EMAS
Engineering Modelling, Analysis & Simulation
THE NAFEMS JOURNAL

NAFEMS
Vol. 1, Issue 1, 2024

Hybrid NVH modeling approach: High quality of NVH results enables psychoacoustic analysis of numerical computations

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Abstract

In the field of acoustics, the human perception of sound is often more important than the overall sound pressure level. The human perception is highly individual and is linked to how the user's expectations of the sound and the actual perceived sound match. Thus, generalization is difficult. However, psychoacoustic parameters that are developed and validated by means of jury tests are an established tool in the field of experimental measurements to quantify the human perception for specific acoustic phenomena like tonality, roughness, and loudness. Since the precision of numerical simulations results is continuously improving, these psychoacoustics parameters can be applied as well to the results of numerical simulation.

In this Paper, the advantages of this approach are shown using the example of a numerical model of an e-bike. E-bikes have become increasingly popular in recent years, used for commuting, transporting loads or, in the case of e-mountain bikes, just for fun. As already mentioned, the acceptance of a sound is strongly linked to the expectations of the user. Since the electric drive unit of an e-bike is added to an acoustically known system, the user expects the sound to be quiet rather than dominant.

Different e-bike analyses are presented using numerical and experimental methods. The numerical model used in this project predicts the sound generated by the electrical drive unit and radiated by the frame. For the calculation of airborne noise the distribution of velocities on the surface of the frame is used as an input, which is taken from a previous simulation of structure-borne noise. The model to simulate the structure-borne noise consists of a detailed representation of the carbon frame and simplified representations of different components such as battery, fork etc. With the help of the numerical model, different combinations of frame and electrical drive can be analyzed and compared by psychoacoustic parameters. The validity of the approach is shown by means of data from experimental measurements.

Keywords

e-bike, NVH, FEA, composites, vibration, acoustics

1 Introduction

In order to comprehensively validate numerical models and make predictions of numerical simulations more reliable, it is mandatory to analyze the data from test and simulation using the same methods and within the same tools.

For the analysis of acoustic measurements, psychoacoustic parameters are a well-known and important method. Without psychoacoustic parameters the analysis focuses more on the sound source, assessing amplitudes and energies. However, when focusing on the human perception of sound, more characteristics than those mentioned above are important, such as the temporal structure of the signal and the position and distribution of the frequencies that are mainly involved. Psychoacoustic parameters

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https://doi.org/10.59972/pvt6hrtg

take these characteristics into account and incorporate the physical specifications of human hearing. The annoyance of many natural and technical sounds is influenced more by these properties than by the overall level. Thus, with the help of psychoacoustic parameters it is possible to evaluate how a sound is perceived by the human. When using a specific product, e.g., a car, an electric toothbrush or a vacuum cleaner, the emitted sound and its perception are very important to convey an impression of the product's properties such as product quality. Human perception of sound does – consciously or unconsciously – significantly influence purchasing decisions and customer satisfaction. It would be of great value if this human perception could be predicted at an early stage of the development process using numerical computations.

In order to make the analysis of numerical results using psychoacoustic parameters possible and meaningful, a high level of accuracy is mandatory. Fortunately, the accuracy that can be achieved through numerical computations is continuously increasing. There are several reasons for this:

- Hardware performance and availability increases, allowing for more detailed models.
- More sophisticated methods are developed to model specific physical phenomena.
- Possibilities for coupling sub-models from test and simulation are developed (hybrid models), leading to more flexibility in selecting the optimum method/model for the specific task or sub-task.

Hybrid methods are a very important step towards a high accuracy of results, as they allow the user to choose the best method based on the availability of data, methods, computing power and physical prototypes [1].

An e-bike is chosen as an example to demonstrate the benefit of applying psychoacoustic parameters to the results of a hybrid model in this work. The perception of sounds is strongly connected to the user's expectation of how the product in the specific use case should sound like. Since the drive unit of an e-bike is added to an acoustically known system - the bicycle- it is expected to be quiet rather than dominant. However, electric drives tend to produce tonal sounds that can be perceived as dominant. One of the leading bicycle manufacturers in U.S. even calls the tonality "a key new metric for what riders experience on an e-bike" [2]. Hence an acoustic assessment of the e-bike based solely on sound pressure level is not sufficient.

The project discussed in this paper is divided into several steps (see Figure 1). In a **first step**, a measurement campaign is carried out with an e-bike of series production. With the method of *in-situ* blocked forces [3] the drive unit is defined as a source of vibration. In the **second step**, a numerical model of an e-bike prototype is built to simulate the structural dynamics of the bicycle frame. The experimentally derived *in-situ* blocked forces from step one are used to excite the model. To put it another way, you could say: The e-drive unit from series production is installed virtually into the prototype bicycle frame. As the output of the second step, the velocities on the surface of the frame are calculated. In the **third step**, a numerical model for calculating the sound radiation is set up, which takes the surface velocities calculated in the second step as input. In the **fourth step**, the predicted sound of the e-bike prototype is validated with a measurement campaign and further analyses of the predicted sound are carried out using psychoacoustic parameters.

This paper covers the steps three and four. For more details on the steps one and two, please read the previous paper [4].

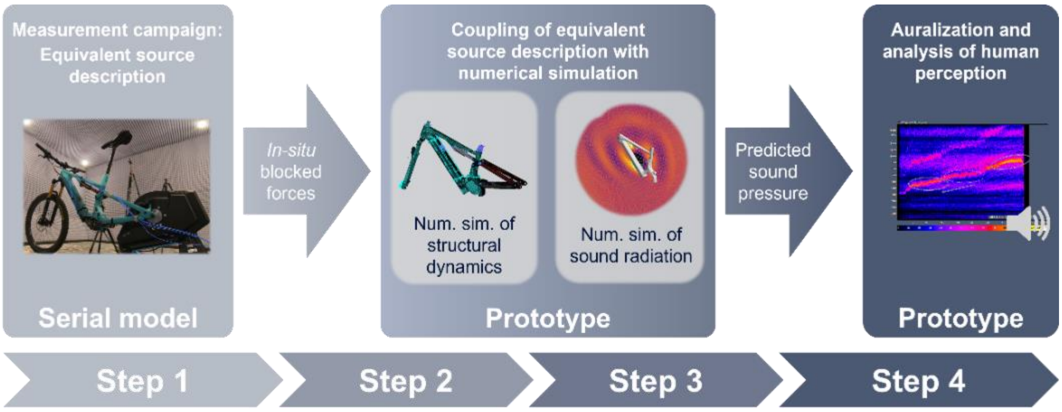

Figure 1. Flowchart of the entire process, the focus of this paper is on Step 3 and 4.

2 Perception of Sound and Psychoacoustic Parameters

The importance of psychoacoustic parameters for the evaluation of the human perception of sounds has been discussed in the previous chapter.

Figure 2 shows an exemplary flowchart of the development of a psychoacoustic parameter. Based on the knowledge of how the human perception of sounds works, signal processing algorithms are developed which assess the physical properties of the signal. The knowledge about the human perception of sounds is taken from the physiology of human hearing, the neural processing in the human brain, and from listening tests which are designed to investigate a specific step in the human processing of sounds. The derived psychoacoustic parameter is again validated by listening tests, which now have a more holistic approach. In order to make sure that psychoacoustic analyses are comparable, standardization is very important.

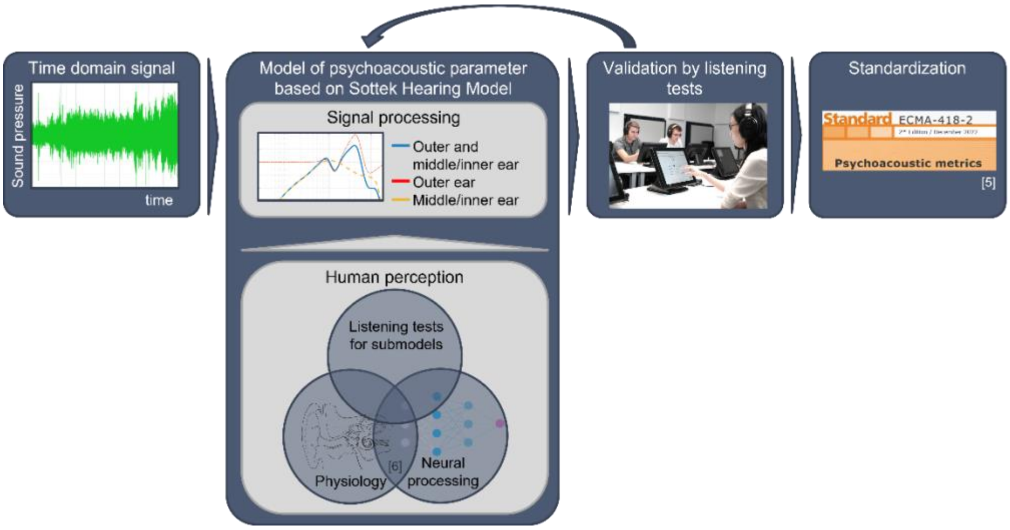

Figure 2. Development of psychoacoustic parameters.

All psychoacoustic parameters used in this paper are taken from the ECMA-418-2 standard [5], which is based on the Sottek Hearing Model [7] for the calculation of loudness [8], tonality [9] and roughness [10]. This model is based on the physiology and nonlinearity of the human hearing and allows special analysis functions in the frequency domain, where time and frequency resolution correspond to those of human hearing. Another important property of the psychoacoustic parameters standardized in the ECMA standard is, that their units scale linearly with the human perception.

2.1 Loudness

Speaking of perceived loudness one might think of the weighted sound power level, which is a very rough simplification of the frequency dependency of the human perception of loudness. Tones of different frequencies are perceived to have different loudnesses even though they have the same sound pressure level. The so-called A-weighting is a filter that takes this frequency dependency roughly into account. Other dependencies of loudness perception are neglected when using the weighted sound pressure level. Psychoacoustic loudness goes much more into detail of the human hearing than the previously-mentioned weighted sound pressure level. Properties of the human hearing based on biology and physics are considered. Some of the main influences on the perceived loudness besides the previously mentioned frequency dependency are listed below.

- The spectral distribution: broadband noises have a higher loudness than narrow band noises of the same level.
- A change in level does not 1:1 translate to a change of loudness.
- Simultaneous masking: though the level changes, the loudness might stay constant because of effects in the frequency domain.
- Time-dependent masking: the structure of the sound in the time domain has an influence on the loudness.
- Duration of the sound: the perceived loudness depends on the duration of the sound. After approximately 1 second the final loudness is reached.

The unit of psychoacoustic loudness according to ECMA-418-2 standard [5] is named sone$_{HMS}$ (sone according to the **H**earing **M**odel of **S**ottek).

2.2 Tonality

Tonality describes the prominence of a tonal component in a natural or a technical sound. Tonal components are perceived very prominently by a human listener and thus significantly influence the individual perception and evaluation of a sound event. Tonal components considerably increase the perceived annoyance of a sound if they are perceived as unwanted. Tonality is very important when analyzing electrical drives because these tend to produce tonal noises. Generally speaking, tonal sounds are often produced by periodicity, for example by a rotating device or by narrow-band excitation such as air flow.

For the analysis of tonality, tonal and non-tonal components are separated and their ratio is evaluated. Additionally, by using the Sottek Hearing Model the hearing threshold as well as masking depending on loudness level and frequency range are considered.

The unit of psychoacoustic tonality standardized in ECMA-418-2 [5] is tu$_{HMS}$. According to ECMA-418-2 a tonality higher than 0.4 tu$_{HMS}$ is perceived as prominent.

2.3 Roughness

Roughness describes the perception of temporal variation of sounds. This includes the variation of frequency as well as the variation of amplitude.

Typically, modulation rates from 20 to 300 Hz contribute to the perceived roughness, while modulation rates below 20 Hz contribute to the so-called fluctuation strength.

Roughness is an important factor for the perceptual evaluation of sounds as well as for sound design. Rough sounds attract attention and tend to be perceived as aggressive and annoying. In context of sound design for sporty cars roughness can be a desirable effect, because a rough sound is associated with a sporty vehicle, illustrating once again that the human is not only a sonic receiver but also an active signal processor with inseparable data/metadata (context) linkages.

In order to evaluate the roughness, several properties of the signal, such as the spectral distribution, modulation rate and modulation depth as well as the sound pressure level are considered.

The unit for roughness standardized in ECMA-418-2 [5] is asper. According to ECMA-418-2 a roughness higher than 0.2 asper is perceived as prominent.

3 Application Example

As application examples two electric-assist mountain bikes are chosen, one model of series production and one prototype. E-bikes become more and more popular and are used often for commuting, transporting loads or in case of electrical-assist mountain bikes, just for fun. Besides the components which are similar to a conventional mountain bike like a frame, fork, rear suspension, wheelset and drivetrain, electrical-assist mountain bikes have an electric drive unit and a battery to support the user while pedaling. While the sound of a conventional mountain bike is dominated by the rolling noise of the tires and some drivetrain related noise, the electrical drive unit adds a significant noise component to the overall user experience of an e-bike. Since acoustics are always influenced by the whole system it is difficult to evaluate the acoustics of the drive unit on its own. Mounting stiffnesses, for example, have an influence on the structural dynamics of the drive unit itself. Furthermore, in the case of the chosen example the sound is not radiated as airborne sound directly by the drive unit, but the excitation of the drive unit induces structure borne noise into the frame which is then radiated by the frame. Therefore, the acoustic perception of the user of the e-bike cannot be predicted taking only the drive unit or the frame into consideration. One must keep the whole system in mind, which is difficult, because as in many other industries, the components of a bicycle often come from different manufacturers. Thus, development knowledge is spread over different companies and compliance issues may prevent collecting and combining all this knowledge to enable a reliable prediction of the acoustic properties. The hybrid modeling approach discussed in this paper helps to cope with these challenges as it increases the flexibility to pick the appropriate method for each submodel, depending on the availability of prototypes, design parameters, calculation capacities and calculation methods for specific phenomena.

4 Test Rig Setup

To provide measurement data for the validation of the hybrid modeling approach, a measurement campaign was conducted on a test rig for e-bikes in an anechoic room. Figure 3 shows the test rig setup.

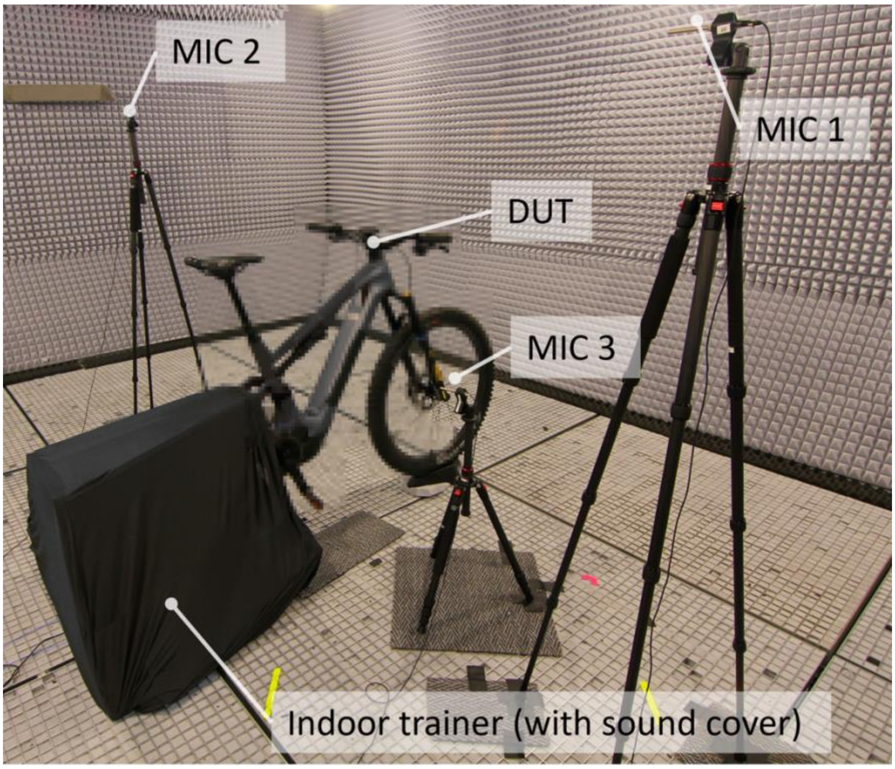

Figure 3. Test rig setup with microphone positions.

Different riding scenarios were analyzed during the measurement campaign. The riding scenarios were characterized by the support level of the drive unit, the cadence, and the consumed power of the indoor trainer. In addition to the scenarios with a constant cadence, run ups were measured with different support levels. Throughout the measurement campaign there was an uncertainty induced by the human test rider involved. The uncertainty was minimized by the fact that every measurement necessary for the project was performed by the same test rider. The indoor trainer was a rather quiet model which additionally was insulated by a sound cover. The sound pressure was measured at three positions (MIC 1, MIC 2, and MIC 3 in Figure 3). Microphones 1 and 2 were placed at a horizontal distance of 1.2 m from the device under test and at 1.6 m height. The position was chosen to be similar to the position of the heads of possible companions in a group ride. The microphone 3 was placed close (at 0.54 m distance) to the lower tube of the frame, which is known to have a significant contribution to the sound radiation.

5 Hybrid modeling approach

Figure 4 shows that two different numerical models were built to predict the structural dynamics and the sound radiation of the e-bike. Both numerical models combine to a set of vibroacoustic transfer functions that is needed to predict the audible sound at a specific location based on the excitation by the experimental source description.

As shown in figure 4 the interface between the two numerical models is given by the velocity on the surface of the frame. The velocity is calculated for every node on the surface of the frame by the structure model and then passed to the radiation model. This is a valid simplification because the feedback of oscillating air molecules onto the vibrating structure can be neglected in this case.

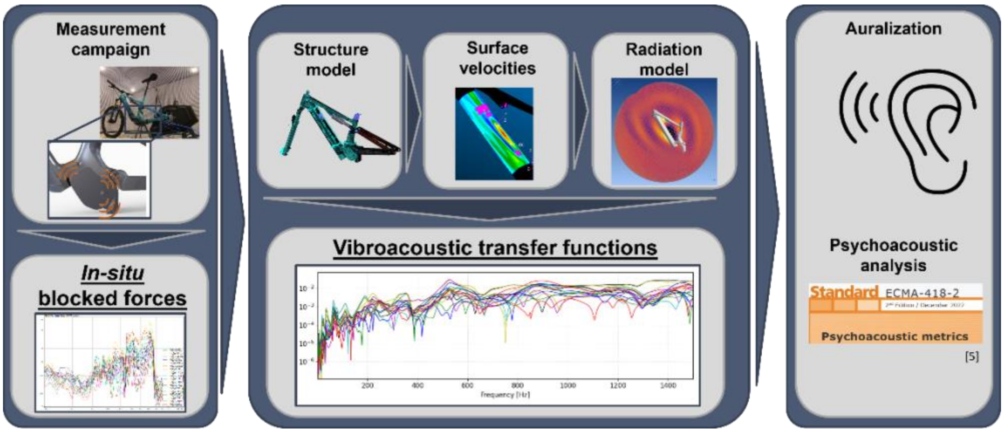

Figure 4. Hybrid modeling approach.

The combination of the vibroacoustic transfer function derived from numerical models with the in-situ blocked forces derived from measurements is called hybrid modeling approach. Of course, it could be the other way around as well: for example, the vibroacoustic transfer function could be derived from measurements and the excitation pattern could be calculated. The main advantage of hybrid modeling is to be able to pick the best-suited method for the given circumstances. If a method is lacking to numerically describe a specific physical phenomenon, or the knowledge of design parameters of a specific component cannot be provided, then probably test-based methods must be chosen for that component. On the other hand, when there is no functional prototype available, a numerical model of the respective component might be the only choice. Another advantage of the hybrid model consisting of source description and vibroacoustic transfer functions is, that in a development process spread over different companies both descriptions could be shared between business partners allowing a full assessment of the acoustic properties without sharing the design details of the respective component which might be confidential.

In the following paragraph a quick overview on the contents and properties of the structure model and the radiation model will be given.

5.1 Structure Model

For the simulation of structural dynamics an FE Model of the bicycle was set up using the software MSC Nastran [11]. The model contains a detailed representation of the bicycle frame including the thickness and orientation of the different layers of Carbon Fiber Reinforced Plastic (CFRP). Other parts such as electrical drive unit, battery, fork, damper, seat post and front wheel are considered as simplified representations. The calculation is done in the frequency domain and substructuring is applied to enable different modal damping for different parts of the model. Furthermore, substructuring significantly reduces the calculation time because the numerical modal analysis is only necessary once, and the derived superelements can be used repeatedly for different excitation scenarios. The structure is excited by the experimentally derived source description of the drive unit by means of *in-situ* blocked forces [3] The structure model is used to calculate the velocities on the surface of the frame which are used as an input for the subsequent radiation model. For more details on the structure model and on the approach using *in-situ* blocked forces, please read the previous paper [4].

5.2 Radiation Model

For the simulation of the radiation of sound another FE Model was set up using the software Actran [12]. Like the simulation of the structural dynamics, the simulation of the radiation is carried out in the frequency domain. The model contains the outer surface of the frame and a mesh for the air surrounding it. The model of the air is divided into two different sections. In the near field there are finite elements with a minimum of 7.5 elements per wavelength and in the far field there are infinite elements. The mesh is automatically redefined dependent on the current frequency step. From the velocities on the outer surface of the frame given as an input, the model calculates the sound pressure at different previously defined microphone positions. When transferred back to the time-domain these sound pressure values can be replayed and the user is able to listen to the predicted sound.

6 Validation and Results

In this chapter the results of the hybrid modeling approach are discussed. To ensure comparability of measurement data and simulation results, both are analyzed within the same software, in this case ArtemiS SUITE [13] is used. The results are presented for two different scenarios.

In the first scenario, the excitation by the drive unit experimentally derived from measurements at the e-bike of series production is applied to the numerical model of the prototype e-bike.

Using this hybrid model approach the influence of different bike frames and the corresponding structural dynamics on the sound of the e-bike can be analyzed, while the excitation is kept equal. For this scenario a functional prototype was available at the end of the presented project. This enables a validation of the hybrid modeling approach. In the first scenario the following questions should be addressed:

- Is it possible to predict the difference between the sound radiated by the e-bike of series production and the prototype e-bike using the hybrid modeling approach?
- If so, is the accuracy of this prediction high enough to be evaluated by means of psychoacoustic parameters?

In the **second scenario,** two different drive units are evaluated. The following questions are addressed:

- Is there a difference between two different models of drive units detectable using psychoacoustic parameters?
- If so, how does this difference show up, when the drive units are virtually mounted into another frame? Is it persistent? Does it change?

To answer these questions two different measurements are performed using the e-bike from series production. Between the two measurements, the drive unit is exchanged. These measurements are analyzed by means of psychoacoustic parameters. In a second step, source descriptions for both drive units are derived from the measurements using the method of *in-situ* blocked forces. The blocked forces are used to virtually mount these different drive units into the numerical model of the prototype e-bike which has been validated in the first scenario.

6.1 First scenario

Figure 5 shows the comparison of the predicted sound pressure level of the prototype (middle) with the measured sound power level of the e-bike from series production (left) and the measured sound pressure level of the prototype (right). For the comparison, a run-up to approximately 110 rpm was measured and simulated. Because the run-up was performed by a human test rider on the test rig, the elapsed time of the measurements of the serial model and the prototype differ slightly. Since the excitation for the calculation is taken from the measurements of the serial model, the elapsed time from the predicted run-up equals the serial model measurements and not the prototype measurements.

In the measurements of the serial model, two potentially critical modes of operation can be identified, which are marked in the left of Figure 5 with white ellipses.

The first mode of operation is in the middle of the run-up, and the second at the end. Using the numerical model of the prototype in combination with the experimentally derived excitation of the serial drive unit, it is predicted that the first potentially critical mode of operation is shifted from the middle of the run-up to the start of the run-up (see Figure 5 middle). The validation measurement of the prototype (see Figure 5 right) confirms this prediction.

Figure 6 shows the comparison of the perceived loudness for the three previously presented cases over rotational speed. The black curve represents the measurement of the serial model, and it corresponds with the potentially critical modes of operation identified during the analysis of the sound pressure level (see Figure 5, left picture). One critical operation condition in terms of perceived loudness is the middle of the run up at around 85 rpm. The numerical simulation of the prototype (hybrid model) shown in red predicts that this peak of perceived loudness is absent for the prototype. Instead, there is a much smaller peak at lower speeds. The measurement of the prototype shown in green confirms this prediction. Looking at the speeds above 100 rpm, Figure 6 reveals that the prediction is less accurate at this operating point and the prediction for the prototype is closer to the measurement of the serial model than to the measurement of the prototype. A possible reason for this might be the interface which was defined between source and receiver in the previous paper [4]. This interface shows weaknesses around 800 Hz – 950 Hz.

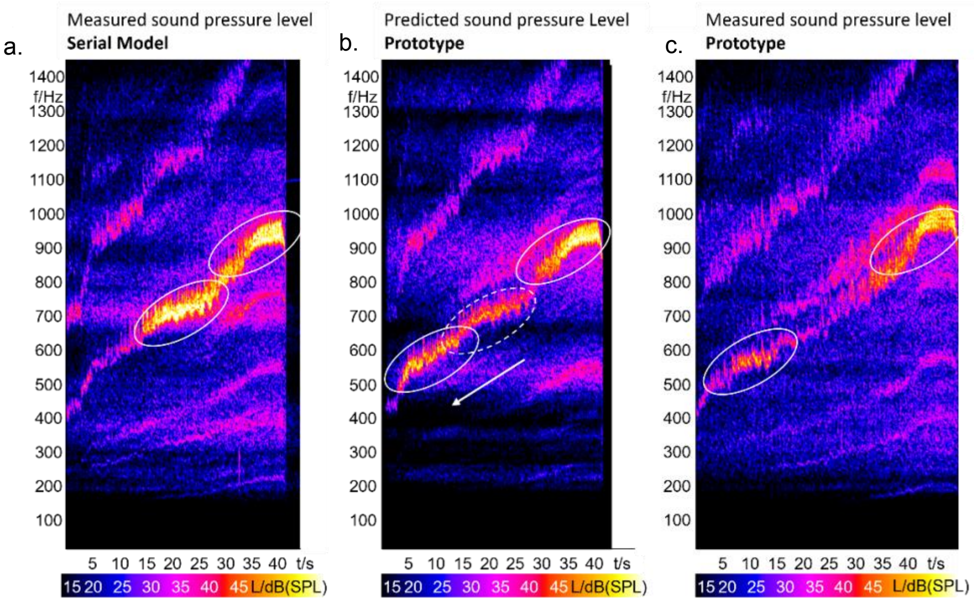

Figure 5. Comparison of measured and simulated sound pressure level (a. measured serial model, b. calculated prototype, c. measured prototype).

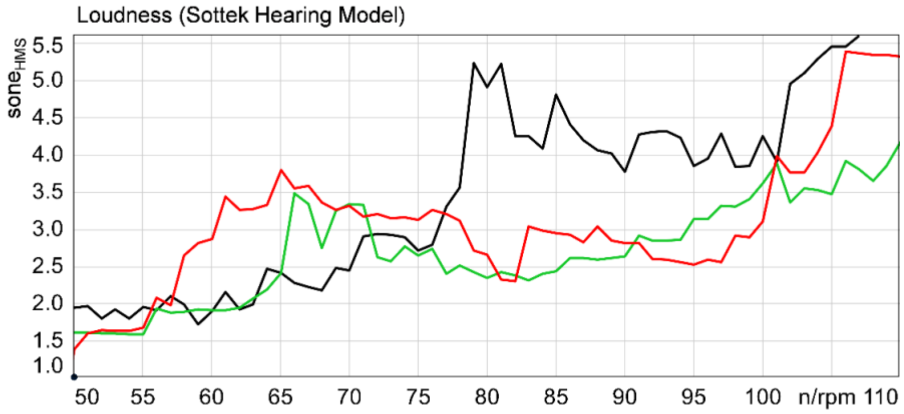

Figure 6. Comparison of perceived loudness (black: measured serial model, red: calculated prototype, green: measured prototype)

Figure 7 shows the comparison of the perceived tonality for the three previously presented cases. Like the analysis of the perceived loudness discussed above, the analysis of perceived tonality corresponds to the potentially critical modes of operation identified during the analysis of sound pressure level.

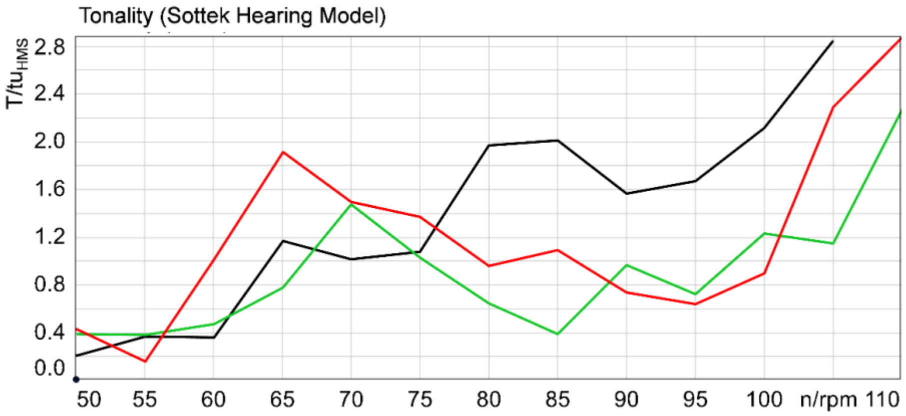

Figure 7. Comparison of perceived tonality (black: measured serial model; red: calculated prototype; green: measured prototype)

The measurement of the serial model depicted in black shows a peak in the middle of the run-up (80-85 rpm) and rises to a maximal value towards the end of the run-up. The hybrid model (red curve) predicts that the peak in the middle of the run up is shifted to lower speeds for the prototype. The measurement of the prototype confirms this prediction (green curve).

The analysis of the first scenario demonstrates that the significant differences between the two e-bike setups are predicted by the hybrid model with a good accuracy in terms of sound pressure level as well as psychoacoustic parameters. Furthermore, it is easy to see how the psychoacoustic parameters enhance the acoustic analysis of the results and give an insight of the human perception of the sound radiated by the e-bike. The analysis of loudness gives an idea whether a change in the sound pressure level leads to a significant change in the perceived loudness of the sound. The tonality is, as stated above, a very important parameter to evaluate the human perception of sounds radiated by e-bikes. Figure 6 and Figure 7 show that the prototype is perceived much less loud and tonal from approximately 78 rpm onwards. On the other hand, it is a little louder and perceived more tonal between 55 and 75 rpm. This knowledge, combined with typical riding profiles and an idea of the user's expectation of what the sound should be like, would be of great value to rate these different e-bike setups against each other.

The results of the first scenario can be summarized as follows:

- The presented hybrid model is suitable to predict the sound radiated by the e-bike prototype based on measurements of the e-bike of series production.
- The accuracy of the predicted sound is high enough to enable the postprocessing using psychoacoustic parameters.

6.2 Second scenario

Figure 8 shows the psychoacoustic analysis of measurement data for two different drive units mounted in the e-bike of series production. A clear difference between the two sounds can be seen, while the perceived loudness is similar for both drive units: drive unit A shows a significantly higher tonality while drive unit B has a much rougher characteristic. To check whether these characteristics persist when the drive units are mounted into another frame, for both drive units the source description was done using *in-situ* blocked forces. The blocked forces were implemented into the model of the prototype e-bike discussed in the previous sections.

Figure 9 shows the comparison between the predicted sound pressure level radiated by the prototype bicycle frame for both drive units. While the main excitation order of drive unit A can be identified as a rather sharp line in the waterfall plot, the excitation order of drive unit B appears to have a broader excitation pattern and the waterfall plot is somewhat blurry.

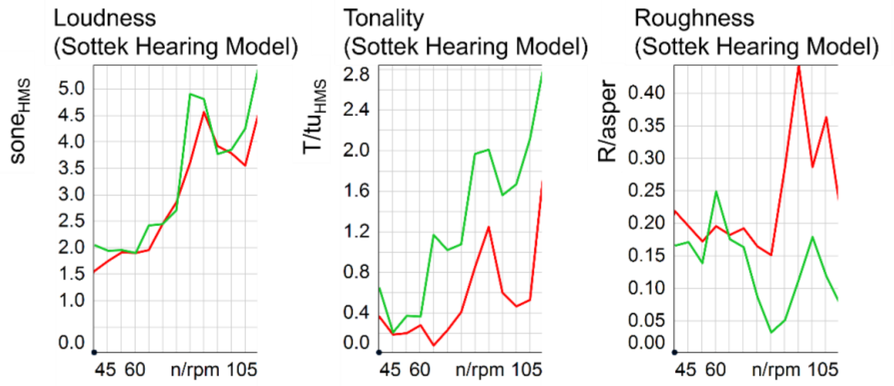

Figure 8. Comparison of psychoacoustic parameters based on measurements at the e- bike from series production (drive unit A (green), drive unit B (red))

Figure 10 shows how this first acoustic analysis of the simulation results is confirmed and enhanced using psychoacoustic parameters. While drive unit A (green) has a slightly higher loudness and a much higher tonality, drive unit B (red) has a much higher roughness. This prediction fits astonishingly well with the measurements of the two different drive units in the e-bike of series production presented in Figure 8. This proves that the general characteristics of the sounds of the different drive unit appear in both frames. Furthermore, with a close look at the results for loudness and tonality in Figure 8 and

Figure 10 the difference between the two frames that has been discussed in the first scenario can also be discovered in the second scenario. The peak in loudness and tonality which can be detected at around 85 rpm for the e-bike of series production is shifted to lower speeds for the prototype and has a lower loudness.

While the assessment of measured and simulated sounds based on psychoacoustic parameters is much more precise than the first statement based on the evaluation of sound pressure level, there is still one question left unanswered: which sound is more pleasant or desirable for the future e-bike? To answer this question reliably we must listen to the resulting sound, which is fortunately possible with the presented approach and the achieved level of accuracy of the results of hybrid simulation. To make the judgement more objective, it is recommended to incorporate a representative group of potential users. If a well-chosen compilation of sounds is benchmarked by a large group of users in a standardized setup, the measurable psychoacoustic parameters can be correlated with an emotional perception (e.g., sporty / aggressive / pleasant / soothing / annoying) and rated. From this jury test a sound quality metric can be derived. Psychoacoustic parameters and metrics are important methods for putting human perception into a formalism that can be used by engineers. HEAD acoustics is currently researching in the field of sound quality metrics for e-bikes.

The results of the second scenario can be summarized as follows:

- There is a distinct difference in the characteristics of the drive units A and B that can be assessed using psychoacoustic parameters.
- The characteristics of both drive units persist, when virtually mounted into another frame.

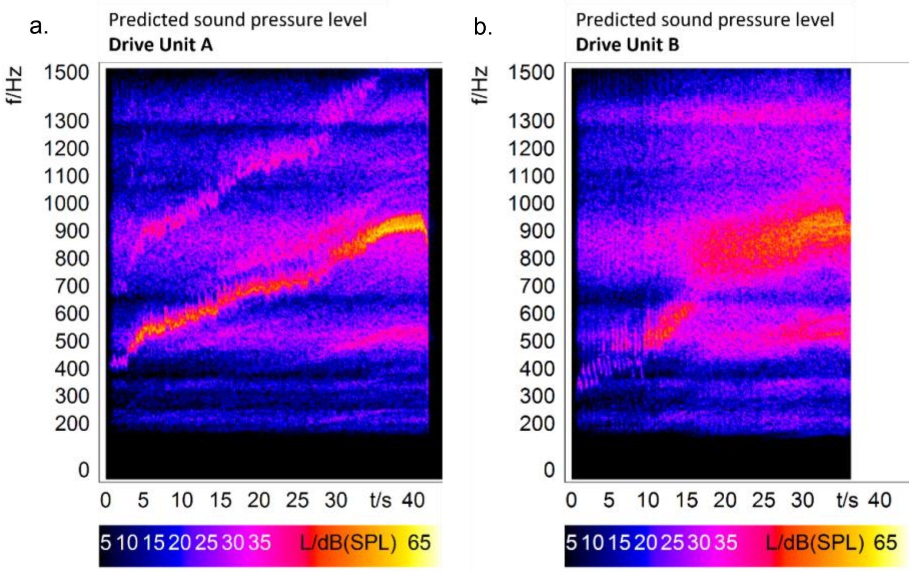

Figure 9. Comparison of sound pressure level based on hybrid simulation of the e-bike prototype (a. drive unit A; b. drive unit B).

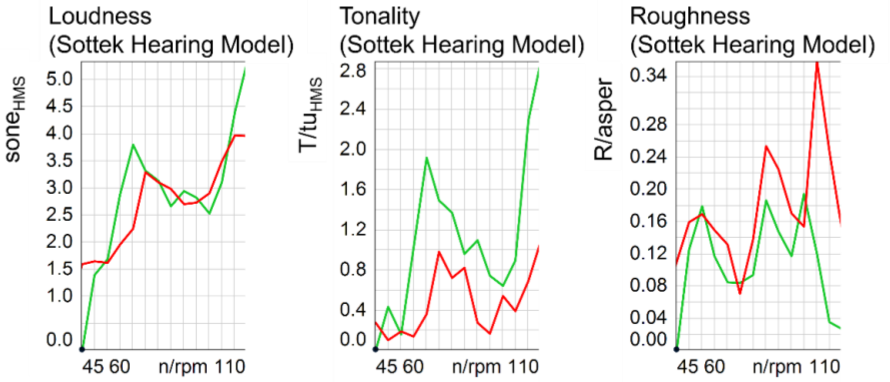

Figure 10. Comparison of psychoacoustic parameters based on hybrid simulation of the e-bike prototype (drive unit A (green), drive unit B (red)).

7 Conclusions

This paper demonstrates the advantages of psychoacoustic analysis, known as a method for evaluating measurement data, in evaluating simulation results. Moreover, it gives an example on how accurately audible sounds and their human perceptions can be predicted using a hybrid model approach. The approach is demonstrated using the application example of an e-bike. Based on a user profile which includes the most common cadence and the type of riding (e.g., sporty/leisure) in addition to the expectation for the sound, the presented approach can be used to rate the sound perceived by the user of an e-bike though it is still in development and does not exist as a functional prototype.

Both the hybrid model approach and the idea to evaluate data from simulation using psychoacoustic parameters can be applied to other products.

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