Acoustic optimization of an electric wheel hub motor

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Abstract

In the context of environmentally friendliness the electrification of passenger cars becomes more and more important. In this paper an innovative concept for designing the electrical drive of automobiles is presented which allows optimizing the acoustic behaviour on a virtual basis. In special, the acoustics of an electric wheel hub motor is studied in detail. Therefore, a holistic simulation workflow has been developed which takes into account the electromagnetic field as the most important vibration excitation as well as the structural vibrations coupled with air volume around the engine to calculate the air pressure. First, the electromagnetic forces are calculated which are then applied to excite the structural vibrations of the engine. Finally, the calculated surface velocity is used to excite the surrounding air volume under free field conditions to determine the radiated sound pressure level. In all three steps of the holistic methodology, the finite element method (FEM) is used for the numerical simulations. The simulation results are validated by measurements. In the paper at hand different design configurations are compared to receive an engine with a reduced sound pressure level in the surrounding air volume. Finally, the best design of the electric wheel hub motor is determined.

Introduction

The developed electric wheel hub motor (see Fig. 1) shows an extraordinary power-to-weight-ratio, as it combines an air gap winding and a slot winding to boost torque sharing the same magnetic circuit [3].

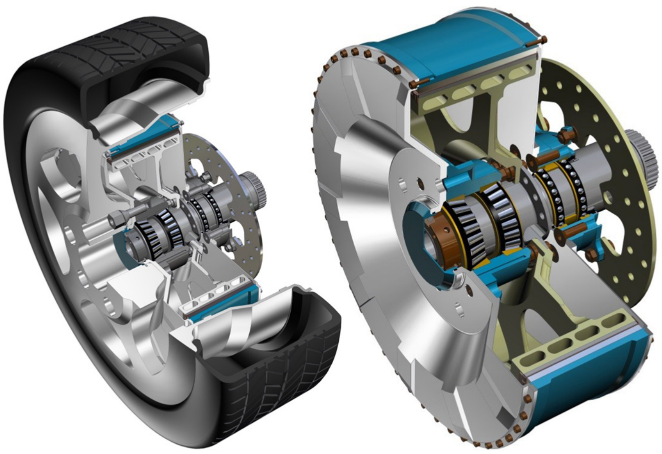

Figure 1: Electric wheel hub motor

In the development process of an engine the acoustics is usually not in the focus of interest. But, it has been proved that the acoustic characteristics of electric engines are a very important topic which should be taken into account in an early stage of the development process. In contrast to combustion engines the first engine orders of electrical engines are related to much higher frequencies (up to 1250 Hz) and the resulting sound pressure level is lower than that of combustion engines. It seems that the radiated sound is caused by a few different frequencies only. Hence, the emitted sound of an electric engine is more like a single high frequency tone. Unfortunately, the human auditory perception is very sensitive with respect to such high frequency sounds. Consequently, the noise emission of electric engines is more annoying than that of combustion engines, even if the amplitudes of the sound of an electric engine are lower. For this reason, it is important to consider the acoustic behavior as early as possible in the product development process of an electric engine.

Holistic simulation workflow

In this section a holistic simulation workflow for the acoustic analysis of an electric machine is presented. Therefore, no real prototypes are needed. The approach was developed in [1], [2] and is visualized in Fig. 2.

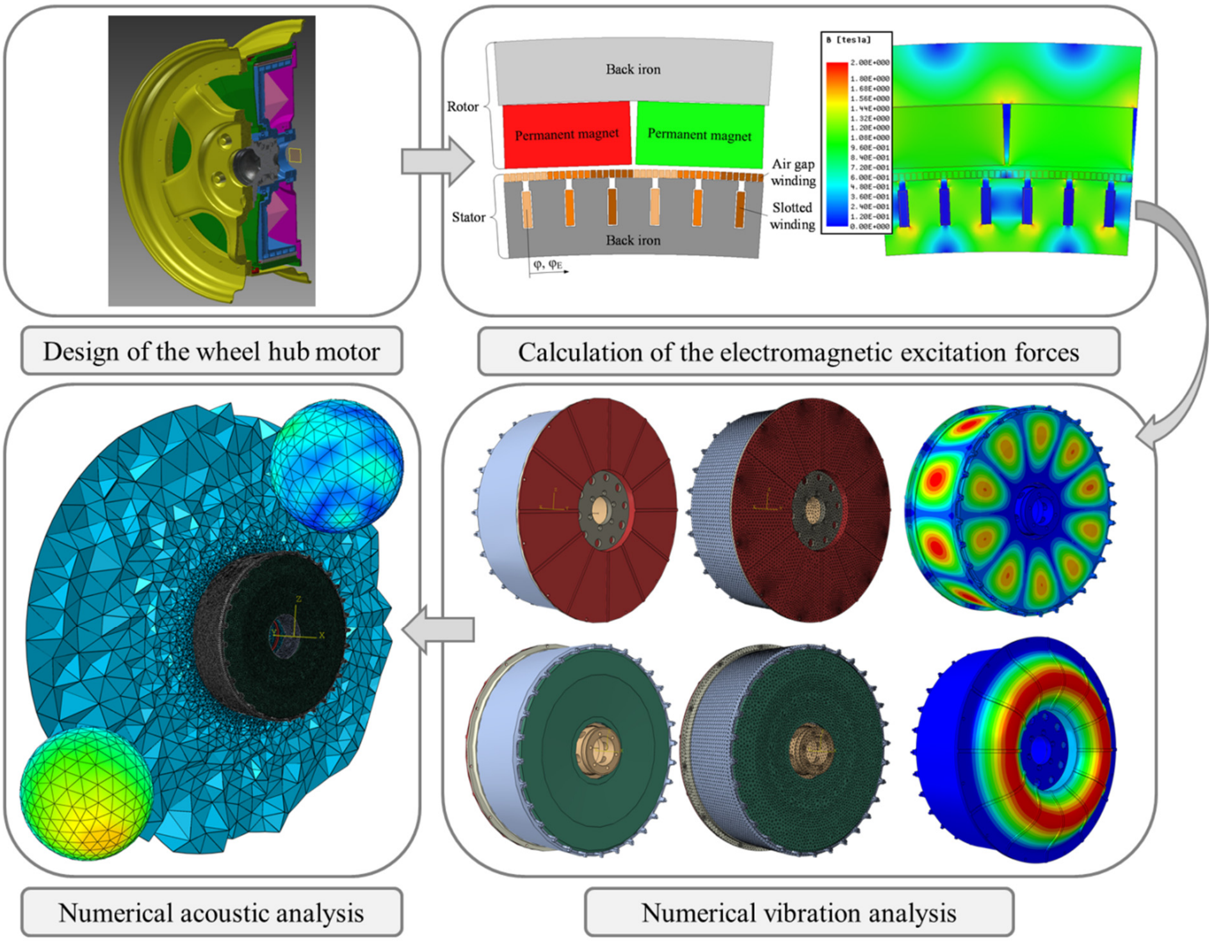

Figure 2: Holistic simulation workflow to evaluate the acoustic behavior of an electric machine

The workflow consists of three steps, as shown in Fig. 2. First, the electromagnetic behavior is modeled, where it is common to neglect the differences in the direction of the rotation axis to increase the efficiency. It is sufficient two use a two dimensional model only (see Fig. 2, right upper corner) [1]. Second, the electromagnetic forces as result of the first step are used to calculate the vibration behavior of the wheel hub motor. Third, the resulting surface velocity is used to excite the surrounding air and to calculate the air pressure at any point of the surrounding air volume under free field conditions. The vibration and acoustic analyses can be solved in an uncoupled manner, as the feedback of the vibrating air on the much stiffer engine housing can be neglected. For all three solution steps, the electrodynamics, the structural dynamics and the acoustics the finite element method (FEM) is used. As result the complex sound pressure in the whole fluid domain is obtained. The simulation results can be auralized [4] and be used in psychoacoustic analyses [5]. The directional characteristics are important and have also to be taken into account [6]. By means of the presented simulation workflow an automated optimization can be executed with the target to achieve both a low overall mass and a lower sound emission of the electric wheel hub motor.

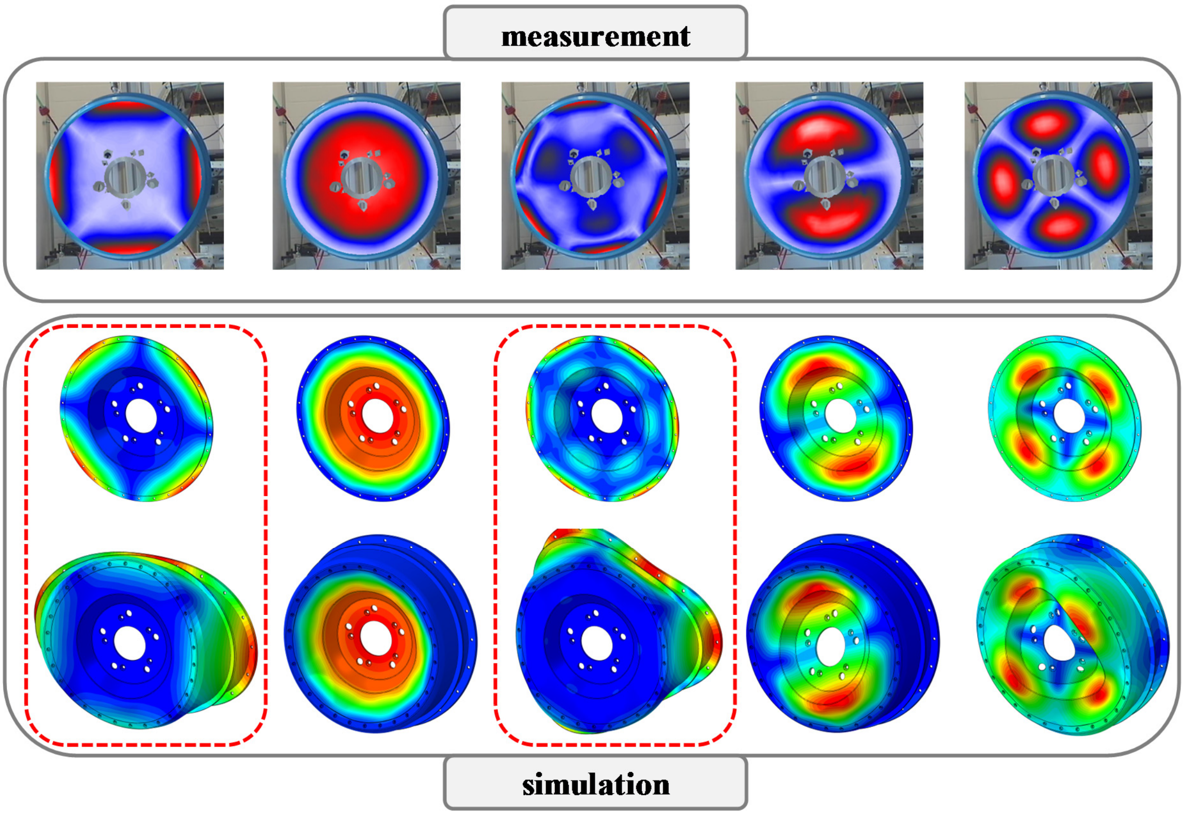

Figure 3: Validation of the simulation model of the electric wheel hub motor

In Fig. 3 the comparison of experimentally and numerically determined eigenmodes is shown. It is obvious that the simulation model is able to predict the resulting vibration modes of the complex system with a lot of components and connections sufficiently. In contrast to the first two columns the third column in Fig. 3 shows the vibration modes of the whole housing. It is easy to see that a numerical analysis provides more information than a measurement, which is executed with the help of a laser vibrometer, as the experiment does not detect the dominating eigenmode of the overall system (see the modes in the second column within the red dashed line). This is due to the fact that the laser vibrometer can only measure the surface velocity in the direction of the laser beam. Furthermore, only surfaces can be measured which can be “seen” by the laser. This example emphasizes the advantages of a numerical vibration analysis. However, an experimental vibration analysis is recommendable to validate the simulation models.

Evaluation of different design configurations of the engine housing

In this section different design configurations of the electric wheel hub motor are investigated with the help of the previously validated simulation models. The modifications of the designs are limited to the outer surface of the rotor, as this is the only part of the electric engine that is not of interest for other design parameters than the acoustics. Consequently, possible target conflicts between different design parameters are avoided. The inner design of the wheel hub motor is defined by components like the cooling circuit and the electronics.

At first, different designs of stiffeners on the side lid of the rotor are compared numerically due to their influence on the resulting vibration behavior. The investigated stringer designs, which differ in number, size and shape, are shown in Fig. 4. In Fig. 5 the calculated sum levels of the structural vibrations of the different design configurations are visualized. Version 0 represents the reference configuration without additional stringers. In comparison to the designs with stringers it becomes clear that these stiffeners cause a significantly lower vibration level. For calculating the sum level of the surface velocity all frequencies up to 5 kHz are considered. Consequently, the experimentally identified most critical frequency band (3.5 – 4 kHz) is taken into account (see Fig. 12 and Fig. 13).

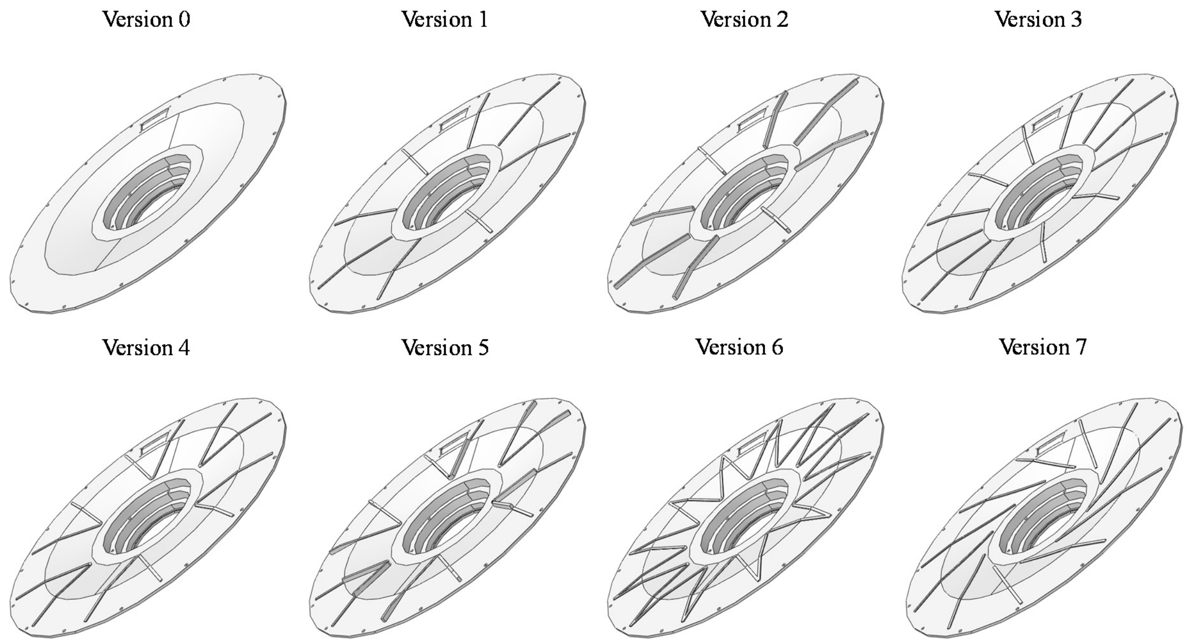

Figure 4: Different design configurations of the side lid of the engine housing

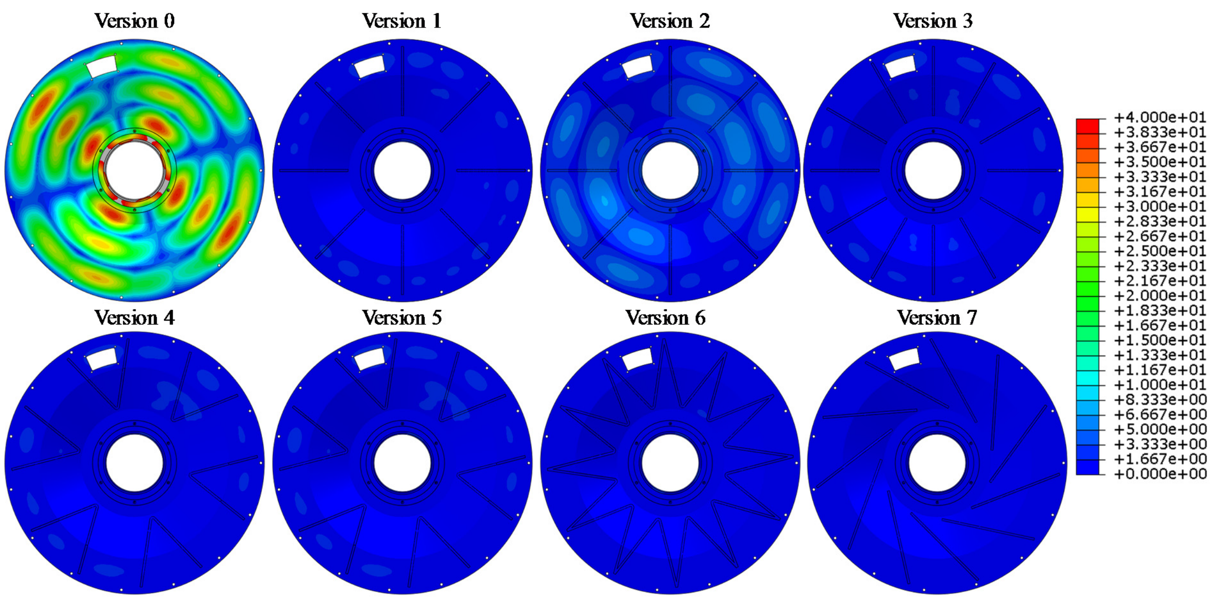

Figure 5: Sum levels of the structural vibrations of the different design configurations of Fig. 4

Further, it can be seen in Fig. 5 that there are also significant differences between the configurations with stringers. To show this more clearly, three exemplarily results are visualized in Fig. 6 with a new scale of the legend. Finally, it can be stated that the Version 7 is the configuration with the lowest vibration sum level. The strategy of this special stringer distribution is based on the assumption that small and irregular surfaces are inefficient radiators from an acoustical point of view. In a previous study [7] it was already observed that asymmetric surfaces (generated by stiffeners) are acoustically advantageously.

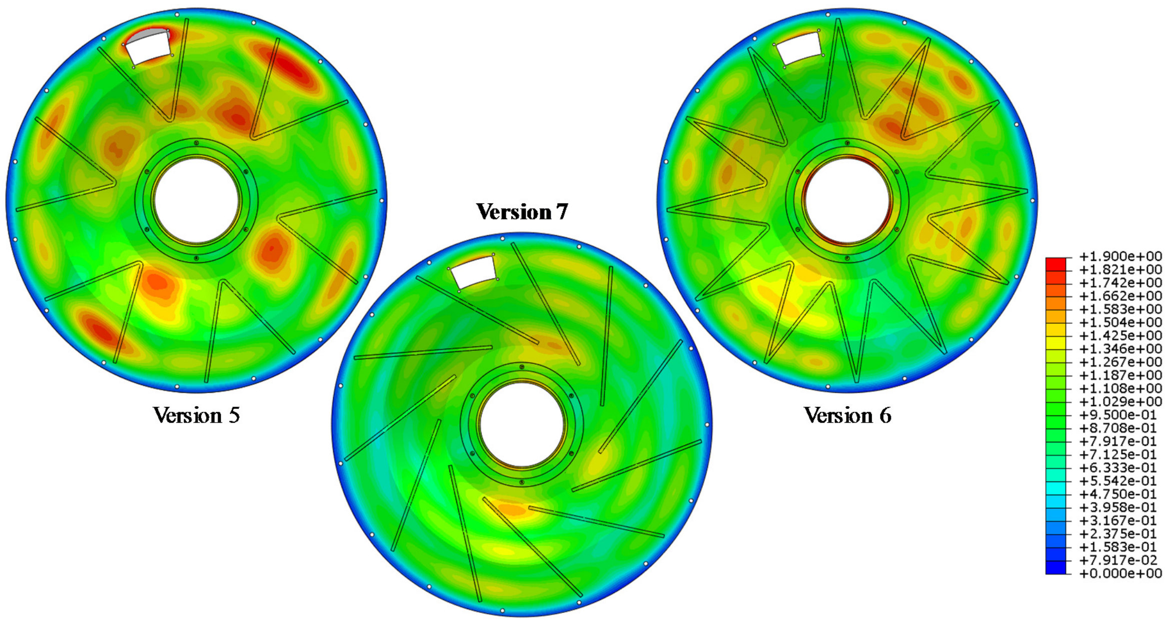

Figure 6: Detailed view of the structural vibrations of the best design configurations of Fig. 4

In the next step a FE-model of the whole rotor of the electric wheel hub motor was generated (see Fig. 7) that already contains the best stringer configuration of the previous investigation. By means of this model different stiffening strategies of the cylinder were studied. These new configurations and the corresponding additional masses are depicted in Fig. 8. They differ in number and height of the stringers, which are realized as rings only, as other shapes would cause inappropriate efforts during the manufacturing process of the prototypes.

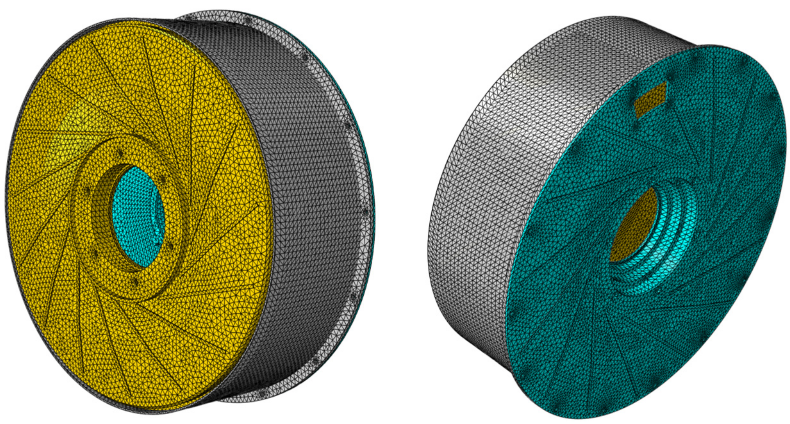

Figure 7: FE-model of the whole rotor of the electric wheel hub motor

The resulting sum levels of the structural vibrations of the different design configurations of Fig. 8 are shown in Fig. 9 for two exemplarily results. It has to be noted that the additional application of stringers on the cylinder of the rotor is disadvantageously, as the vibration energy is forced back into other regions and especially to the sides of the rotors, which were just stiffened in the previous step. As a result, the side lids of the rotor show higher vibration amplitudes than in the case without stringers on the surface of the cylinder. This is a problem, as from an acoustical point of view this comparably large and thin part of the rotor is a much better radiator than the cylinder. Furthermore, the sides of the rotor are directed toward the passers-by of a car on the street. Finally, it has to be stated that the stringers on the cylinder cause both higher vibration amplitudes and an increased mass. Therefore, the stiffening of the cylinder cannot be recommended for the application example at hand.

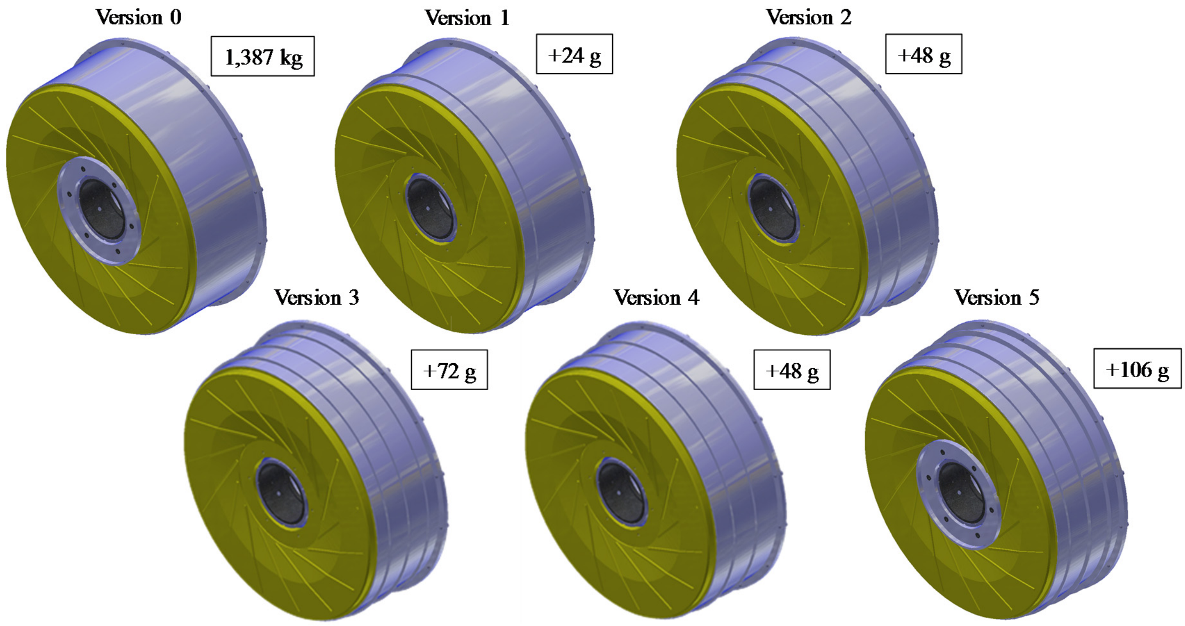

Figure 8: Different stiffener configurations of the rotor of the electric wheel hub motor

It has to be noted that the number of stringers on both sides of the rotor has not to be identical. It is possible that different stringer distributions on both sides of the rotor lead to a better acoustic behavior of the wheel hub motor. The specific number and height of the stringers for each side of the rotor are determined by additional extensive numerical studies (some configurations can be seen in Fig. 10). For these studies the model without stringers on the cylinder was used. The best combination is 15 stringers on the felly side (2 mm height) and 15 stringers on the chassis side (1 mm height).

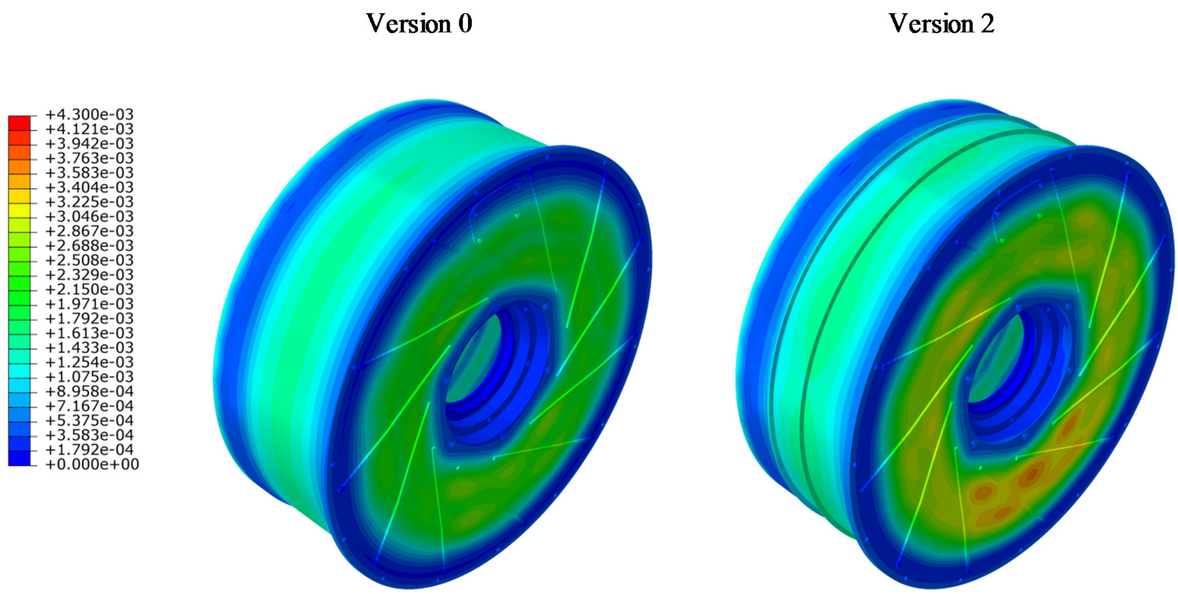

Figure 9: Sum levels of the structural vibrations with (right) and without (left) stringers on the cylinder

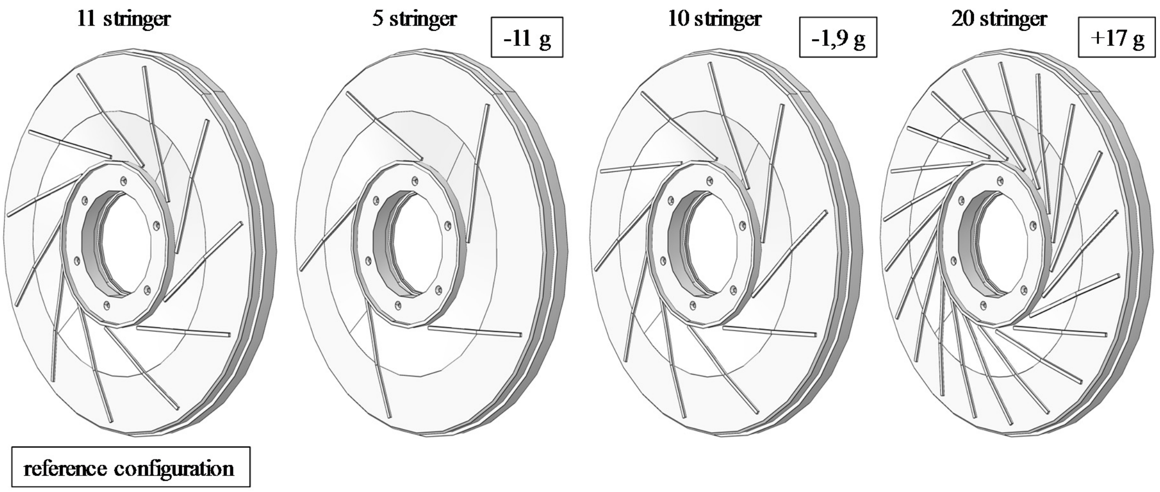

Figure 10: Stiffener design with a different number of stringers on the felly side lid

Another idea to improve the acoustic behavior of the electric wheel hub motor was to introduce cavities within the sides of the engine housing and to fill these cavities with absorbing materials [8]. For filling the cavities different materials were studied. Beside several foams, for example impregnated foams as in [9], an innovative vibration reduction concept was applied that was developed in [10]. For this concept granular materials are used. Hence, this strategy is suitable for applying to a structure with inner cavities [11]. Moreover, in [12] different granular materials were tested and it was figured out that granular rubber provides the best reduction of the vibration amplitudes while having a comparably low density. However, the filling and assembling of a part with filled cavities is easier to apply with foam than with granular materials.

Experimental vibration analysis of the running engine

All prototypes of the electric wheel hub motors are also investigated experimentally. For this reason a laser scanning vibrometer in combination with a derotator is used. So, the vibration behavior of the running engine can be measured. The experimental setup is shown in Fig. 11.

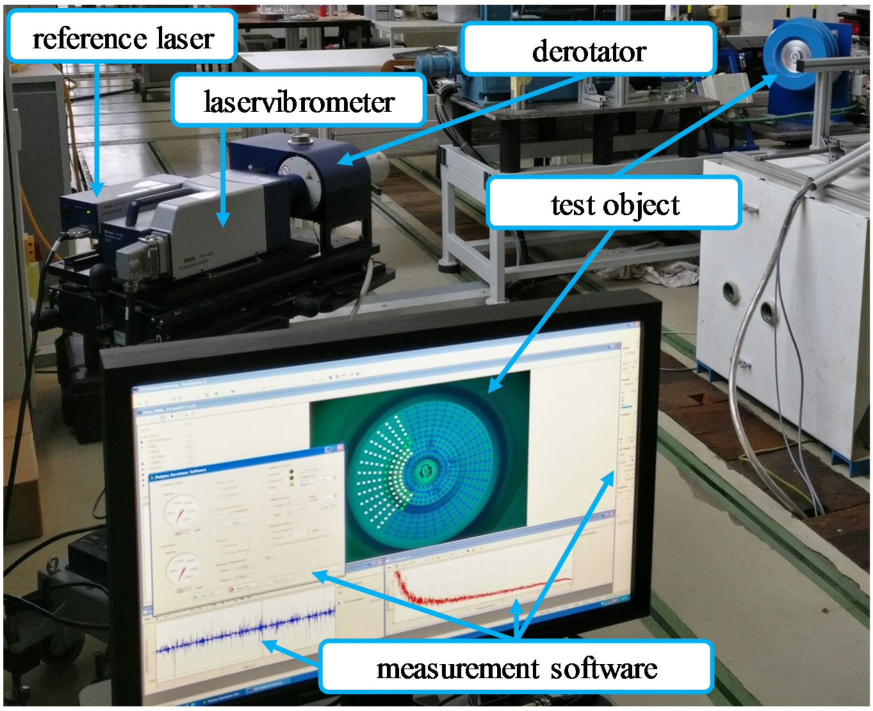

Figure 11: Experimental setup to measure the vibrations of the running wheel hub motor

In Fig. 12 an exemplarily result of a measurement in the rotating system is presented. It shows the frequency response of the electric engine at a stationary operating point and the vibration modes of all conspicuous frequencies.

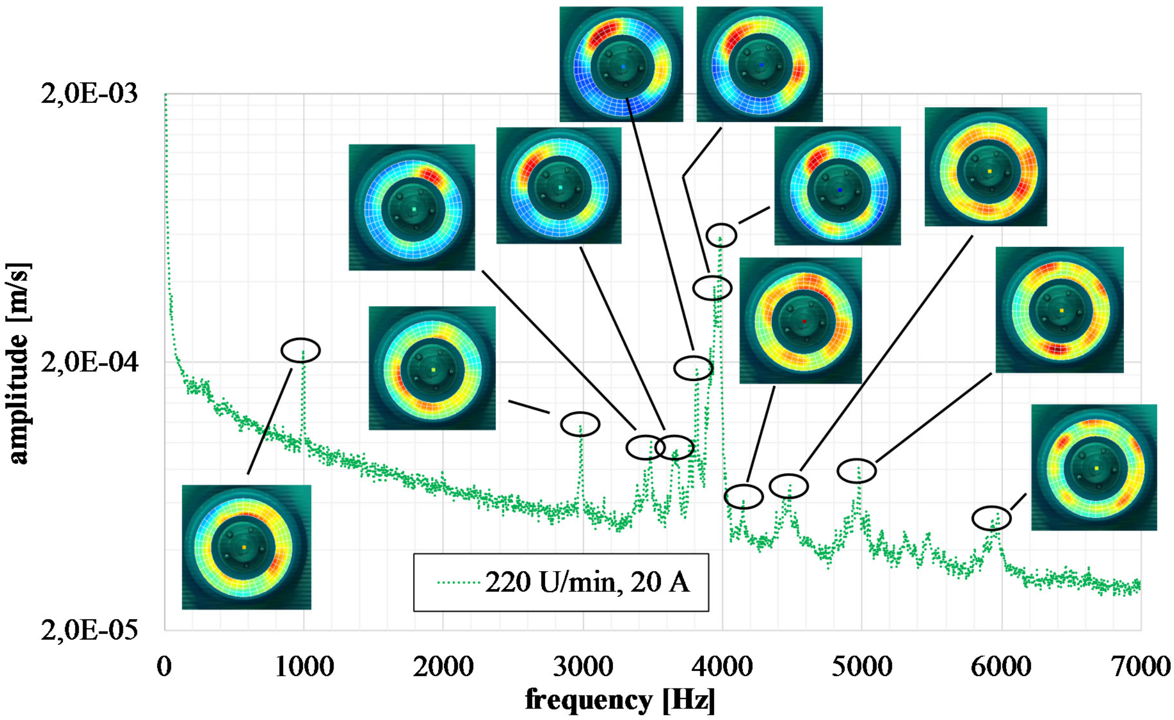

Figure 12: Frequency response of the electric engine at a stationary operating point

Different operating points were investigated during the derotator measurements. These operating points differ in the rotational speed and the applied current. The results are summarized in Fig. 13. It can be stated that higher loads as well as higher rotational speeds lead to an acoustically more critical behavior, as it was expected.

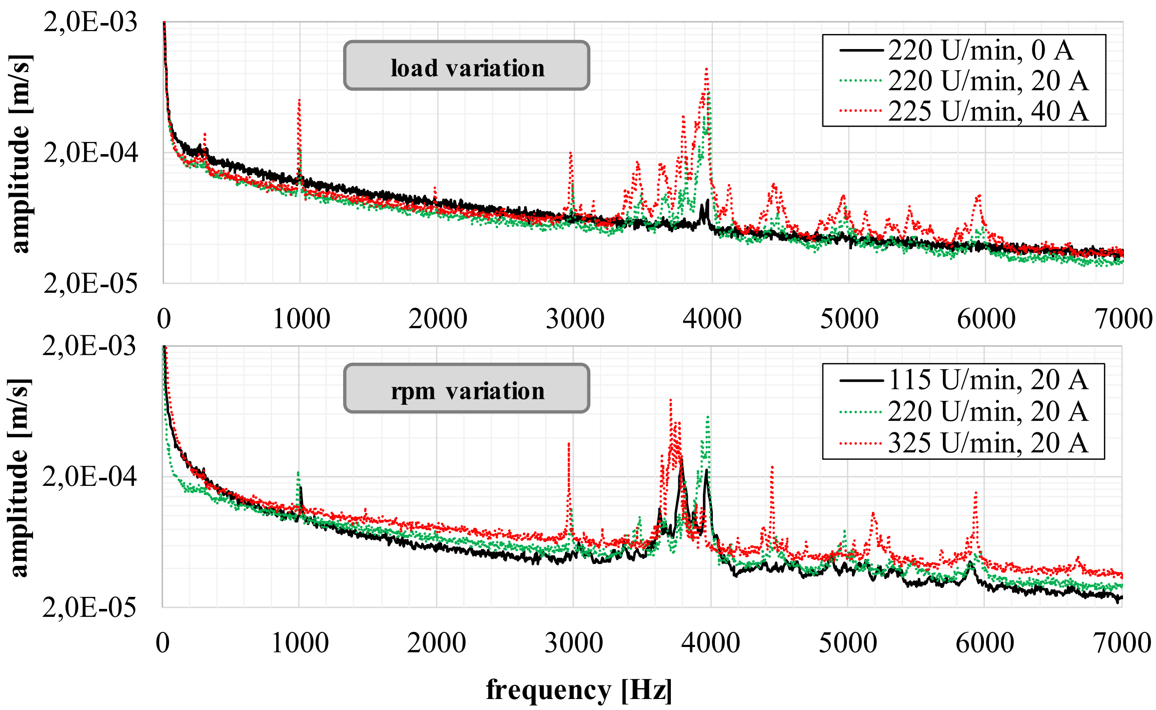

Figure 13: Frequency response functions of the engine at different stationary operating points

Investigation of alternative materials

The idea is to substitute some of the aluminum components of the electric wheel hub motor by applying innovative sandwich materials made of aluminum foam and fiber-reinforced composites, which can be seen in Fig. 14. In an ongoing investigation, both carbon and glass fiber composites are investigated. The aim is to reduce the mass as well as to improve the acoustic behavior. The different types of materials are compared by acoustic measurements, which are executed in an anechoic room with the help of a microphone array and a rotatable far-field microphone that can analyze also the directional characteristics of the test samples. But, these investigations are still in progress.

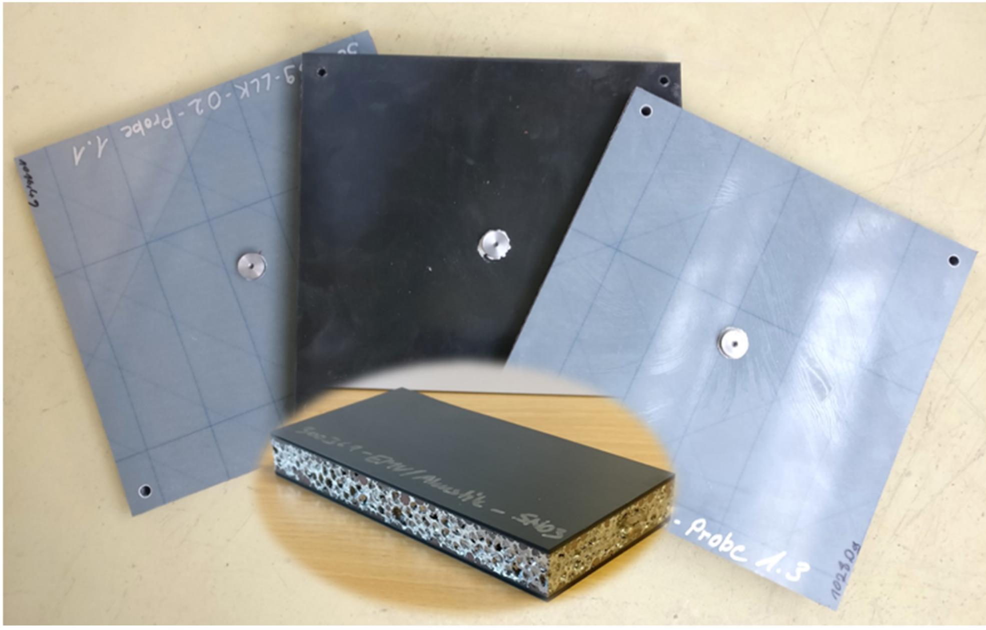

Figure 14: Test samples of innovative sandwich materials

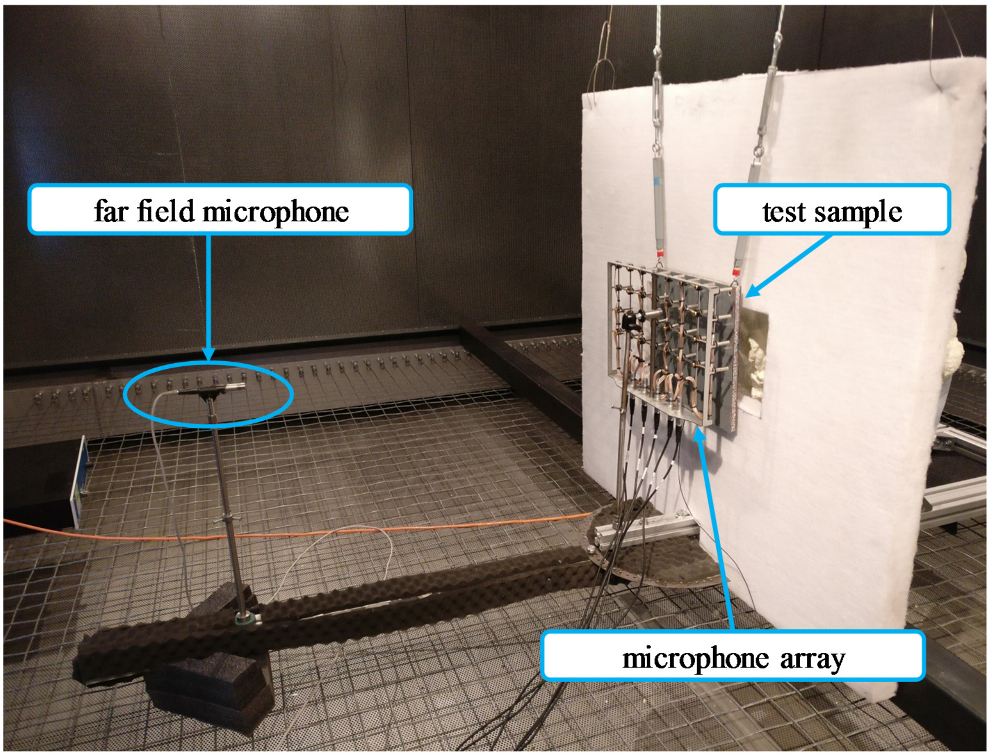

Figure 15: Experimental setup to compare different materials acoustically

Summary

In the paper the acoustic behavior of an electric wheel hub motor is analyzed numerically as well as experimentally. For simulation and optimization reasons a holistic simulation workflow is presented and applied to a wheel hub motor. The quality of the simulation results is validated by means of experimental investigation. To improve the acoustics several design version have been developed and numerically studied with the help of the proposed holistic simulation workflow. The best design configurations will be realized as the next prototype of the wheel hub motor. The optimization of the acoustic behavior of an electric wheel hub motor is still under development in the frame of an ongoing project.

Acknowledgment

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