Development of a Validation Environment for a Hub Motor used in Light Mobility Solutions

Johannes Kern[1], Kai Wolter[1], Katharina Bause[1], Sascha Ott[1]

[1]IPEK - Institut für Produktentwicklung am Karlsruher Institut für Technologie, Kaiserstr.10, 76131 Karlsruhe

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Abstract: The validation of technical systems is the central activity of product engineering. In order to validate a system, the requirements of users and other stakeholders must be compared continuously with the current state of the system. In the development of e-Bikes, which are becoming increasingly popular, a central gap is emerging: There is hardly any field data to compare the system behavior against realistic loads.

1 Introduction

In the powertrain development of passenger cars, according to state of the art, load spectra are used to evaluate the fatigue strength of the components based on stress time histories taken from the field. For bicycles with electric pedal assistance up to 45 km/h (s-pedelec), currently there is no or very little data available to develop representative load collectives. Therefore, within the scope of this work, a simulation model for the determination of load-time functions for a s-pedelec is developed. The model is capable of simulating different parameter configurations under various boundary conditions. In addition to the one-dimensional torsional oscillator chain developed for the analysis of torques and speeds, the model includes a multi-mass oscillator for the analysis of vibration excitations resulting from the unevenness of the road surface. A validation configuration was designed and built to impress the determined forces on a physical wheel hub motor. In addition to the torque fluctuations from the rider's pedaling and the resulting lateral forces from cornering, the configuration also reproduces the radial forces from road irregularities.

2 General

2.1 Basics of the s-pedelec

The type of e-bike considered in this article is the pedelec45, also called s-pedelec. S-pedelecs are permitted in Europe up to a speed of 45 km/h to assist the rider. However, the power provided by the electric motor for assistance is limited as well, as it may not exceed the rider's input power by a factor of four.

Pedelecs are usually equipped with a parallel hybrid drive and a sensor to detect pedaling speed, pedaling force or both. The power delivered during pedaling has a direct driving effect and is electrically assisted. The drive concepts of pedelecs can be differentiated by the location where the power currents converge (see Figure 1). There are three different concepts in market for e-Bikes: Front hub motor, middle motor and rear hub motor. In this article the rear hub motor is considered, in which the power flows from the rider into the motor via the gearbox, usually a derailleur, and is multiplied and supplied to the road. Regenerative braking is possible with rear hub motor concepts. [BOM2016]

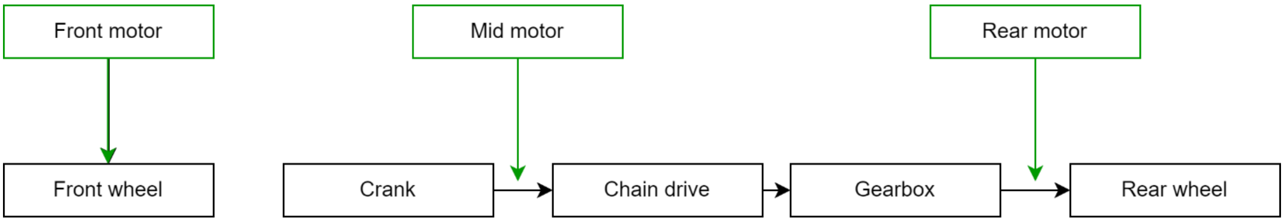

Figure 1 Points of attack of the three drive concepts on the mechanical drive train of a bicycle [BOM2016]

2.2 Modelling of the system

In the development of powertrain components, the main requirement is the service life of the components. The suitability of the developed system for the required service life must be proven within the scope of a suitable validation. This validation of drivetrain components can be carried out in general form through the application of the IPEK-XiL Framework [ALB2010]. This approach is taking into account the systems rider, vehicle and environment and is used in this work.

For the validation of powertrain components in passenger cars, the time functions for the influence of rider and environment, which are derived from field data recorded over many years, are used. However, for hub motors to be used in s-pedelecs, neither data nor standards on the loads that occur are available. In addition, physical prototypes of the entire system are hardly available. For this reason, there is a need for a validation environment with coupling systems that enables the coupling between virtual and physical domains. On the one hand, this shows the need to calculate the stress-time-function in the virtual domain, on the other hand, the need for a test configuration that allows to investigate the response of the physical component under load.

The stresses on s-pedelecs can be of a varied nature and there is no clear guideline indicating which stresses cause the main damage. The main types of damage to racing bikes and mountain bikes are used. For racing bikes, according to Bluemel and Senner [BLU2010], the human-induced torques and speeds that are introduced into the system via the crank are the main cause of damage to the components. On the other hand, according to Groß [GRO1997], however, environmentally induced stresses are largely responsible for the damage to the components. Due to this fact, it is assumed that both types of stress are relevant for the s-pedelec. To model the human-induced stresses, a torsional oscillator is set up, which calculates the stresses caused by the rider as well as those arising from the hub motor. The environmentally induced stresses are divided into general forces and forces from ground unevenness. The general forces include stresses from inertia forces as a result of cornering and weight. To determine the forces from unevenness, a multi-mass transducer is used analogous to the state of the art. First, however, the relevant contained subsystems and interactions must be determined.

The scope of the interactions to be mapped for the overall system is set up in the top-down topology of the IPEK-XiL, see Figure 2. The virtual-virtual coupling systems between the individual subsystems are not highlighted in this representation, as the entire modelling takes place in Simulink and therefore no data interfaces are necessary on the virtual level. For the interaction between the virtual and physical domain the power flow has to be taken in account as shown in Figure 1. In addition to the power flow, the rider system interacts directly with the hub motor by setting a support factor in case of rider fatigue or a wish for reaching the desired speed faster. The interactions of the environment-induced stresses contain the subsystems wheel and frame, the environment and the rider. The environment transmits the unevenness of the ground to the wheel subsystem, from there the force is transferred to the hub motor in the frame system. Since the wheel subsystem contains a model of the front and rear wheel of the s-pedelec, forces from the front wheel are also impressed on the frame. Finally, the rider system interacts with the model as a result of its mass and speed. On the basis of the interactions described above, three superordinate models can be derived: the environment model, the rider model and the s-pedelec model, which are described in the following sections.

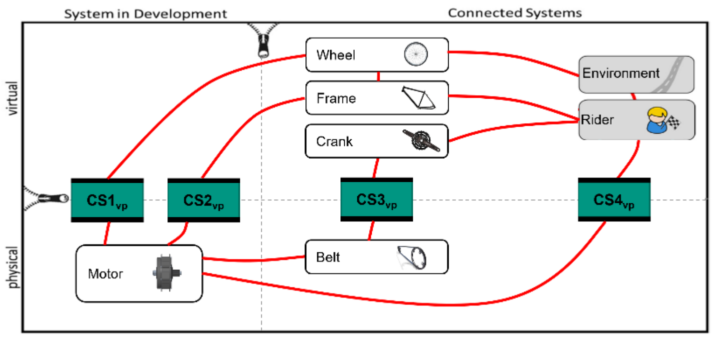

Figure 2 Validation configuration for an s-pedelec, shown as a model of the IPEK-XiL-Architecture based on Albers, Mandel et al. [ALB2018]

2.2.1 Modelling of the s-pedelec

In this section the modelling of the drive train as a torsional oscillator chain and a multi-mass oscillator system are described. In accordance with the current state of research on the modelling of vibrations and fatigue, the drive train of the s-pedelec is transformed into a torsional oscillator chain following the example of Dresig und Holzweißig [DRE2006]. For this purpose, the individual components are reduced to rotational inertia, spring stiffnesses and internal torques. Figure 3 shows the resulting model of the torsional vibration chain with the connections to the rider and environment models described in sections 0 and 2.2.3.

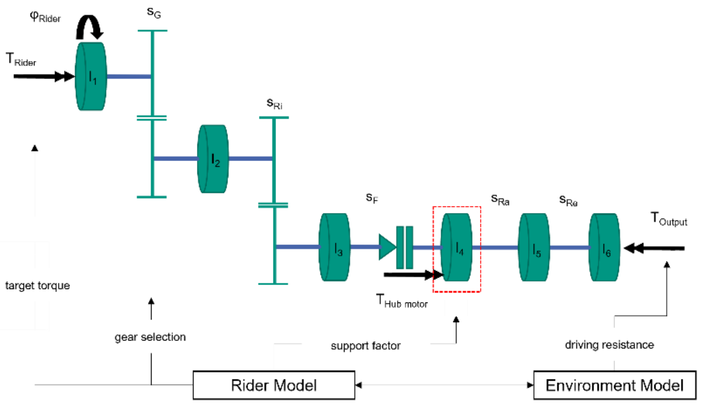

Figure 3 Illustration of the modelling of the s-pedelec as a torsional oscillator

The input torque is the torque established by the rider, due to human biomechanics, dependent on the pedaling crank angle. From there the power flows to the gearbox model. The gear ratio is set by the rider model according to the premise of reaching an optimal cadence. The belt system and the freewheel transfer the power to the hub motor. The additional torque of the hub motor is then applied in range of its operating area, in dependence of the support factor which is set by the rider model. To determine the level of support factor, the speed requirement as well as the rider's fatigue is taken into account. The torsional oscillator is completed with the rotational inertia of the rims, wheel and the residual mass of the s-pedelec. Lastly, the environmental model specifies the output torque as a function of the driving resistances and the wheel diameter.

The mass vibration system is intended to model the environmentally induced stresses. Three assumptions were made for the mass vibration system. Firstly, the wheels of the bicycle travel in the same track. It follows that the excitation front and rear are the same, but phases are shifted. Secondly, the influence of the wheel suspension as well as the handlebar structure is neglected. Thirdly, the rider follows the pitching vibrations of the body completely and can only move in the z-direction. The above assumptions result in the vibration compensation scheme shown in Figure 4 Vibration compensation system of a two-axle motor vehicle with single-track excitation according to

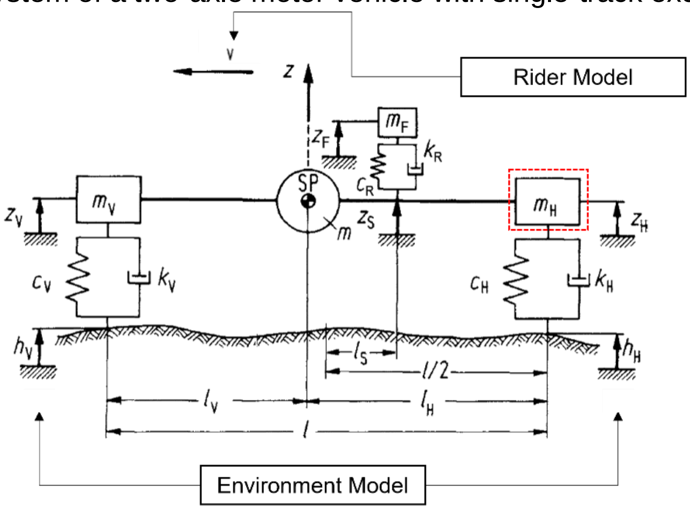

Figure 4 Vibration compensation system of a two-axle motor vehicle with single-track excitation according to Mitschke and Wallentowitz [MIS2014]

Mitschke and Wallentowitz [MIS2014].

Two single-mass systems are connected by a massless rod at the distance of the wheelbase, the mass m_H, marked red, is representing the hub motor in the rear wheel. The mass m_F reflects the rider and is shifted from the center of the wheelbase. Furthermore, the connection between the rider model and the mass vibration system is shown, the rider model sets the desired speed of the system and thus influences the delay between the excitation of the front and rear wheel.

2.2.2 Modelling of the environment

According to the interactions described above, one aim of the environment modelling is to predict the force acting on the tire, which is composed of the driving resistances. As a basis for calculating the driving resistances the state-of-the-art equations are used [GRE2002]. The calculation of driving resistances is based on the change of position of the wheels. While moving, curve radii can be determined which are the basis of acting lateral acceleration on the wheel due centrifugal forces. However, the curve radius alone is not sufficient to make a statement about the existing lateral force of the system, since a cyclist usually leans into the curve and thus part of the lateral force is absorbed. For the calculation of the roll angle the assumption is made that the rider is always in optimum equilibrium between centrifugal force and gravitational force. Additional to the lateral force, ground unevenness acts through the frame and wheel on the hub motor. The unevenness of the

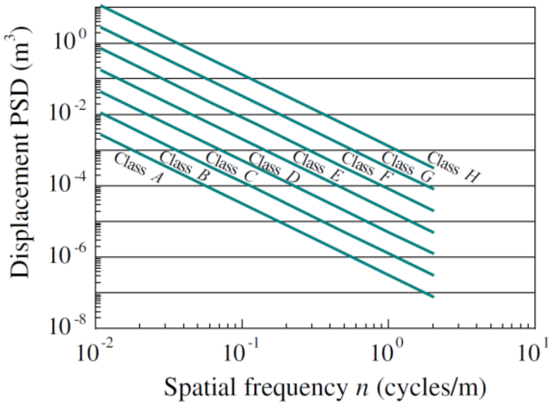

Figure 5 Classification of road profiles according to ISO8608 [ISO2016]

ground can be represented by different methods, one approach being a constant sinusoidal oscillation. However, this is an inadequate modeling of the real occurring ground unevenness. For this reason, road profiles are artificially generated on the base of road profiles classified by the ISO8608 [ISO2016]. The ISO8608 classifies road profiles in classes from A-H with the help of stochastic spectral densities resulting from roughness measurements of real road profiles. The spectral densities are plotted in Figure 5 Classification of road profiles according to ISO8608 against the path angular frequency, where class A corresponds to a very good road with the lowest spectral density and class H corresponds to the road with the highest and thus the worst quality class. Using the spectral densities, an artificial roughness profile can be created with equations according to Agostinacchio, Ciampa and Olita [AGO2014]. In addition to the specification of the class, there is the interface to enter two classes of kerbs with an equally distributed probability of occurrence over the length of the road section. The specification of the kerb height is integrated via a normal distribution around a mean value for typical kerb heights.

2.2.3 Modelling of the rider

The rider as a control element of the s-pedelec has a great influence on the overall system. However, the construction of an all-encompassing rider model is costly due to the human behavior and its states, and is therefore limited to the following features. From the point of view of stress and resulting damage to the components, the power output of the rider, which is limited in time, as well as the relationship between torque and cadence, are the most relevant aspects of the rider. In addition, the human anatomy has an influence on the generation of the torque which must be taken into account. Another property that the rider model must represent is the control of the support factor of the hub motor. In the context of this work, the control of the support factor is related to fatigue following the research of Ebenealipour and the speed wish [EBN2020]. It is assumed that with increasing fatigue the rider increases the assistance factor and thus the torque of the hub motor. In addition, the rider model is supposed to determine the drive torque and braking torque and their change over time.

2.3 Simulation

The following section describes the simulation results of the individual submodels, torsional vibration chain, mass oscillator system and the general forces. In addition to the permanent weight forces acting on the axle of the hub motor due to the mass of the s-pedelec and the rider, lateral forces arise from cornering. Based on the curve travel for the curve radii shown in Figure 6 (a), the lateral forces shown in Figure 6 (b) can be determined. It can be seen that with rapid temporal the lateral forces increase as a result of the acceleration.

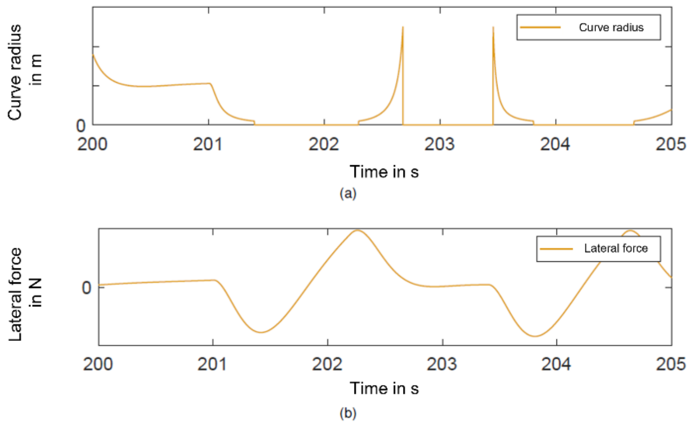

Figure 6 (a) Curve radii (b) Lateral forces

For an exemplary simulation the unevenness profile over time shown in Figure 7 is to be traversed at a speed of 1 m/s. The excitation of the front wheel is shown in yellow and the time-delayed excitation of the rear wheel in blue. The total height difference of the curves amounts to 200 mm whereby small fluctuations in the range of 10 mm occur permanently as well as rare larger fluctuations of up to 50 mm. The determined accelerations of the multi-mass oscillator in connection with the mass via Newton's law are shown in Figure 7 (b) as a force in Newton over time. The radial forces on the rear wheel are in the range of ±500 N.

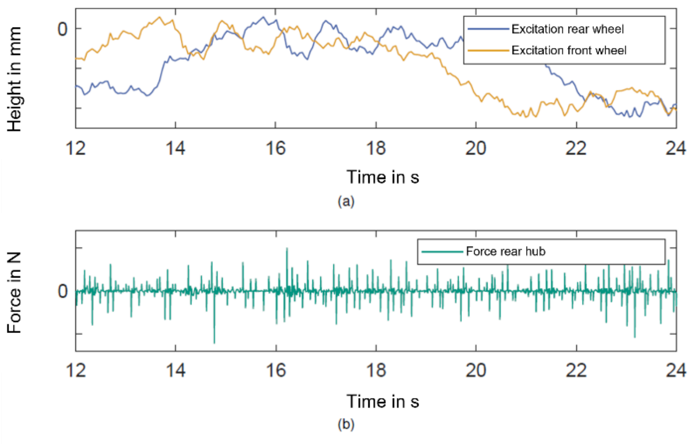

Figure 7 (a) Excitation front and rear wheel (b) Stress-time function

For a flat example route in the city with an average number of start-stop operations, the result of the simulation model is shown. Figure 8 shows the target speed and the actual speed of the s-pedelec over time. The course of the target speed curve represents start-stop processes with subsequent acceleration to constant speeds. The corresponding actual speed curve follows the course of the target speed curve except for minor deviations resulting from the inertias of the model. The hub motor torque and gearbox torque, which is related to the resistance torque, is shown in Figure 8 (b).

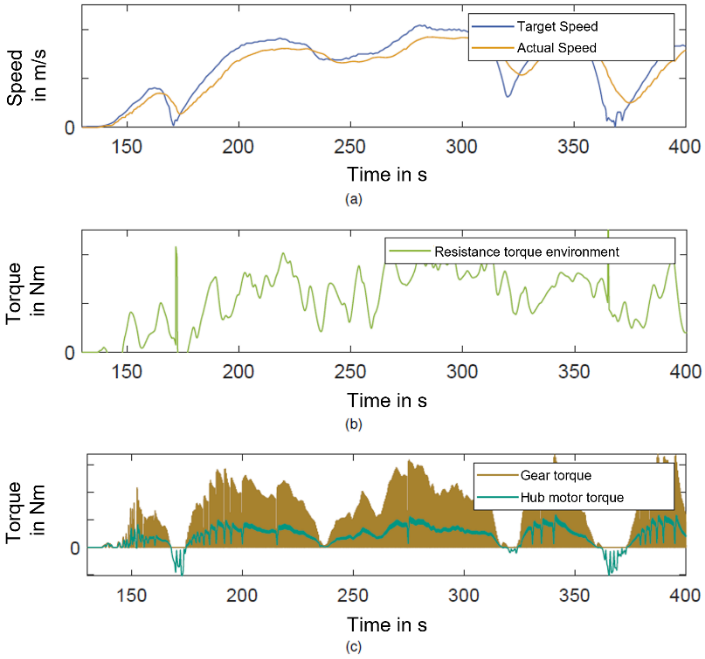

Figure 8 (a) Target and actual speed (b) Resistance torque (c) Stress-time function

The course of the gear torque is shown in brown, which is influenced by the rider's unsteady pedaling and therefore varies between 0 and maximum torque. In green the hub motor torque is shown, which is directly linked to the gearbox torque via the support factor.

Afterwards with the stress time functions it is possible to determine load collectives (see Figure 9) or test the system under real load conditions.

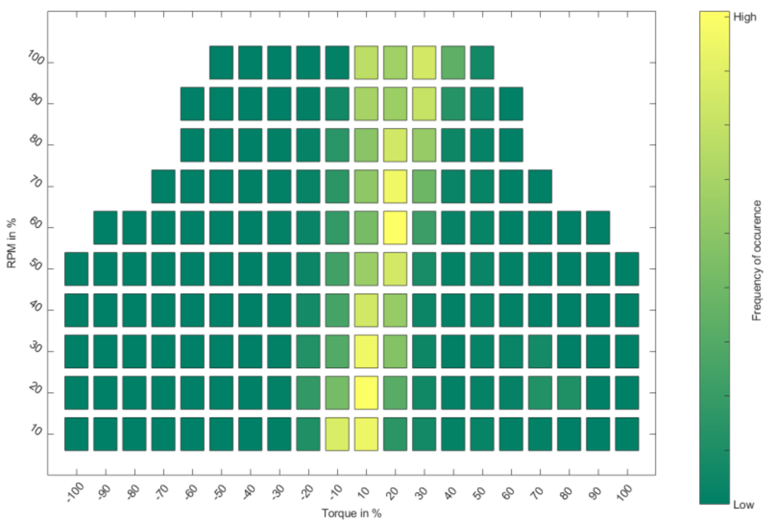

Figure 9 Load Collective derived of the stress-time function

3 Testbench configuration

In the previous chapter, the simulation of stress-time functions for the hub motor of an s-pedelec was developed. In order to carry out a complete validation of the physical prototype and thus demonstrate the suitability of the system, a testbench configuration is necessary. On the one hand, this configuration must be capable of applying the calculated forces, and on the other hand, it must be able to imprint them as they would occur in reality. The coupling systems necessary are shown in Figure 2. The tire of the s-pedelec transmits lateral forces from cornering and the torque from the environment to the hub motor. In addition, there is a coupling between the frame and the hub motor, in which the forces from the acceleration of the masses, due to ground unevenness, are transmitted. To impress the forces, two shakers are used which act on the hub motor via a roller bearing guide. The required torques are impressed on the hub motor via electric motors of the test bench and a belt system. Figure 10 shows a test configuration that’s capable to impress the described forces on the hub motor. This test bench has been realized and used for the validation of wheel hub motors for s-pedelecs at the IPEK - Institute of Product Engineering at the Karlsruhe Institute of Technology.

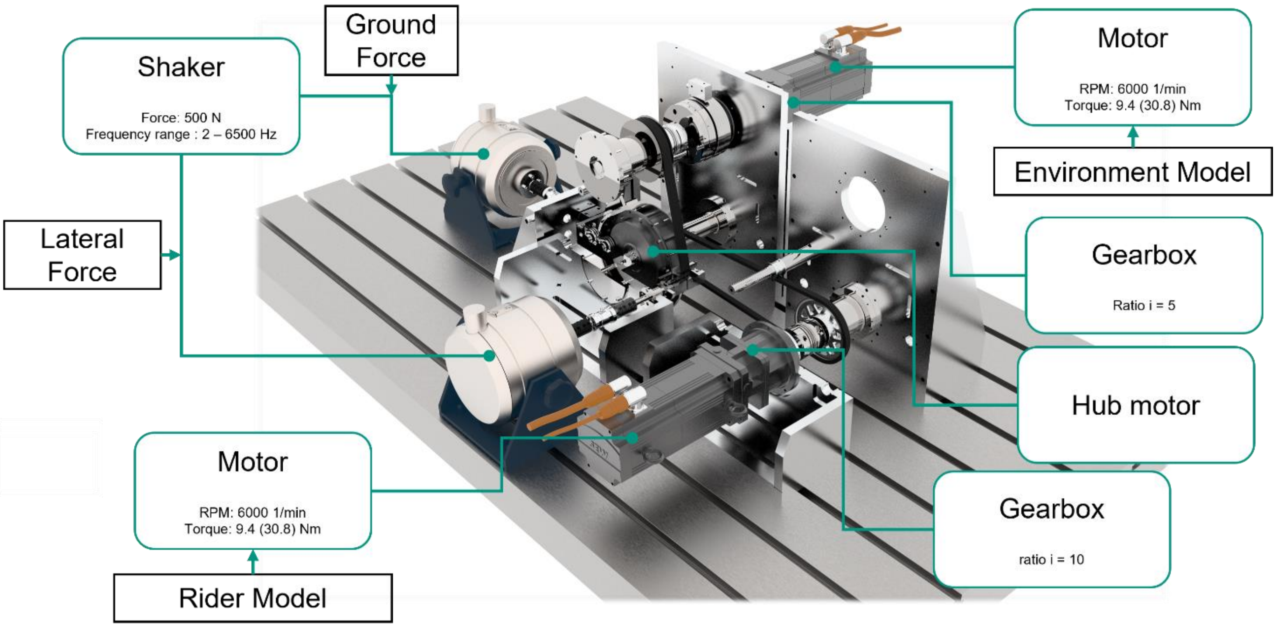

Figure 10 validation configuration on the Mini-HIL2

4 Summary

A validation environment for wheel hub motors used in s-pedelecs including a rider model, an environment model and a model for the s-pedelec itself has been presented in this work. In the environment model, the driving resistances and the cornering were modelled. The developed rider model represents the characteristics of the cyclist. This includes the specification of a support factor that is related to the cyclist's power output decreasing with fatigue and target speed. In addition, a control of the cyclist's desired torque was implemented. In the s-pedelec model, there are two sub-models that determine the relevant stresses. On the one hand, for torque and speed via a torsional oscillator chain and, on the other hand, a mass oscillator system that determines the accelerations at the hub motor from the specified ground unevenness. From this point, it is then possible to create load spectra that can be used to stress individual components. The developed validation environment has been realized and used for the validation of wheel hub motors.

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