NVH in Electric Mobility – Vibration Analysis Using a Derotator

Wheel hub motors favor package, but are demanding in terms of NVH due to their installation position. A working group of the Otto von Guericke University Magdeburg uses an optical vibration measurement system to analyze the vibrations behavior of external rotor electric motors in order to optimize the acoustics of wheel hub motors.

AUTHORS

Dr.-Ing. Fabian Duvigneau is Postdoctoral Researcher at the Institute of Mechanics of the Otto von Guericke University Magdeburg (Germany).

Dr.-Ing. Christian Daniel is Postdoctoral Researcher at the Institute of Mechanics of the Otto von Guericke University Magdeburg (Germany).

Dipl.-Ing. Sebastian Koch is Researcher at the Institute of Mechanics of the Otto von Guericke University Magdeburg (Germany).

Jun.-Prof. Dr.-Ing. Elmar Woschke is Junior Professor at the Institute of Mechanics of the Otto von Guericke University Magdeburg (Germany).

1 RESEARCH ON CLOSE-TO-WHEEL ELECTRIC DRIVES

At the Otto von Guericke University Magdeburg, the field of electric mobility has increasingly been in the focus of research since 2011. The working group "Editha" developed several electric drive concepts using a Smart fortwo MC450 as a base. The aim was to develop a street-legal prototype, which uses close-to-wheel driving concepts to create space for the traction batteries.

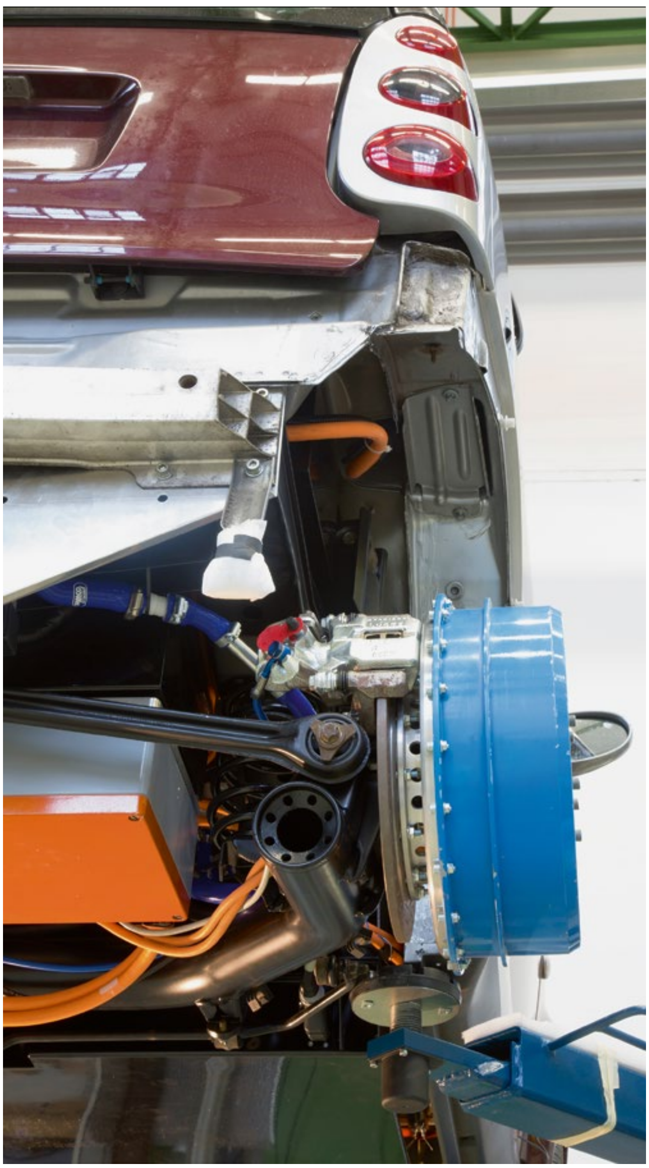

FIGURE 1 Wheel hub motor implemented in the research vehicle Editha 3 (© OVGU)

In 2012, the concept vehicle Editha 1 was completed and got an official approval and homologation for road service. The heart of the driving concept are two DC motors, which are mounted rigidly by a single-stage planetary gear directly on the rear axle. As a further development of this concept, Editha 2 has been initiated to replace the DC motors by permanent-magnet synchronous motors and to improve the drivetrain. With Editha 3 the step has been taken towards wheel hub motors, **FIGURE 1**. This wheel hub motor was developed at the Institute of Mobile Systems. The aim is to save the entire drive train and the planetary gear in the interior of the vehicle and thus to obtain even more space for batteries. Another advantage is that each wheel can be controlled separately, realizing a more intelligent vehicle dynamics control. The developed wheel hub motor is an external rotor motor. By combining an air gap winding with an additional slot winding, a high power density is achieved.

Due to their decentralized driving concept, all three series of Editha vehicles have an increased unsprung mass. The effects of this additional masses in the wheels are among others the subject of experimental and numerical investigations at the Institute of Mechanics [1]. In addition to changed vertical dynamics, the sound radiation of the wheel hub motor is an important issue, as the motor is placed in the rim, which can lead to increased noise emission due to the large flat components.

Although electric motors are generally considered to be less noisy compared to internal combustion engines, it is necessary to evaluate the acoustic behavior of electric vehicles. On the one hand, electric machines emit tonal high-frequency noises that are perceived as particularly annoying by human hearing even at low volumes. On the other hand, other sources of noise are no longer masked. In the case of a wheel hub motor the acoustic shielding of the car body is missing and the application of passive measures is not easily possible. The aim of the experimental analyses is the generation of a validation basis for complex simulation models, which allow a holistic view of the entire chain of effects, that means take into account all relevant sources of excitation as well as transmission phenomena. Using the validated numerical models, computer-aided optimizations will then be carried out in order to improve the acoustic behavior of the wheel hub prototypes.

2 INVESTIGATION OF THE STRUCTURE WITH A SCANNING VIBROMETER

After generating suitable simulation models for the complex overall system, these were validated using conventional experimental vibration analyses in the stationary system. This was done at component as well as assembly level. For vibration analysis, a one-dimensional laser scanning Doppler vibrometer from Polytec was used, **FIGURE 2** (left). For the measurements, the test object was attached to a frame made of aluminum profiles via synthetic polymer threads, since this so-called free-free mounting is particularly suitable for being able to compare numerical and experimental vibration analyses in a simple manner. **FIGURE 2** (left) shows the entire assembled rotor as an exemplary test object. Other boundary conditions, such as clamping or jointed mounting, cannot be easily realized in a finite element model identical to the experiment [2]. The uncertainties due to the influence of the boundary conditions can require time-consuming model updating processes in order to achieve a good match between the simulation model and the experiment.

In order to avoid an undefined boundary condition by the coupling of the excitation to the structure, the vibration excitation was

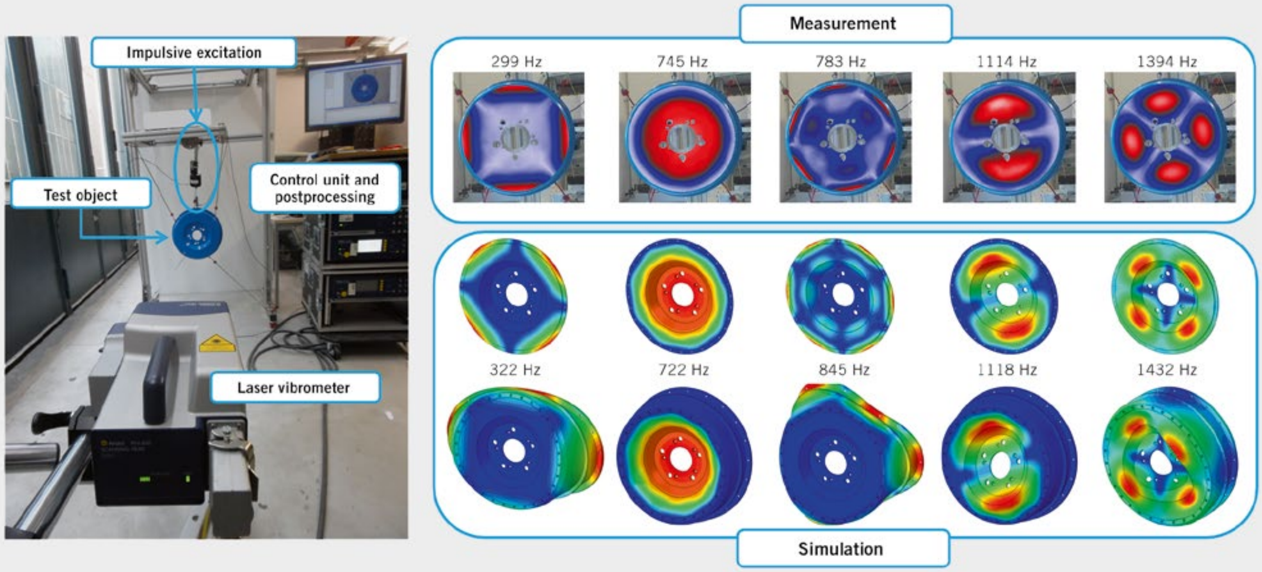

FIGURE 2 Experimental setup used for validation measurement (left) and results of experimental and numerical vibration analysis (right) (© OVGU)

realized with the aid of an impact hammer. Thus, free-free boundary conditions are maintained. The excitation must be reproducible since it must be repeated for each individual scan point of the measurement grid and the corresponding number of averages. For this reason, the head of the impact hammer was mounted on an electrodynamic shaker. This combination is highlighted in **FIGURE 2** (left) by the blue ellipse.

FIGURE 2 (right) shows the comparison of the experimentally measured (first row) with the numerically calculated eigenmodes (middle row) for five conspicuous natural frequencies. The comparison of the eigenmodes is executed for the measured surface of the laser vibrometer, that means the outer side surface of the rotor. It can be seen that the simulation model is able to predict the resulting vibration behavior of the complex overall system very well, although the assembly has several joints. In this case, both the natural frequencies and the natural vibration modes have a very good match.

In the third row in **FIGURE 2** (right), the eigenmodes of the entire rotor are additionally illustrated in order to show that the numerical analysis offers the possibility to get a better impression of the vibration behavior of the whole system compared to the laser vibrometer measurement. The first and third columns demonstrate that the investigation of the side surface in these cases is not representative for the eigenmode of the overall system and the critical vibration regions are not detected. This shows the value of a numerical vibration analysis that provides information about all

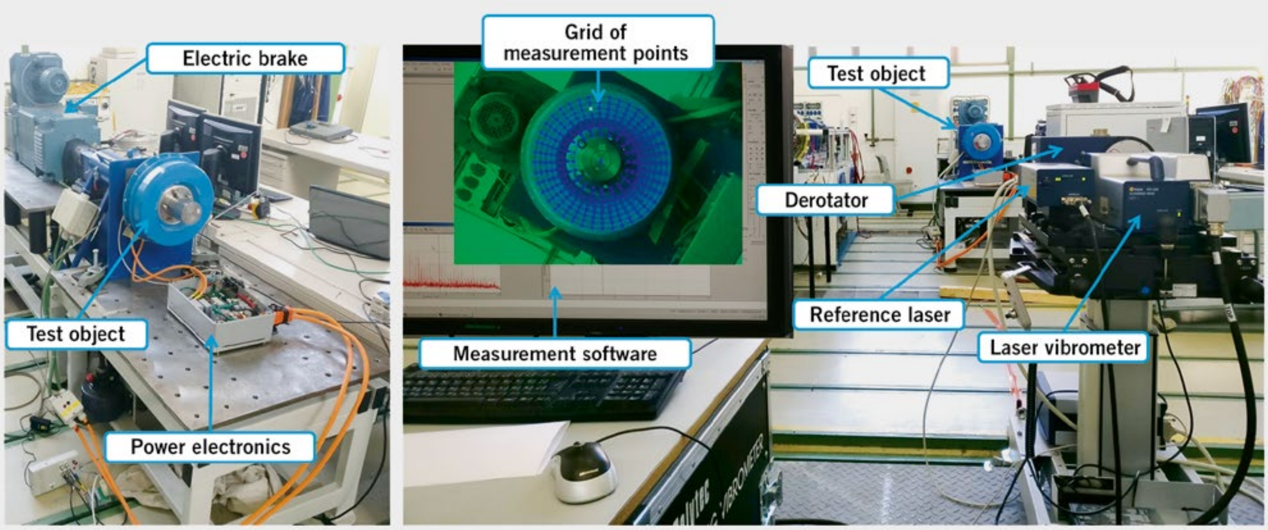

FIGURE 3 Experimental setup for the vibration analysis of the running wheel hub motor (© OVGU)

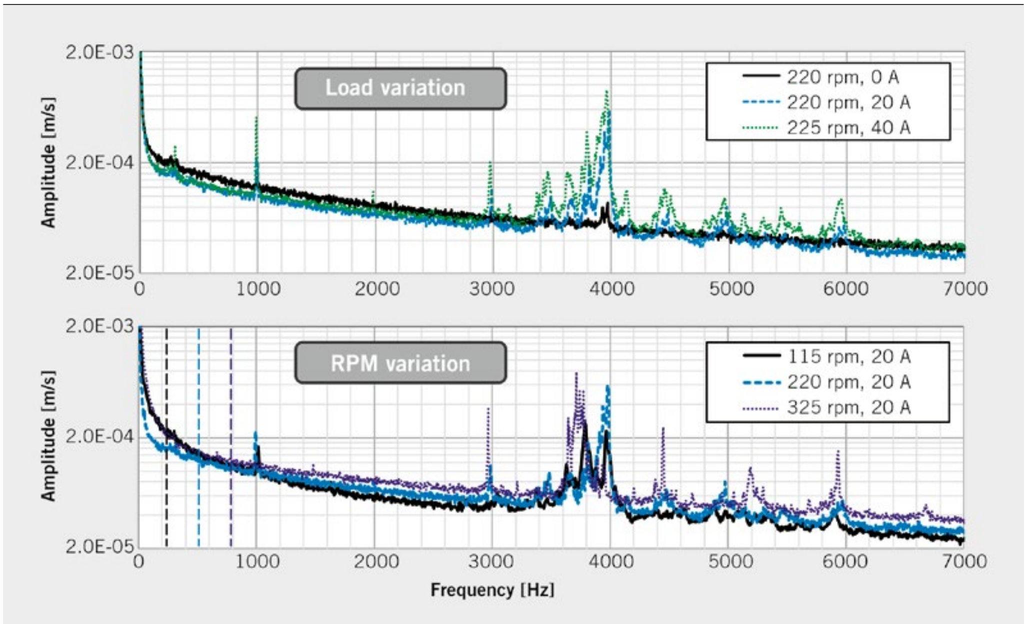

FIGURE 4 Vibration amplitude spectra of different operating points averaged over the measurement surface (© OVGU)

areas of the examined structure. Nevertheless, validation measurements are always recommended to prove the predictive capability of the simulation models.

3 MEASURING PRINCIPLE AND EXPERIMENTAL SETUP

For an assessment of the vibroacoustic behavior of an engine, the behavior of the overall system during operation is particularly important. Therefore, experimental vibration analyses were carried out for different stationary operating points of the electric wheel hub motor in order to obtain a broad validation basis for the holistic simulation method developed in [3, 4]. A one-dimensional laser vibrometer is used to measure the operating vibrations of the wheel hub motor. The excitation of the motor structure is achieved by the electrical commutation, whereby the motor must rotate for the operating vibration measurement. Since the wheel hub motor is designed as an external rotor motor, the rotor forms the motor housing, which rotates together with the rim. The measurement of local out of plane vibrations on the rotor is not possible with a conventional vibrometer.

Therefore, a rotating glass prism is attached in front of the vibrometer. As a result, the rotating surface can be measured in accordance with the defined measuring point grid by means of a laser scanning vibrometer as if it would not rotate. This so-called Polytec derotator is used for the scanning beam of the scanning vibrometer and another fixed-beam vibrometer, which acts as a reference channel. The reference is required to obtain a correct phase reference for each point that is measured by the scanning vibrometer. The experimental setup is shown in **FIGURE 3**. The electric brake, see left, was used to apply different loads and thus to realize different stationary operating points. At the prototype stage, the power electrics of the wheel hub motor was installed outside the stator during the test bench measurements. For later use, the power electronics will be integrated into the wheel hub motor.

The angular velocity of the glass prism of the derotator must be synchronized with the angular velocity of the rotating test object. This was done in the present case with an incremental encoder with 1024 increments. The mechanical connection of the incremental encoder to the measurement object must be torsionally rigid, otherwise the angular position of the test object cannot be detected correctly and the prism cannot be driven with the correct speed. The consequence would be a temporally variable rotation of the measurement object in relation to the defined measurement grid of the scanning vibrometer, whereby the location reference would no longer be correct. The derotator, laser scanning vibrometer and reference laser system is mounted on an adjustable base and must be precisely aligned with the axis of rotation of the target to obtain reliable results.

4 RESULTS

In this section, some results of the optical vibration analysis of the operating system are presented exemplarily. **FIGURE 4** shows the frequency response functions of the vibration amplitudes averaged over all points of the measurement grid for different load and speed variations. As expected, both higher loads and higher speeds lead to a more acoustically noticeable behavior. The typical tonal frequency content for electric machines can be clearly seen. In addition, it can be seen that the frequency range of 3.7 to 4 kHz has particularly high amplitudes.

FIGURE 5 shows an exemplary result for a stationary idling operating point. Here again the averaged frequency spectrum is shown. In addition, the most conspicuous vibration modes are illustrated. It is noticeable that both symmetrical and asymmetric vibration modes occur. Due to the symmetrical rotor design, only symmetrical operating vibration modes were expected, as observed in the measurements in the stationary system, **FIGURE 2**. The asymmetric modes are a clear indication of a non-symmetrical electrical excitation or a non-symmetric boundary condition.

For comparison, **FIGURE 6** shows the result for an operating point with comparable speed and a defined torque. In contrast to **FIGURE 5**, it shows no symmetrical vibration modes. As the elec-

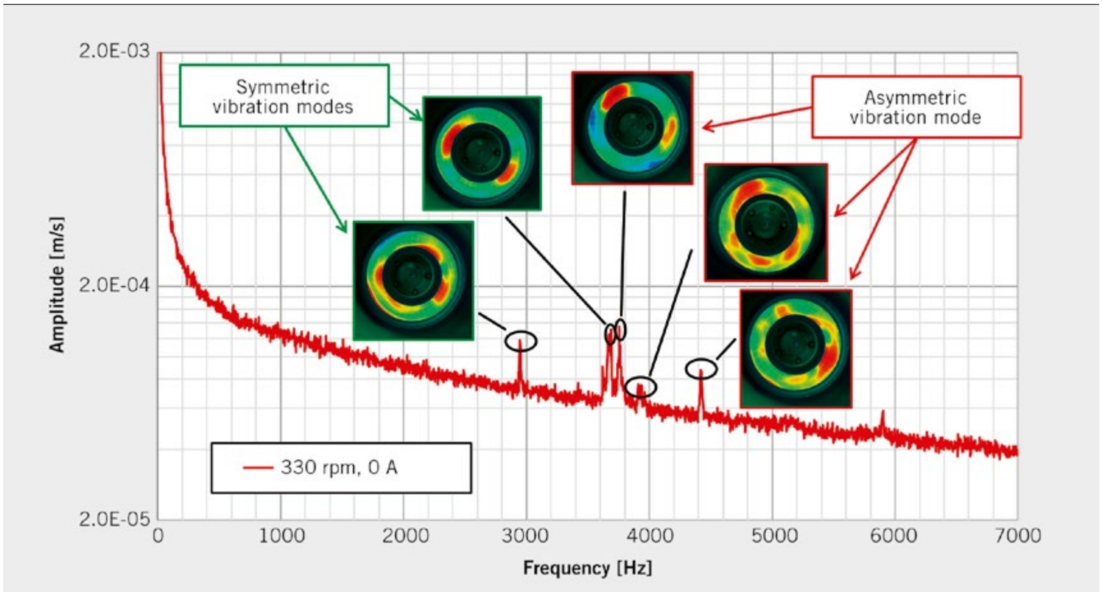

FIGURE 5 Spectrum of the vibration amplitudes averaged over the measurement grid with conspicuous vibration modes during idling (© OVGU)

trical excitation forces are significantly higher in the case of the operating point shown in **FIGURE 6**, it can be concluded that the asymmetrical vibration modes of the operating engine are probably caused by a spatially non-uniform electrical excitation.

Due to the optical measurement of the wheel hub motor during operation, possible explanations for an acoustically conspicuous behavior could be found in the present case. Further steps are still pending. The experimental operating vibration analysis is repeated as soon as the problems are solved. The results obtained should then serve as the first validation basis for the holistic simulation methodology.

5 SUMMARY AND OUTLOOK

In this article of the Otto von Guericke University Magdeburg, Germany, an optical vibration analysis of an innovative wheel hub motor, as a special case of an electric drive unit, during operation was presented. It has been shown that optical vibration measurement can be used beneficial for both vibroacoustic characterization and problem cause analysis. Currently, different prototypes are manufactured that differ significantly from the engine measured in this paper. The differences range from the basic design of the magnetic circuit (Hallbach array), through the design of the

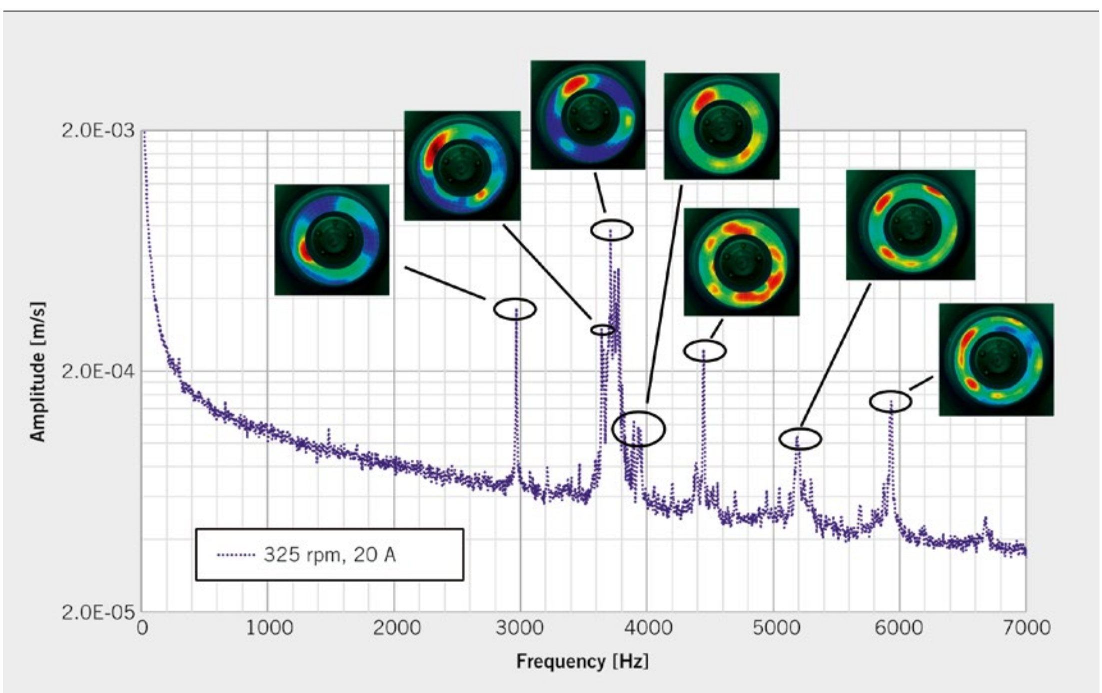

FIGURE 6 Spectrum of the vibration amplitudes averaged over the measurement grid with conspicuous vibration modes at a stationary operating point (© OVGU)

outer geometry, to the material selection of the main engine components (aluminum, aluminum foams, fiber reinforced composites). The subsequent experimental analysis of the new prototypes will provide a broad validation basis for holistic simulation methodology. The aim is to use the qualified methodology to develop a comprehensive understanding of the system and to carry out numerical optimizations in order to resolve the trade-offs between performance, lightweight design and acoustics in the future.

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THANKS

The presented work is part of the joint project "Kompetenzzentrum eMobility (KeM)," which is financially supported by the European Union through the European Funds for Regional Development (EFRE) as well as the German State of Saxony-Anhalt. This support is gratefully acknowledged.