measurements called Helmholtz Inverse Beamforming (HIBF) [12]. In this paper, we present an extension to HIBF and validate the results are against our SIFAH algorithm [13-15]. SIFAH stands for Spherical Integration Farfield Acoustic Holography and allows the virtualization of simulated pass-by noise measurements based on sound field extrapolation.

The presented study is part of ongoing work in a larger context [16, 17]. The overlying project called "SimlationsTool Außengeräusch" (S!TA) includes cooperation from Mercedes-Benz AG with Society for the Advancement of Applied Computer Science, DataZoo GmbH and Next Data Service AG. The main goal of the project is the derivation of individual acoustic thresholds of different car components in the early, digital stages of the product development process. Besides HIBF the second key component of S!TA is the ML-based prediction of pass-by noise based on gradient boosted models (GBMs) [18, 19]. A short overview of S!TA and the embedding of HIBF in this project for pass-by noise virtualization is illustrated.

2. PASS-BY MEASUREMENTS

This section contains an overview of the ECE R51.03 and corresponding real pass-by measurements on outdoor tracks as well as a short introduction in measuring simulated pass-by.

2.1. ECE R51.03

The requirements for measuring pass-by noise are legally regulated. Figure 1 shows the measurement area according to ISO 362 [20].

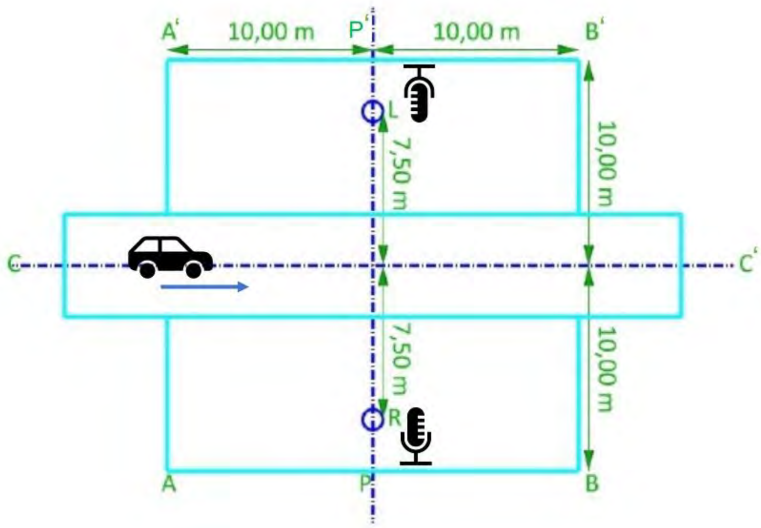

Figure 1: Pass-by measurement area according to [20].

The ECE R51.03 [1], in contrast to the ECE 51.02, shall represent real urban driving conditions. Measurements according to ECE 51.02 are performed under full longitudinal acceleration of cars (not representing typical urban driving situations) [21]. Depending on multiple car parameters, such as vehicle mass, engine power and the acceleration of the car, the ECE R51.03 demands measurements in more than one gear [1]. For reasons of simplicity, we will focus their research on examples where measurements in a single gear i are sufficient.

According to the ECE R51.03 two different types of measurements have to performed. For a single gear, the required measurements are the following:

- Constant pass-by: The car must have a speed of 13.9 $\pm$ 0.3 m/s (50 km/h) between the lines AA' and BB'.
- Accelerated pass-by: When the reference point of the car passes the AA' line the driver fully accelerates until passing the BB' line. The speed of the car must be 13.9 $\pm$ 0.3 m/s at line PP'.

Four consecutive measurements, so-called runs, with a maximum divergence of 2 dB(A) must be performed. The results are averaged for both microphones and the louder average is chosen. With the resulting values $L_{crs\,i}$ (constant) and $L_{wot\,i}$ (accelerated) the final value, L_{urban}, which represents the SPL at the typical urban acceleration (a_{urban}) is calculated [1].

2.2. Simulated Pass-by

OEMs also perform pass-by measurements indoors at test benches in hemi-anechoic chambers. Two lines of microphones and crossfading of the signals according to the speed of the car on the test bench create a virtual pass-by microphone passing the car. Figure 2 shows the microphone lines.

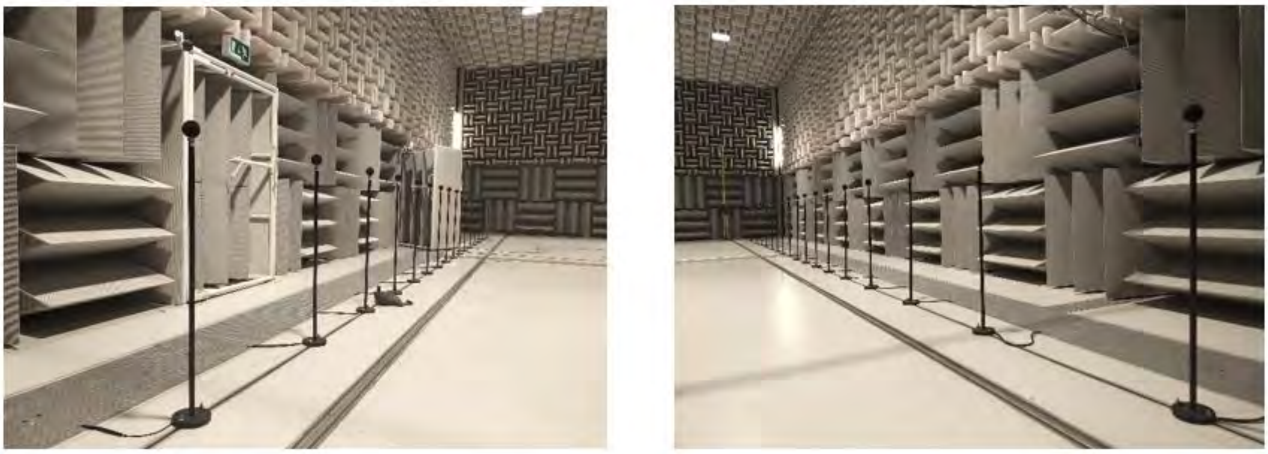

Figure 2: Two microphone lines for simulated pass-by measurements in a hemi-anechoic chamber.

Via crossfading of the microphone signals, the relative motion of the vehicle and the microphone of real pass-by measurements is reversed for simulated pass-by. Here the virtual microphones are passing the car. Figure 3 shows a car placed at a test bench.

Figure 3: Car placed at a test bench.

Simulated pass-by measurements offer the opportunity for detailed acoustic analyses, e.g., with TPA methods or with our HIBF algorithm, which will be explained in the next chapter.

3. HELMHOLTZ INVERSE BEAMFORMING

After a short introduction to the state-of-the-art algorithms based on TPA, we present our algorithm for partial sound source estimation named Helmholtz Inverse Beamforming (HIBF, see [12]) and its recent modification.

3.1. Airborne Source Quantification

Indoor simulated pass-by measurements offer the possibility of applying additional measurement hardware, e.g., microphones, around the vehicle to perform a more detailed analysis of the acoustic behavior. One class of acoustic analysis techniques is transfer path analysis (TPA), whereas airborne source quantification (ASQ) is one of its variants. The idea of ASQ in form of source-path-receiver models is known for many decades [22]. According to [8] the mathematical formulation of the concept of power-based ASQ is the following:

$$y_k^2(\omega) = \sum_{i=1}^{N} NTF_{ki}^2(\omega) \cdot Q_i^2(\omega), \tag{1}$$

where y_k is the sum of the sound signal at receiver position k from all sources, NTF_{ki} is the airborne noise transfer function between source $i = 1,2,3,\dots,N$ and receiver $k = 1,2,3,\dots,M_{pass}$ and Q_i is the acoustic load (volume acceleration) of airborne source i. The receivers consist of the microphones for simulated pass-by. The acoustic loads are calculated via Equation 2 [8]:

$$Q_i^2(\omega) = \left[H_{j,i}^2(\omega)\right]^{-1} \cdot u_j^2(\omega), \tag{2}$$

where H_{ji} is the transfer function matrix between all sources and indication microphones $j = 1,2,3,\dots,M_{ind}$ and u_j is the sound pressure at the so-called indicator microphone j. The indicator microphones are placed near the relevant acoustic sound sources of the vehicle. ASQ shows some distinct disadvantages, e.g., the representation of the substitute acoustic sources defined by Q_i consists of acoustic monopoles. In contrast to that, tires radiate sound in a highly directed pattern. Furthermore, ASQ needs time-consuming measurements because many indicator microphones have to be placed around the relevant acoustic sources of the vehicle. We address these disadvantages by HIBF. Instead of the indicator microphones used for ASQ, the estimation of the acoustic loads with HIBF is based on a permanently installed microphone array and the substitute acoustic sources are represented via spherical harmonics. With HIBF, directed sound radiation is modeled.

3.2. Mathematical Derivation and Extension of HIBF

Assume that the total pressure field p_{tot} of a vehicle recorded with the microphone array is a composition of N acoustic monopoles at prescribed positions $x_1, \dots, x_N \in \mathbb{R}^3$. Via the acoustic monopole transfer functions $t_1, \dots, t_N$, p_{tot} can be expressed as in Equation 3:

$$p_{tot}(x) = \sum_{i=1}^{N} Q^i \cdot t_i\,(x), \tag{3}$$

where Q^i denotes the acoustic volume flow. Simply rewriting Equation 3 leads to Equation 4:

$$p_{tot}(x) = \sum_{i=1}^{N} Q^i \cdot h_0^{(2)}(kr_x) \cdot Y_0^0(\theta_x, \phi_x) \cdot \frac{t_i(x)}{h_0^{(2)}(kr_x) \cdot Y_0^0(\theta_x, \phi_x)}, \tag{4}$$

where $h_0^{(2)}$ denotes the spherical Hankel functions of the second kind of degree 0 and Y_0^0 is the spherical harmonic of degree 0 and order 0. By using the identity $Q_{00}^i = Q^i$, the monopole assumption can then be generalized as presented in Equation 5:

$$p_{tot}(x) = \sum_{i=1}^{N} \sum_{l=0}^{L} \sum_{m=-l}^{l} Q_{lm}^i \cdot h_l^{(2)}(kr_x) \cdot Y_l^m(\theta_x, \phi_x) \cdot \frac{t_i(x)}{h_0^{(2)}(kr_x) \cdot Y_0^0(\theta_x, \phi_x)}. \tag{5}$$

In other words, the chosen acoustic model consists of N sources at positions $x_1, \dots, x_N \in \mathbb{R}^3$ with a total of $N \cdot (L+1)^2$ complex parameters Q_{lm}^i to model p_{tot}. By using measured values of $t_1, \dots, t_N$ at the microphone array positions $x_1^m, \dots, x_{M_{arr}}^m \in \mathbb{R}^3$, we can construct the function shown in Equation 6 that is to be minimized for a given array measurement:

$$F(Q_{00}^1, \dots, Q_{LL}^N) = \parallel C^{meas} - \; hh^+ \parallel_2^2, \tag{6}$$

where + denotes the Hermitian adjoint and C^{meas} is the measured cross-power spectral density matrix of the microphone array. The column vector h is defined as in Equation 7:

$$h(Q_{00}^1, \dots, Q_{LL}^N) = \left(p_{tot}(x_1^m), \dots, p_{tot}(x_{M_{arr}}^m)\right)^T. \tag{7}$$

A more detailed mathematical derivation of HIBF and a comparison with ASQ can be found in [12]. Although this method is able to model complicated directivity patterns, as those radiated by car tires for example, it is still susceptible to errors in the positioning of sources in the transfer function measurement and to the non-point-like nature of real-world sources in general. Motivated by the CLEAN-SC method [23], we tackle the latter and extend HIBF by working with the so-called source coherent component vector

$$\tau_i(x) = C^{meas} t_i(x) \tag{8}$$

while interpreting the t_i's as steering vectors of sort. In addition, we approach errors in positioning by shifting the transfer functions,

$$t_i^\delta(x) = \frac{h_0^{(2)}(kr_{x+\delta}) \cdot Y_0^0(\theta_{x+\delta}, \phi_{x+\delta})}{h_0^{(2)}(kr_x) \cdot Y_0^0(\theta_x, \phi_x)} t_i(x). \tag{9}$$

Having these two ingredients, we replace the t_i's in Equation 6 with t_i^δ's that maximize the quotient $\| \tau_i^\delta(x) \|_2 / \| t_i^\delta(x) \|_2$ on a small translation grid, i.e. for each model source, we shift the transfer function slightly such that it generates the largest source coherent component with respect to the measurement under consideration. Finally, we renormalize the $(L+1)^2$ dimensions of the BFGS optimizer for Q_{lm}^i using the determined maximum of $\| \tau_i^\delta(x) \|_2 / \| t_i^\delta(x) \|_2$.

3.3 Simulated Pass-by with Sound Field Extrapolation

Established methods for acoustic holography are HELS [24] or nearfield holography [25]. In the context of HIBF, we use holography for virtual generation of microphone signals for simulated pass-in our SIFAH algorithm [13-15]. SIFAH stands for Spherical Integration Farfield Acoustical Holography and allows the sound field extrapolation from the plane of the microphone array to the locations of the microphones used for simulated pass-by.

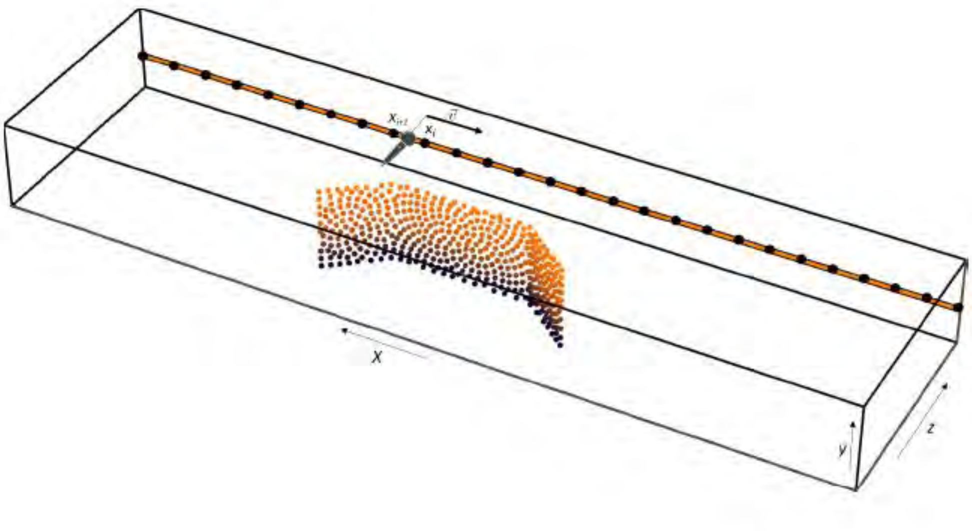

Figure 4: The sound field is measured via the array microphones and extrapolated to the target microphones x_i, located at the orange line. Along this line, a virtual microphone is passing the car according to vehicle speed at the test bench [14].

In the context of HIBF, we use SIFAH for two reasons. Firstly, we calculate the acoustic transfer functions from the vehicle components to the microphone positions for simulated pass-by with SIFAH. Secondly, we validate the results of HIBF against SIFAH. In [14] a comprehensive validation of SIFAH against a well-established system for simulated pass-by [26] can be found. For different operational conditions of four vehicles almost all deviations are smaller than 1 dB(A). Thus, in our opinion it is legit to use SIFAH as ground truth for all validations of HIBF.

4. MEASUREMENTS

HIBF requires two kinds of measurements. Firstly, the measurement of the acoustic transfer functions from the vehicle components to the array microphones via a so-called volume velocity source (VVS). Secondly, operational measurements of the vehicle under investigation.

4.1 Acoustic Transfer Function Measurement

We measure the acoustic transfer functions via the VVS while the car is placed on the dynamometer (dyno). Figure 5 shows a car placed at a dyno and the microphone array used for HIBF.

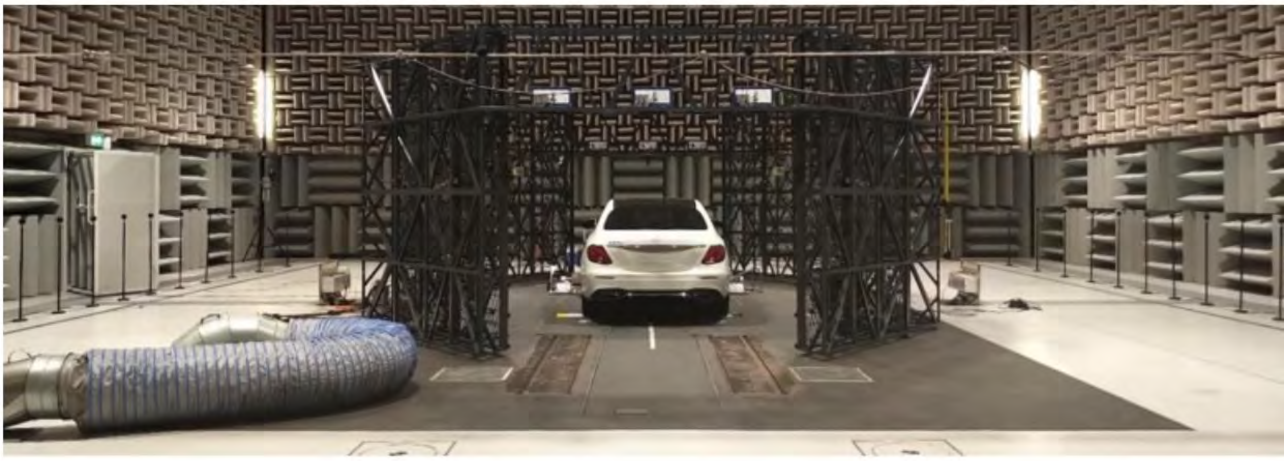

Figure 5: Car placed on the dyno surrounded by the microphone array for HIBF and the two microphone lines for simulated pass-by (at the left and right wall) [12].

The array in Figure 5 consists of 864 microphones. 16 VVS positions at the sill, tires and the exhaust system are measured. The VVS position of the exhaust is showed in Figure 6.

Figure 6: VVS (red arrow) to measure the transfer functions [12].

4.2 Operational Measurements

The acoustic volume flows of the vehicle components cannot be measured directly, i.e., the validation of HIBF is only possible by comparing the acoustic sum of the substitute acoustic sources with the over-all signals, if the measured signals consist of a real vehicle. Validations with synthetic signals can be found in [12]. Another way for a higher interpretability are special operational conditions, e.g., coasting of the vehicle, where the interaction of the dyno and the tires is the dominant sound source. According to the ECE R51.03, measurements with constant speed and under full acceleration of the car are necessary. Finally, we have measured three operational conditions: coasting, constant pass-by and fully accelerated pass-by.

5. RESULTS and DISCUSSION

For all calculations, the SC variant of HIBF, described in Section 3.2, is used. Figure 7 shows the results of a coasting of the car with a speed of 50 km/h.

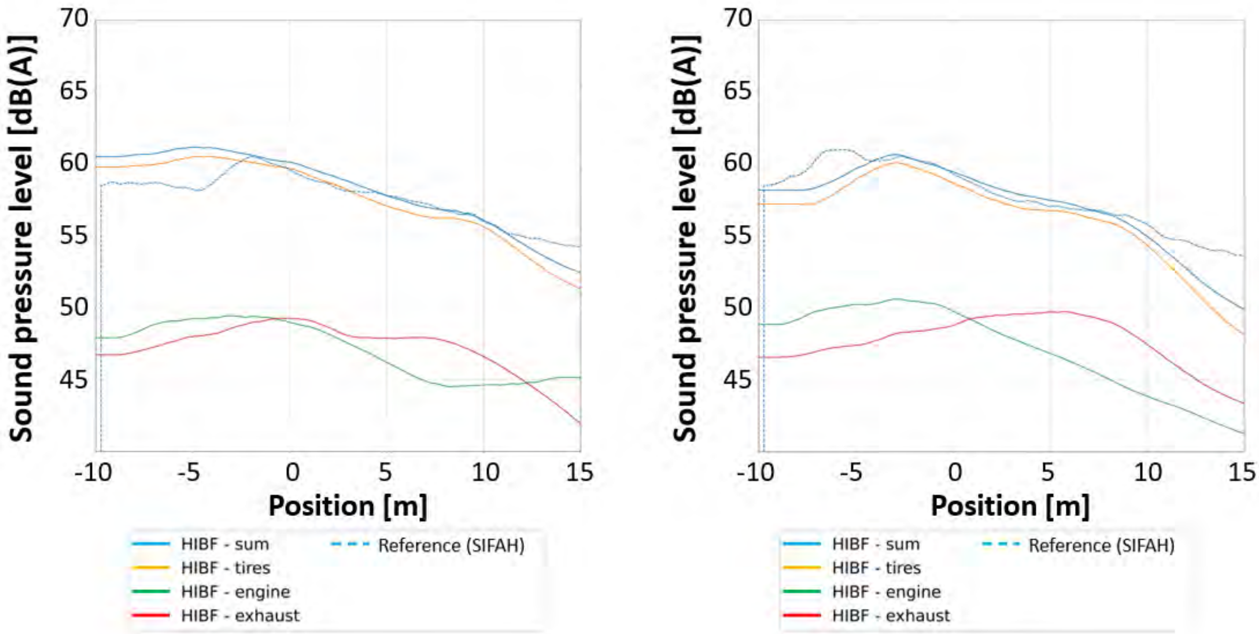

Figure 7: Results of partial sound source analysis of a coasting of a car with 50 km/h for left pass-by microphone (left) and right pass-by microphone (right). The sum of HIBF is compared to simulated pass-by calculated with SIFAH.

Figure 7 shows, that in case of coasting the tires are the most relevant sound sources. As expected, the engine and the exhaust system do not relevantly contribute to the over-all pass-by noise. Especially the maximum SPL, which is the relevant value for the ECE R51.03 is very close for HIBF and SIFAH. Figure 8 shows the results for constant pass-by in gear 4 with a speed of 50 km/h.

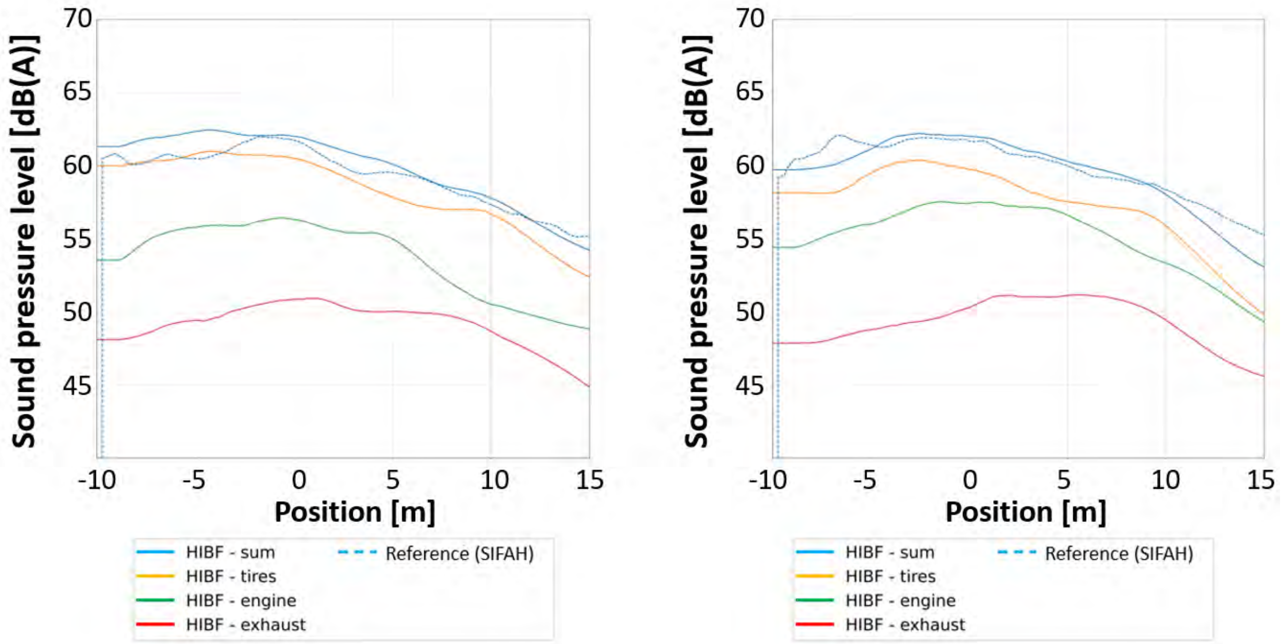

Figure 8: Results of partial sound source analysis of constant pass-by of a car with a speed of 50 km/h for left pass-by microphone (left) and right pass-by microphone (right).

Figure 8 shows, that in case of constant pass-by of a car in gear 4 with a speed of 50 km/h the tires are the most relevant sound sources. This is expected, as the engine does not show high rpm and torque at this speed. Figure 9 shows the results for a car under full acceleration in gear 4 with a speed of 50 km/h at the position 0 m.

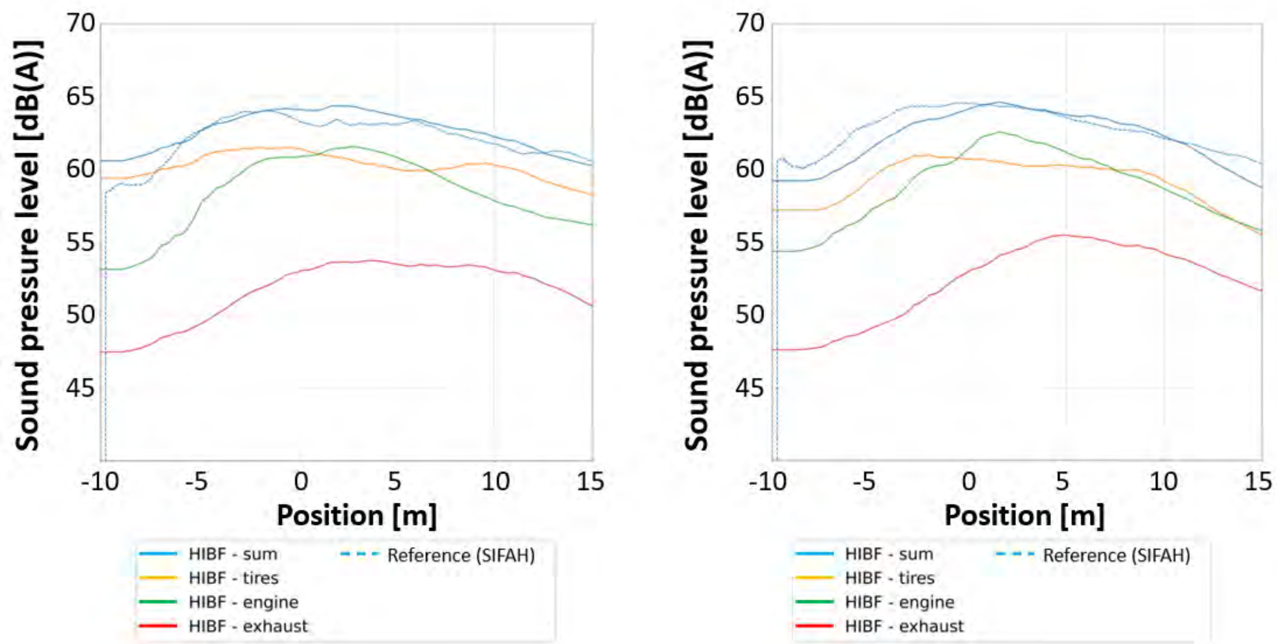

Figure 9: Results of partial sound source analysis of accelerated pass-by of a car with a speed of 50 km/h at 0 m for left pass-by microphone (left) and right pass-by microphone (right).

Figure 9 shows, that in case of fully accelerated pass-by of a car in gear 4 with a speed of 50 km/h at 0 m the tires and the engine are relevantly contributing to the over-all pass-by noise. This is expected, as the engine shows high torque and rising rpm under full acceleration. Besides the difference at the beginning of the position axis, HIBF and SIFAH do match with a sufficient precision. Only in the middle of the position axis in the left figure, there is a significant difference between

HIBF and SIFAH. Especially the maximum SPL, which is the relevant value for the ECE R51.03 is very close for HIBF and SIFAH. For all calculations, the results show a high plausibility and a sufficient match between HIBF and SIFAH.

6. S!TA PROJECT

This section consists of an overview of the comprehensive research project, in which the present work is embedded. Six main requirements (req. 1-6) for the intended digitalization of pass-by noise engineering are derived [17]:

1. Prediction of the over-all pass-by noise level of future cars
2. Analysis of the partial pass-by noise levels of different car components
3. Derivation of acoustical specifications for the car components
4. Transfer of the specifications into component-specific target values
5. Aggregation of the results in form of digital twins in a database
6. Industrialization of the algorithms in a professional software

The main goal of the project is the derivation of component specific target values in the early stages of the digital development process of future cars (req. 4). To fulfill req. 4 we combine the solutions for req. 1-3. Figure 10 shows the combination of the involved algorithms.

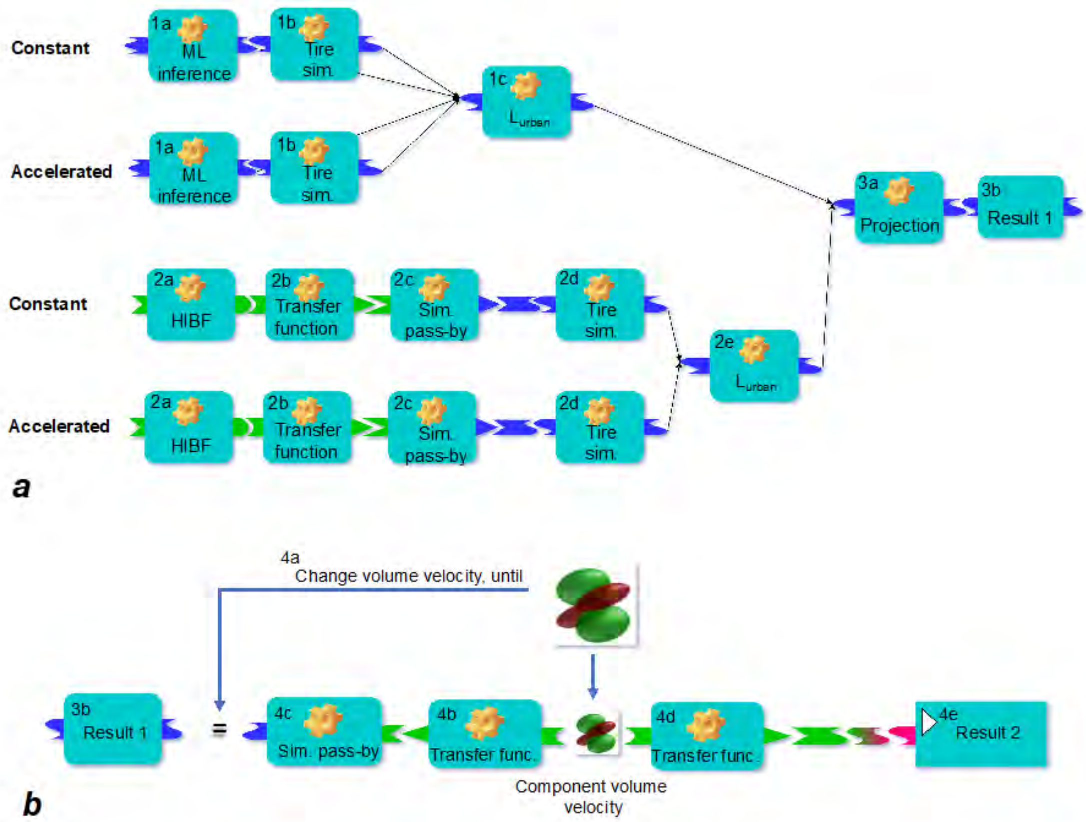

Figure 10: **a:** Derivation of acoustical component specifications (req. 3) by using ML models to predict the over-all pass-by noise of future cars and HIBF to analyze partial sound source contributions of individual car components. **b:** Transfer of the specifications into component-specific target values (req. 4) by manipulating the volume velocity of the component until the specifications are fulfilled [19].

"Result 1" (3b) in Figure 10 defines the max. allowed partial SPL for the exhaust system. The concept of S!TA assumes that the future car (represented by the digital twins in form of ML models) only differs significantly in the total SPL compared to its predecessor. The distribution of the partial sound sources of the predecessor (analyzed via HIBF) compared to the future car is assumed to show a sufficient correlation. Thus, the "Projection" (3a) in Figure 10 is legit. The validation of this hypothesis is part of the ongoing project. The maximum allowed partial SPL of the exhaust system (req. 3) is calculated by comparing the projection of the partial sound source distribution to the overall SPL of the future car with the legally allowed SPL defined in the ECE R51.03. Finally, we transform this value in the typical domain of the component's supplier. For the exhaust system, this means SPL over rpm at a static position with 1 m distance from the exhaust (target position). This calculation step is part of the HIBF implementation. By manipulation of the corresponding volume velocity, the max. allowed SPL at a virtual microphone at the target position is calculated ("Result 2" in Figure 10) [19]. For results of a prototypical implementation of the algorithmic chain (see [16]).

7. CONCLUSIONS

In this study, we presented a new algorithm for partial sound source estimation for pass-by noise in hemi-anechoic test benches called HIBF and its extensions in form of the SC variant. Rising legal requirements according to exterior noise of motor vehicles lead to the necessity of more precise partial sound source estimation for pass-by noise. We validated the results of HIBF against our SIFAH algorithm for simulated pass-by noise calculation via sound field extrapolation. We validated three different operational conditions: coasting, constant pass-by and fully accelerated pass-by. The results for all calculations are plausible and meet the expectations of pass-by noise experts. For all calculations, especially for the maximum SPL, there is a good match between HIBF and SIFAH. Currently there is ongoing work on visualization techniques for the directivity of the acoustic load estimation via HIBF. All algorithms according to the overlying research project are currently industrialized in a professional software application. In this context modern software concepts like software-as-a-service and cloud-based architectures are used.

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REFERENCES

1. UNECE. Uniform provisions concerning the approval of motor vehicles having at least four wheels with regard to their sound emissions, European Standard ECE R51.03:2018. United Nations Economic Commision for Europe (UNECE), Geneva, Switzerland, 2018.
2. ISO. Measurement of noise emitted by accelerating road vehicles - Engineering method - Part 1: M and N categories, International Standard ISO 362-1:2015, International Organization for Standardization, Geneva, Switzerland, 2015.
3. W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn. Digital twin in manufacturing: A categorical literature review and classification. In *INCOM, 16th IFAC Symposium on Information Control Problems in Manufacturing*, pages 1016-1022. Bergamo, Italy, June 2018.
4. R. Rasor, D. Göllner, R. Bernijazov, L. Kaiser, and R. Dumitrescu. Towards collaborative life cycle specification of digital twins in manufacturing value chains. In *Proceedings of 28th CIRP Conference on Life Cycle Engineering*, pages 229-243. Jaipur, India, March 2021.
5. G. Rajagopal, G. Santosh, M. Abhilash, GS. Krishnamurthy, and R. Giles. Pass-by noise prediction of a vehicle. In *25th Small Engine technology Conference & Exposition*. Himeji, Japan, January 2020.
6. Z. Xue, H. Kuehnelt, and W. De Roeck. Pass-by noise modelling applying machine learning. In *e-Forum Acusticum 2020*, pages 2019-2026. Lyon, France, December 2020.
7. J. Fry and P. Jennings. Using multi-layer perceptrons to predict vehicle pass-by noise. *Neural Comput. Appl*., 11(3-4): 161-167, 2003.
8. K. Janssens, F. Bianciardi, L. Britte, P. Van de Ponseele, and H. Van der Auwrear. Pass-by noise engineering: a review of different transfer path analysis techniques. In *Proceedings of*

ISMA, International Conference on Noise and Vibration Engineering, pages 3923-3940. Leuven, Belgium, September 2014.
9. F. Bock, M. Pohl, D. Arsić, and S. Becker. A statistical analysis of the influence of a vehicles exterior appearance on exterior noise. In *Proceedings of Aachen Acoustics Colloquium*. Aachen, Germany, 2016.
10. D. Arsić and M. Pohl. A framework for the sensitivity analysis of transfer paths combining contribution analysis and response modification analysis. *In* Automotive Acoustics Conference, pages 341-351. Zurich, Switzerland, July 2019.
11. J. Putner, M. Lohrmann, and H. Fastl. Contribution analysis of vehicle exterior noise with operational transfer path analysis. In *Proceedings of Meetings on Acoustics,* pages 1-9. Montreal, Canada, June 2013.
12. C. Puhle, V. Becker, A. Jahnke, and F. Knappe. Estimation of partial sound sources with non-spherical directivity for analysis of pass-by noise in hemi-anechoic indoor test benches. In *Proceedings of 9th Berlin Beamforming Conference.* Berlin, Germany, June 2022.
13. C. Puhle. Spherical integration in acoustical holography. In *48th International Congress and Exposition on Noise Control Engineering*. Madrid, Spain, 2019.
14. V. Becker, C. Puhle, A. Jahnke, and D. Döbler. Sound field extrapolation with microphone arrays. In *8th Berlin Beamforming Conference*, Berlin, Germany, June 2020.
15. C. Puhle. Spherical acoustical holography using planar microphone arrays. In *Proceedings of 8th Berlin Beamforming Conference.* 2020.
16. F. Knappe, C. Puhle, and J. Rosskopf. Der Digitale Akustische Zwilling - Ableitung von Komponenten-Grenzwerten für die Außengeräusch-Homologation in der digitalen Phase des Fahrzeugentwicklungsprozesses. In *DAGA 48. Jahrestagung Für Akustik.* Stuttgart, Germany, March 2022.
17. M. Fazal-Baqaie, F. Knappe, and R. Sperber. Wie laut ist der Digitale Zwilling? – Agile Digitalisierung von Produktentstehungsprozessen am Beispiel der Außengeräusch-Homologation als Kombination von akustischen Methoden und KI. In *Proceedings of 16. Symposium für Vorausschau und Technologieplanung*, pages 105-124. Berlin, Germany, May 2022.
18. F. Knappe and J. Rosskopf. Pass-by noise prediction of motor vehicles using gradient boosted models and physical calculations of longitudinal driving dynamics. *Noise Control Engineering Journal*, 70(3): 246-263, 2022.
19. F. Knappe, J. Rosskopf, and M. Vorländer. Pass-by noise prediction with gradient boosted models as a part of the acoustical digitalization of automotive product development processes. In *12th Aachen Acoustics Colloquium*, Aachen, Germany, November 2021.
20. ISO. Acoustics-Measurement of noise emitted by accelerating road vehicles - Engineering method. International Standard ISO 362:1998. International Organization for Standardization, Geneva, Switzerland, 1998.
21. Douglas Moore. Development of ECE R51.03 noise emission regulation. *SAE International*, 10(3), 2017.
22. J.W. Verheij. Inverse and reciprocity methods for machinery noise source characterization and sound path quantification, part 1: sources. *International Journal of Acoustics and Vibration.* 2(1): 11-20, 1997.
23. P. Sijtsma. CLEAN based on spatial source coherence. *International Journal of Aeroacoustics*. 6(4): 357-374, 2007.
24. T. Semenova and S. Wu. The helmholtz equation least-squares method and rayleigh hypothesis in near-field acoustical holography. *Journal of The Acoustical Society of America.* 115:1632–1640, 2004.
25. S. I. Hayek. *Nearfield Acoustical Holography*. Springer, New York, USA, 2008.
26. Müller BBM: PAK PASS-BY 3.X https://www.mbbm-vas.com/produkte/datenanalyse/pak-pass-by. Last accessed 2023-03-30.