WRITTEN BY

Katja Fröhlingsdorf, M. Sc. is Research Associate at the Chair of Thermodynamics of Mobile Energy Conversion Systems (TME) at RWTH Aachen University (Germany).

Florian Doleschal, M. Sc. is Research Associate at the Department of Experimental Audiology (EXA) of the Otto von Guericke University (OVGU) Magdeburg (Germany).

Prof. Dr.-Ing. Stefan Pischinger is Head of the Chair of Thermodynamics of Mobile Energy Conversion Systems (TME) at RWTH Aachen University (Germany).

Prof. Dr. Jesko L. Verhey is Head of the Department of Experimental Audiology (EXA) of the Otto von Guericke University (OVGU) Magdeburg (Germany).

Efficient Analysis of the Interior Noise of Electric Vehicles

Since the high-frequency noise components of the electric drive train are often perceived as unpleasant in the vehicle interior, a method for efficient analysis is essential. In the project “eMSI – Interference Noise in the Vehicle Compartment with Electrified Drives” (FVV project no. 1369), a method for the automated separation of electric vehicle interior noise and allocation of the noise components to the emitting parts was developed at RWTH Aachen University. And researchers at Otto von Guericke University Magdeburg created a model for assessing psychoacoustic pleasantness.

© TME

1 NOISE MEASUREMENTS

With increasing electrification of the powertrain and the elimination of the combustion engine as a masking component, new challenges in vehicle acoustics arise. High-frequency tonal noise components of the electric powertrain become audible. These often have a negative impact on the perceived pleasantness of the overall noise in the interior. In addition, tire and wind noise are prominent. Acoustic optimization is a complex and time-consuming process, based on precise identification of the originators of the noise components. Therefore, an efficient way of analyzing the vehicle interior noise is indispensable already in the development process in order to save time and costs for necessary measurements and evaluations. The measurements for automated noise separation carried out at the Chair of Thermodynamics of Mobile Energy Conversion Systems (TME) at RWTH Aachen University were performed using microphones and accelerometers. They were run in eleven different electric and hybrid vehicles with different machine types during various acceleration and coasting maneuvers. The assessment of pleasantness was performed at the Department of Experimental Audiology (EXA) of OVGU Magdeburg.

2 AUTOMATED NOISE SEPARATION AND ALLOCATION

The automated separation of interior noise is performed component-wise and is based on noise detection using image processing. The tonal components of the electric machine arise primarily from the electromagnetic forces in the air gap of the machine and those of the gear from the gear meshing frequencies. **FIGURE 1** shows the detected noise of a microphone measurement at the left driver's ear position during an acceleration maneuver as a conversion of an order spectrogram into an intensity and binary image. The orders are speed-dependent and thus can be seen as horizontal lines in the order spectrogram, **FIGURE 1** (left). By local normalization of the order spectrogram into an intensity image, **FIGURE 1** (center), and binarization by means of a fixed threshold, a binary image is derived, **FIGURE 1** (right). The detection of the horizontal lines is performed by means of the Hough transformation: The lines are transformed into points in the Hough space, so that the complexity is reduced to the determination of the point maxima. The clearer a line is, the clearer is the maximum in the Hough space [1]. In the binary image, it can be seen that all orders visible in the spectrogram can be reliably detected using the Hough transform. The average detection accuracy is 94 %. The automated assignment of the detected orders to the emitting parts of the electric machine and the gear is performed by means of a decision tree with preceding parameter selection due to Sequential Feature Selection. The optimized selection of the descriptive statistical parameters results in a final classification accuracy of 86 %. For vehicles with asynchronous machines, slip must also be considered. In an order spectrogram based on the speed before slip, the tonal components do not run horizontally but with a concave curvature depending on the slip, as can be seen in **FIGURE 2** (left). By means of a developed iterative method, the slip

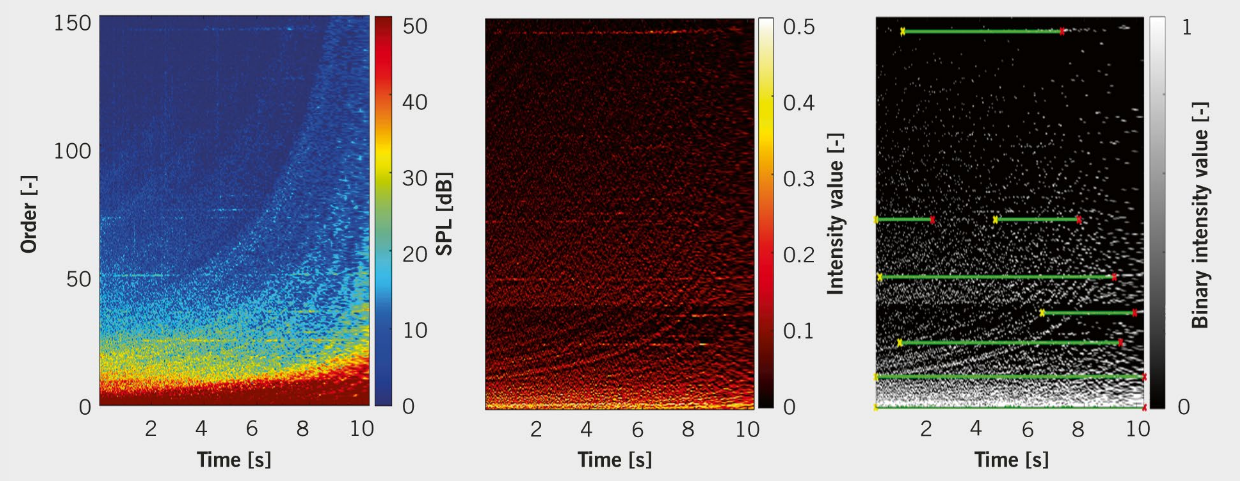

FIGURE 1 Order spectrogram with Sound Pressure Level (SPL) scale (left), intensity image (center) and binary image (right) (© TME)

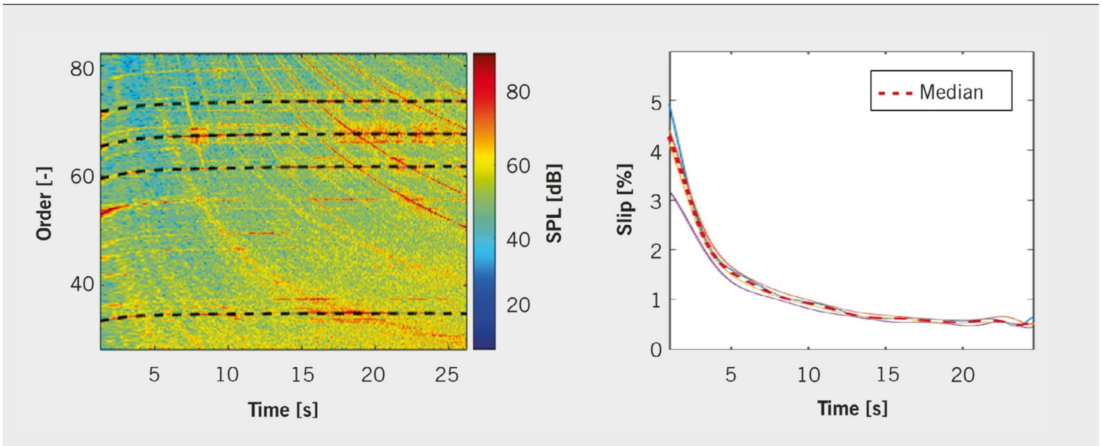

FIGURE 2 Order spectrogram for an asynchronous motor (left) slip curve derived from it (right) (© TME)

can be determined based on a noise measurement and tonal orders found therein. **FIGURE 2** (right) shows the slip curve. After correction of the order spectrogram by means of the slip, the previously described process for automated separation and assignment of the electric machine and gear orders is applicable, resulting in a detection accuracy of 93 % and a classification accuracy of 88 %. The automated detection of the tonal components of the inverter is also performed with the Hough transformation. Due to the clear geometric correlations of an inverter noise in the spectrogram, the detected components can be separated without an additional allocation stage. In the first step, due to the low signal-to-noise ratio, the intensity image is processed using

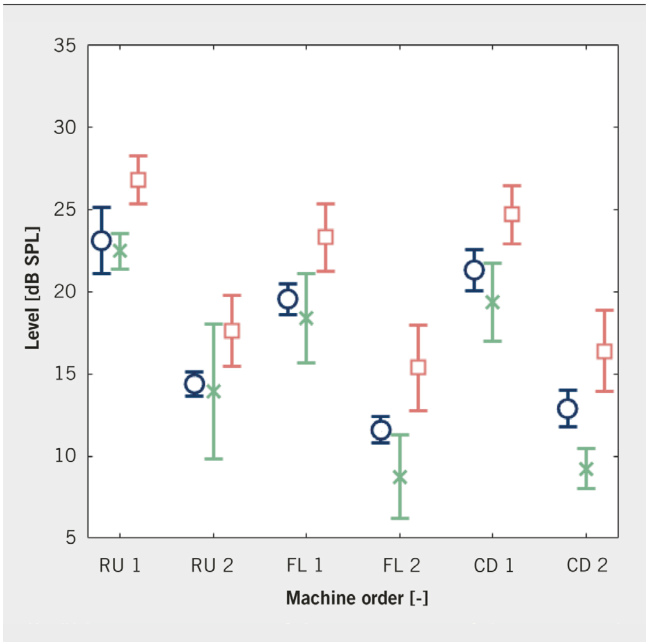

FIGURE 3 Mean values and standard deviations of the listening threshold of the perceptual model (blue), the critical masking ratio (red) and the experiment (green) [7] for two synthetic machine orders in each of the driving states run-up (RU), full-load run-up (FL) and coast-down (CD) (© EXA)

the Kirsch-Compass filter, and then binarized using Otsu's method [2] to identify the switching frequency and its multiples in the spectrogram. Possible non-detected multiples are determined with an arithmetic methodology. Based on the switching frequencies and their multiples, the inverter harmonics can be detected, which span around the respective horizontal line depending on the electric machines speed. The detection accuracy for the switching frequency and its multiples is 94 %, for the harmonics 87 % [3]. In addition, the tire cavity is detected automatically. Since the cavity mode is dependent on the wheel speed, it can also be detected with the Hough transformation based on a binarized spectrogram, resulting in a detection accuracy of 92 %.

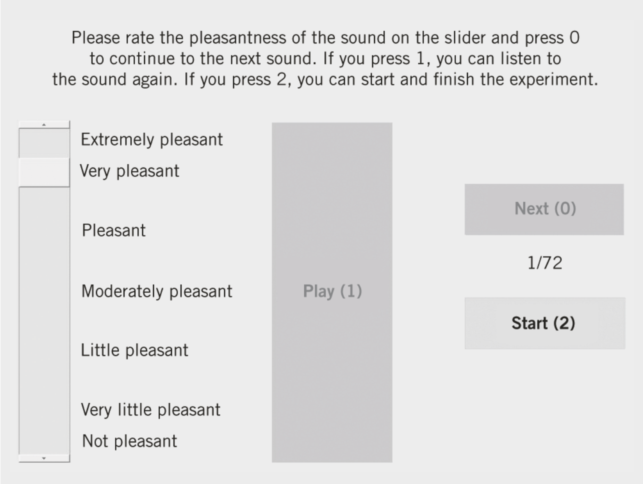
Please rate the pleasantness of the sound on the slider and press 0 to continue to the next sound. If you press 1, you can listen to the sound again. If you press 2, you can start and finish the experiment.

FIGURE 4 User interface for the experimental recording of pleasantness (© EXA)

All methods for detecting the tonal components of the noise emitting parts do not require any additional component-specific parameters, such as the number of pole pairs of the electric machine, the number of teeth of the gear stages or the tire dimensions. All detected tonal noise components are separated using the Vold-Kalman filter. The separation of the remaining noise into the tire and wind components can be predicted based on a database created with an Operational Transfer Path Analysis. In order to achieve independence from a measured machine speed for the separation methods, a machine speed calculation from a noise signal was developed within the research project [4].

3 PREDICTION OF THE AUDIBILITY OF INDIVIDUAL NOISE COMPONENTS

Individual noise components only influence the pleasantness of the overall noise if they are audible, that means, if the respective level is above the listening threshold. Audibility is usually determined with real test subjects. The high time expenditure for such measurements can be avoided by using models. One possibility is the use of a modified version of the perception model according to Dau et al., 1996 [5], which considers essential aspects of human hearing: Thresholds are predicted by simulating the procedure used in the experiment, where the model acts as a virtual test subject. In this way, monitoring thresholds for all tonal and noise components can be determined with a high degree of accuracy. A disadvantage is the high computational effort, especially when determining the monitoring threshold of broadband noise components. For a first rough estimation, the Critical Masking Ratio [6], which can only be used for tonal components, is suitable, where the component level and the noise background of the surrounding frequency group are considered. The data are compared to those of the experiment and the perceptual model in **FIGURE 3**.

4 PREDICTION OF PLEASANTNESS

Due to the large amount of time involved, one goal of the project was to be able to reduce the extent by modeling the pleasantness. The basis for the adaptation of the model is formed by listening tests for the acquisition of the pleasantness of binaural noise recordings by means of a slider where the positions of the slider were converted into a numerical value from 0 to 100. **FIGURE 4** depicts the user interface. Spectro-temporal manipulations increased the amount of data available for model fitting by varying the level of individual components based on automated noise separation and adding artificial components as subharmonics [8]. In addition, the effects of individual components can be analyzed. A Long Short-Term Memory [9] was chosen as the model structure, as this allows time-dependent input parameters such as loudness, tonality, and sharpness to be considered in the prediction of pleasantness. The data was divided into a training set, a test set and a validation set, with the prediction deviation of the test data used for evaluation after the training process was completed, and the deviations of the validation data used as a goodness-of-fit criterion. With a mean square error of 6.7 for the training set and 5.2 for the test set, the model achieves high prediction quality, **FIGURE 5**.

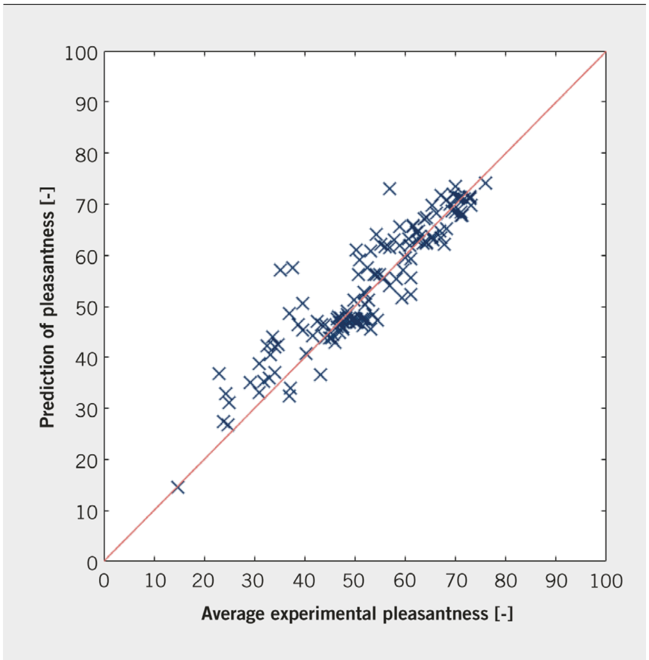

FIGURE 5 Prediction of pleasantness versus experimental means (© EXA)

5 MEASURES TO IMPROVE THE PLEASANTNESS

In experiments with synthetic and real sounds, it has been shown that high-frequency tonal components reduce the pleasantness: In the case of high annoyance, artificial subharmonics can be added to the noise, with the relative frequency of the components having a fixed ratio to the frequency of the annoying component. This can lower the perceived pitch of the component, leading to an increase in pleasantness [10].

6 SUMMARY AND OUTLOOK

With the automated separation of noise components and allocation of these to the emitting parts as well as the model for the evaluation of psychoacoustic pleasantness, a method has been created to efficiently analyze the interior noise of electric vehicles. Due to the high detection and allocation rates for the variety of measurement vehicles used, the method proves to be robust and contributes to acoustic optimization in the development of future electric vehicles.

REFERENCES

[1] Hough, P.: Method and Means for Recognizing Complex Patterns. Patent: US3069654A, United States Patent Office, 1962

[2] Gonzales, R.; Woods, R.: Digital Image Processing. 4th ed., Harlow: Pearson Education Limited, 2018

[3] Fröhlingsdorf, K.; Pischinger, S.; Günther, M.; Steffens, C.; Heuer, S.: Automated inverter noise separation in the interior of electric vehicles using adapted Kirsch-Compass kernel and Hough-Transformation. In: Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering (2022), article 2022-02-112022

[4] Fröhlingsdorf, K.; Pischinger, S.: Motordrehzahlbestimmung aus dem Innengeräusch von Elektrofahrzeugen. Annual Conference on Acoustics (The German Acoustical Society, DEGA), Stuttgart, 2022

[5] Dau, T.; Püschel, D.; Kohlrausch, A.: A quantitative model of the "effective" signal processing in the auditory system. I. Model structure. In: The Journal of the Acoustical Society of America 99 (1996), no. 6, pp. 3615-3622

[6] Kinsler, L.; Frey, A.: Fundamentals of Acoustics. Hoboken: John Wiley & Sons, 1962

[7] Doleschal, F.; Rottengruber, H.; Verhey, J. L.: Influence parameters on the perceived magnitude of tonal content of electric vehicle interior sounds. In: Applied Acoustics 181 (2021), article 108155

[8] Gwak, D. Y.; Kiseop, Y.; Seong, Y.; Lee, S.: Application of subharmonics for active sound design of electric vehicles. In: The Journal of the Acoustical Society of America 136 (2014), no. EL391, S. EL391-EL397

[9] Hochreiter, S.; Schmidhuber, J.: Long Short-Term Memory. In: Neural Computation 9 (1997), no. 8, pp. 1735-1780

[10] Doleschal, F.; Verhey, J. L.: Pleasantness and magnitude of tonal content of electric vehicle interior sounds containing subharmonics. In: Applied Acoustics 185 (2022), article 108442

THANKS

The research project (FVV project no. 1369) was carried out by the Chair of Thermodynamics of Mobile Energy Conversion Systems under the direction of Prof. Dr.-Ing. (USA) Stefan Pischinger in cooperation with the Department of Experimental Audiology under the direction of Prof. Dr. Jesko L. Verhey. The project was accompanied by a group of experts led by Dr.-Ing. Stefan Heuer (MAN Truck & Bus SE). The authors would like to thank both the Research Association for Combustion Engines (FVV) and all participants in the project for their support.

GREEN IGNITION WITH PRECISION
SEM

PANEL DISCUSSION
Moderation:
DR. ALEXANDER HEINTZEL, ATZ | MTZ Group
PROF. DR. CHRISTIAN BEIDL, Institute for Internal Combustion Engines and Powertrain Systems (VKM), TU Darmstadt
ATZ live

FEV