Determination and systematization of load situations for eBike drive units as basis for their design and optimization

Marco Steck, PhD Student at TU Ilmenau, Product and Systems Engineering Group, Bosch eBike Systems, 72770 Reutlingen, Germany, marco.steck2@de.bosch.com
Prof. Dr. Stephan Husung, TU Ilmenau, Product and Systems Engineering Group, 98693 Ilmenau, Germany, stephan.husung@tu-ilmenau.de
Julien Hassler, Bosch eBike Systems, 72770 Reutlingen, Germany, julien.hassler@de.bosch.com

Abstract

Currently, eBikes are becoming increasingly popular, which means that the pressure for better drive units is constantly growing. Compared to the first models, the dimensions and weight of the drive units have been significantly reduced despite increased performance. For further optimization of the drive unit, precise knowledge of the real field load is essential. To determine this, pedal force measurements were carried out in common riding situations in order to transfer these into a bicycle-specific load collective. The analysis of the pedal force measurements shows not only clear differences between the individual riding situations but also to the existing normative requirements for eBike drive units, which are discussed in this paper.

1 Introduction

Today's eBike drive units are viewed as standard components in the eyes of the bicycle manufacturers. Therefore, they are mounted to all types of bikes and frame geometries and must withstand a wide range of loads resulting from different riders, their interests, and their driving behaviour. This results in very diverse and complex load spectra for which the drive unit and its connection to the frame interface must be developed. To enable a more optimized (according to load, mass, efficiency) design it is crucial to have a deep understanding of the wide range of possible field loads, which are not known in detail yet. Current designs are based on normative specifications that have been adopted from conventional, purely mechanical bicycles [1,2]. Therefore, the aim of this investigation is to determine a representative load collective for the drive unit related to different bicycle types. This paper presents a methodology for the determination of these load collectives, the first results of pedal force measurements, their evaluation and the first conclusions that could be drawn.

2 Load situations of the drive unit

For a systematic classification the dynamic forces acting on the drive unit can be divided into loads that are introduced by the driver, the frame, and the engine itself. On top of that static loads due to mounting and production processes or preloading forces must be added. Depending on the actual driving situation and the mounting position different combinations and variations of these loads cause varying stress and strain conditions. This means that different proportions of bending, torsional and tensile or compressive loads can occur within the housing.

In dynamic load situations especially the interaction of the force components of both pedals and their combination with the chain force have a major influence on the dominant load type. Because of that it is crucial to determine the three-dimensional force components of both pedals for common driving manoeuvres and for the entire crank rotation. Regarding the reliability of the drive unit especially the maximum pedal forces must be characterized to prevent early fatigue.

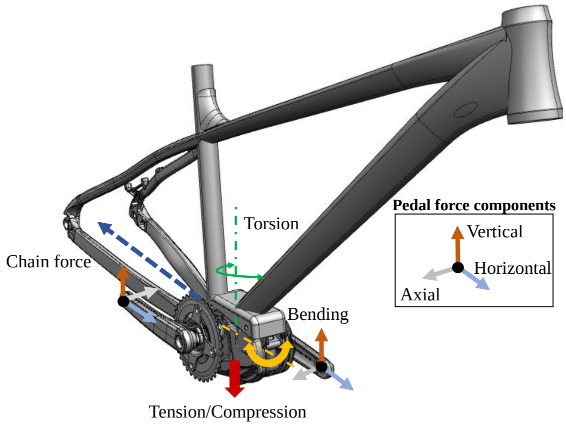

Fig. 1. External loads acting on the drive unit

3 State of the art

Previous investigations of pedal forces were mostly performed to study the biomechanical motion of cyclists or in the context of sports medicine questions [3-5]. Due to the different scientific approaches and motivation, these measurements were carried out for rides under constant power and at high cadences, which makes it impossible to draw conclusions about maximum pedal forces and their orientations. In addition to that, many measurements as for example in [3-4] only considered the force components in the vertical and horizontal direction.

With regard to a specific component design of the frame Soden et. al investigated the maximum pedal forces for climbing and starting or accelerating situations and estimated the resulting loads on the handlebar. However, a derivation of the cartesian orientations of the pedal force is also not possible here either [3]. The investigations by Mimmi et. al as well as Stone and Hull considered the axial component of the pedal force and thus formed a force vector in all three spatial directions. Yet, they too do not allow any conclusions about the maximum loads due to measurements at constant speeds and at higher cadences [4,5].

The current normative requirements for the mechanical component safety of the eBike drive unit consist of two tests in which the complex load case of a bicycle drive is reduced to a one-dimensional, exclusively vertically acting pedal force. In a universally valid test, various bicycle types must withstand cyclically forces of 1300-1800 N alternating the pedals. This test must be performed in a suitable setup and with the chain fixed (see Fig. 2). Besides that, there are no further requirements on crank length or the stiffness of the mounting bracket. The force for the opposite side of the chainring can be applied either pulling or pushing and at a crank angle of 45° to the upper or lower dead centre. In the second test which is compulsory for "off-road" bicycles, a cyclic force is applied without a chain and with one pedal fixed. For both tests the number of cycles which the drive unit must pass without damage varies from 50 000 - 100 000 cycles depending on the type of bicycle and the test variant. [1,2]

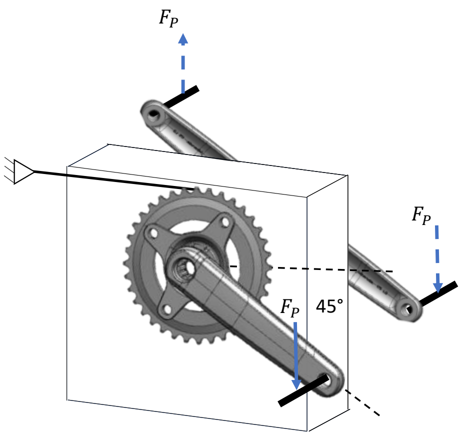

Fig. 2. A schematic representation of the normative load case for universal cycling. Based on [1,2]

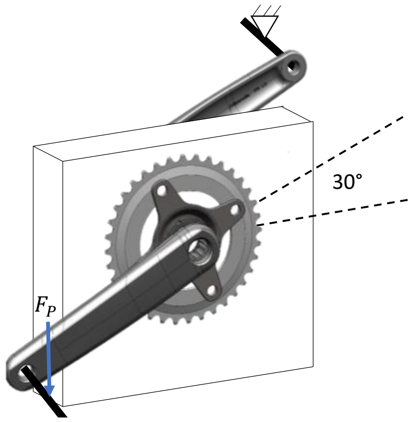

Fig. 2. A schematic representation of the normative load case for downhill situations. Based on [1,2]

For the assessment of these normative requirements, it must be mentioned that normal bike users do not bring exclusively vertical orientated forces to their pedals. On the one hand, this can be derived from the measurements which were mentioned earlier. On the other hand, this seems just logical considering that the drivers should be eager to have the highest possible tangential load application to increase their pedal efficiency. Likewise, an exclusively vertical pedal load cannot be assumed for off-road situations due to the different centre of gravity positions and the body inertia of the driver. At this point, the measurement by Soden and Adeyefa should be mentioned, in which a resulting pedal force of up to 2000 N was determined with a ratio of the pedal force to the body mass of the rider in a factor of 2.4-3.0 [3]. Regarding the eBike, it must be noted that the normative test does not consider the actual effect of the eBike motor and its ability to increase the chain forces.

Looking at the actual load situation of the component during the normative test, it can be seen that at a horizontal mounting angle, the one-dimensional load in a specific crank angle brings a constant share of the bending and torsional stress (test 1), or a constant tension/compression load (test 2). This of course always depends on the mounting angle of the drive unit. However, in real cycling the whole crank rotation is indispensable. Therefore, even if only vertical pedal forces are assumed, there will be a varying amount of the chain force and thus different proportions of the types of load to be resisted. Hence it is questionable whether the normative load case can be seen as a universal and sufficiently accurate substitute load for ensuring the component safety of an eBike drive unit. These doubts are reinforced by the fact that the increased chain force and consequently the torsional load due to the motor assistance of the eBike drive are completely neglected.

4 Methodical approach

It is assumable that there are notable differences for real pedal forces depending on the actual cycling situation or bike setup. If this is taken into account for a load-specific design, it is absolutely necessary to measure different load situations and to combine them to a bike specific load collective. For the selection of the relevant driving situations influencing parameters were defined that could either effect the amount of the resulting pedal force and their orientation or change the total load situation. In this study, the following parameters and driving situations were defined and systematically varied during the measurement:

- **Body position:** sitting, standing
- **Pedal type:** clipless pedals, classic pedals
- **Motor support**: with motor support/without motor support
- **Gradient:** Ride on the level/on the slope

In addition to these parameters for regular cycling, downhill rides were also to be evaluated. Hence, pedal forces were measured for trails with varying degrees of difficulty and gradients to examine the real pedal forces in the terrain. Furthermore, measurements were taken for jumps at different heights.

The classification of measurements should then provide the basis for a load collective that can be determined for specific types of bicycles. This calculation shall be performed starting from a given or estimated ratio of the measured cycling situations regarding a required mileage and a given engine and bike setup.

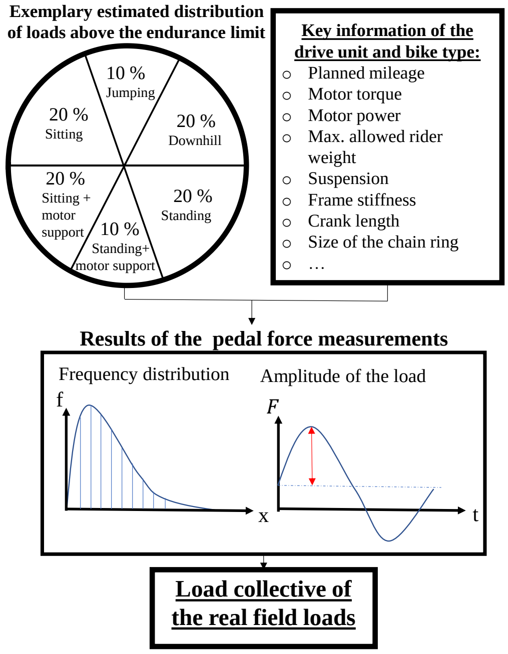

Fig. 4. Process of the calculation of a bicycle-specific load collective

Given that the peak loads are particularly relevant from the point of view of fatigue strength calculation, the focus for the pedal forces measurements was set for the starting and acceleration situations where the maximum pedal forces can be expected. This is also based on the assumption that pedals forces occurring from cycling at constant speeds or at higher cadences must be settled in the region of infinite life regarding the SN-curve of the drive unit.

5 Measurements

5.1 Measurement system

To determine the pedal forces in all spatial directions, both cranks of a full-suspension mountain bike with 140 mm suspension were fitted with six strain gauges to determine the tangential, radial and axial force components. To correct the offset of the measured stress due to the crank geometry, lateral contraction or slightly incorrect orientations of the strain gauges correction factors were determined in an empirical approach. This calibration was performed for a specific loading at the centre of the pedal. The correction factors were then taken into account for the stress calculation. For further information on the measurement system, please refer to [6], where a similar measurement system is described in detail.

The angular position of the crank, which is required for the calculation of the resulting forces on the drive unit, is measured by an angle sensor on the crankshaft. This data and further signals from the drive unit as for example the motor torque, rotation speed, bike velocity and the drive unit temperature were extracted in kHz frequency and stored over time.

5.2 Results

All test rides show relevant components of the pedal forces in all three cartesian directions, regardless of the choice of parameters. It must be emphasized that despite a motor support of 85 Nm, a comparable and slightly lower pedal force occurs (see Fig. 5). Taking a look at the amplitude of the resulting force component reveals maximum values just below the normative load at 1400 -1600 N. The factor between the measured pedal force and the rider's weight varies between 1.6 and 1.9 in the measurements. Compared to [3], the lower pedal forces in relation to the rider's weight in this measurement are presumable due to the suspension of the measuring bicycle.

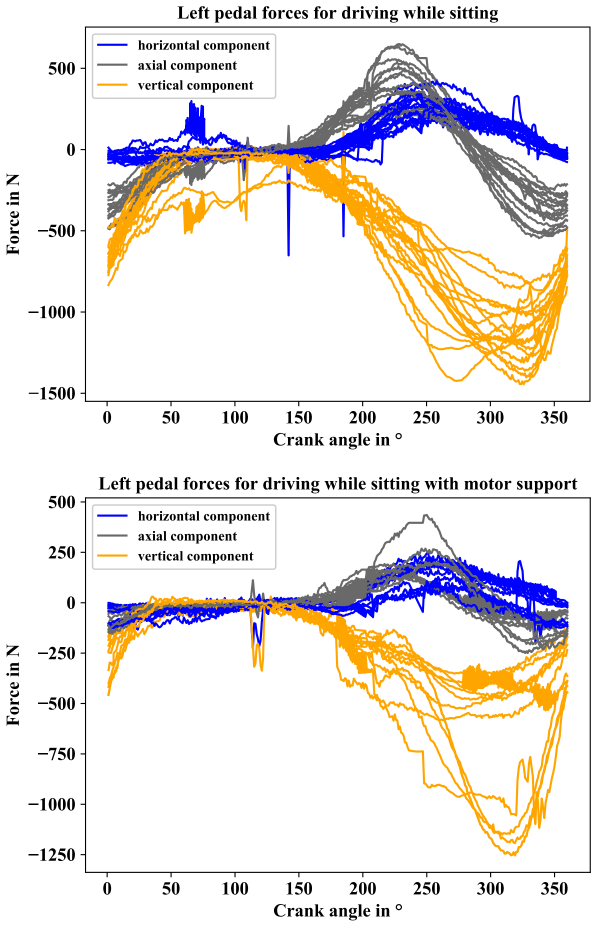

Fig. 5. Force components of standing cycling with and without motor support plotted over the crank angel (crank angle starts at 0°= right pedal in upper dead centre position)

For the axial force component, a characteristic curve is observed over all cycling situations. In each case it reaches its peak in the area of the two dead centres with a change in direction between them. Similar results were found in the measurements of [5] for lower pedal forces at a higher cadence. Obviously, an increased amplitude of the axial force component can be found for the standing position due to the higher inclination of the bicycle and the impact of the whole driver's mass.

In comparison to that, the components of the horizontal and vertical forces showed clear discrepancies for the individual riding situations. Further deviations could be determined for the crank angle at which the highest resulting pedal force and the highest chain force are achieved.

Rides in standing position tend to have horizontal force components against the driving direction, while rides in a seated position showed more force components in the direction of travel, which can be explained by the shift of the body's centre of gravity in relation to the crankshaft. Consequently, there are different combinations of pedal forces in relation to the resulting chain force.

Similarly, the influence of clipless pedals resulted in an increasingly tangential pedalling force and thus increased force components in the horizontal direction and in the chain force. Likewise, click pedals also recorded relevant force components beyond the bottom dead centre because of the possible uplift of the pedal. For a more detailed and reliable statement on the amplitude of the pedal forces for clipless pedals, further measurements are required. The following figures show the distribution of the pedal forces in a radial and vectorial representation and illustrate the differences between the cycling situations in a graphic way.

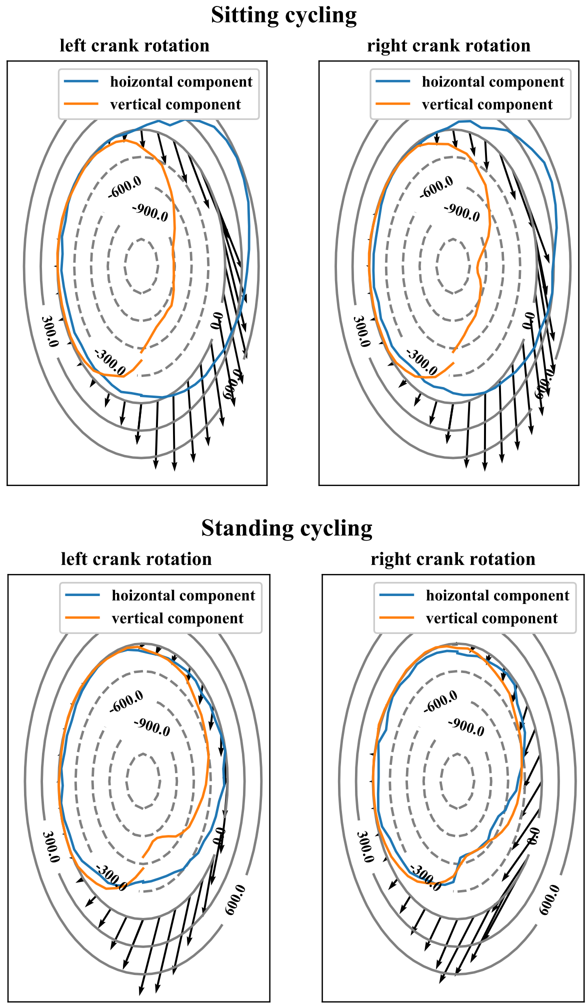

Fig. 6. Illustration of exemplary pedal forces over a whole crank rotation (sitting and standing cycling situation)

When analysing the force distributions between the right and left side of the pedal, an asymmetry can be observed between both legs in terms of force distribution. This is consistent with the studies by Bani et. al. and W. Smak et. al. who investigated a rider-dependent asymmetry for the effectiveness of the cycling motion between the dominant and non-dominant leg of 5-30 % [7,8].

Regarding the extreme load situations of the drive unit, force distributions such as those shown in Fig. 7 are especially impressive.

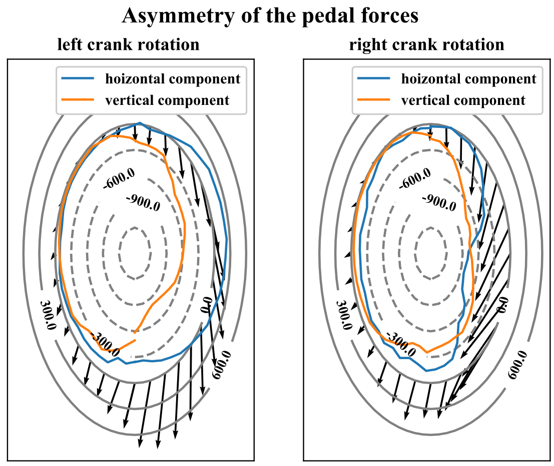

Fig. 7. Exemplary pedal forces over a whole crank rotation showing possible asymmetry

The measurements of the downhill rides also did not reveal any exclusively vertically directed forces. Two typical patterns could be found for the cushioning of bumps or jumps. For both pedal sides, either opposite directions in the horizontal force component or force distribution that pushes both pedals against the driving direction could be found.

In the case of the opposite force directions, starting from an almost horizontal pedal position, the front pedal is loaded in the direction of travel and the rear pedal is loaded against the direction of travel. The horizontally acting forces determined in this way are up to 600 - 800 N per pedal. In the vertical direction, forces of 1500 N per pedal were determined for a rider weight of 75 kg. It was also possible to measure less dominant values of the axial force component.

For well-founded statements about the frequency distribution and dispersion of the pedal forces and their asymmetries, further measurements must be performed on a larger number of candidates.

6 Evaluation and discussion

The real measured pedal forces reveal a clearly different load situation in the different driving situations. Both the motor assistance and the pedal forces in the horizontal and axial directions have a variable effect on the applied type of load situation. In particular, the horizontally acting force components result in a strong increase or decrease of the torsional load depending on their direction. In their case, the lower amplitude compared to the chain force is compensated by the increased lever, which is related to the pedal forces. The influence of the axial force component also contributes to different types of load depending on the crank angle. It also provides a new dimension for the load situation on the crankshaft, bearings and gears. In addition, no constant proportion of the vertical force component can be assumed. Due to the rider-dependent asymmetry of the pedalling forces, significantly different load situations can occur even over one pedalling cycle.

Based on these measurements, it can be stated from a conservative point of view that the amplitude of the resulting measured pedal forces is comparable to the amount of the normative test. However, due to the exclusively vertical application of force, an excessive bending load is applied to the drive unit at the normative load case. In return, however, the torsional load in particular is significantly underestimated. This observation can also be transferred to the downhill load test. Regarding the amplitude, it is questionable whether this result can also be transferred to potentially increased force amplitudes on non-suspended bicycles. In addition, a further increase in pedal forces must be expected with higher rider weights. This correlation has already been proven in [9].

Due to the asymmetry of the chain force and the wide range of possible pedal forces, a multiaxial and non-proportional load case can be assumed over the course of one crank revolution. This complex load case and the equally complex housing geometry of the eBike drive unit prevents the definition of a clear angular position and load at which the highest amplitude and damage can be expected. Likewise, the superposition of different load situations - which is not taken into account in the normative load case - must be examined in more detail.

In this case, a correct evaluation of the effective damage of a pedal cycle must be carried out using a suitable, multi-axial damage model. One possible calculation method would be the critical planes method paired with a suitable damage criterion. More details on such methods can be found, for example, in [10-12]. Such a calculation method would also allow to compare the different loading situations among each other and in combination, as the individual loads are correctly evaluated by different principal stress and principal shear stress directions based on the cutting planes.

For both normative load cases, it should be noted that the real pedalling loads of eBikes have significant differences in their orientation and cannot be considered as an exclusively vertical force. In combination with the reduction of the entire crank revolution to a specific crank position and load and the neglection of the motor effect, it is unclear whether these normative requirements are appropriate as a safety requirement of an eBike drive unit.

For further investigations it is inevitable to measure the pedal forces of more riders to consolidate the statistical data. In addition, the same measurements must be made for non-suspended bikes to proof the assumption of potentially higher pedal loads. Furthermore, the individual real load situations will be assessed using a multi-axial damage model. The focus of these following investigations will be on the comparability of the individual driving situations with each other and in relation to the existing normative standard. In further investigations, the influence of forces induced by the frame and different stiffnesses at the frame interface should be considered. At an advanced stage, the production-related variation of the pretensioning and assembly forces as well as mechanical and thermal loads caused by the engine should be considered in the calculation in order to reveal further potential for an optimized drive unit.

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