Determination and characterization of the influences of the bike frame on eBike drive units as the basis for their design and optimization

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Abstract

In this paper, the influence of the bike frame on the loading of the eBike drive unit is determined. For this purpose, relevant load cases and boundary conditions are derived based on the existing norms for the individual consideration of the frame and the drive. In this context, external loads on the frame and the forces acting on the engine must be taken into account. The following simulative study shows that the bike frame has an enormous and load-dependent influence on the load situation of the frame interface and the stresses within the housing of the drive unit. In general, this influence can be explained by the stiffness of the frame construction. Altogether, these results show that the design of the eBike drive unit according to its current standard requirements is not sufficient to cover these enormous influences of the bike frame.

1 Introduction

Today eBike drive units are developed and build for every bike type, frame and cycling situation. Due to the novelty of the product class eBike there is just a limited state of the art, considering the normative requirements. Thereby, only individual aspects of the components used in the eBike are specified [1,2].

Especially for eBike middle engines, which replace the usual crankshaft and are mounted at a suitable frame interface, many influencing factors arise through the entire bike system. For the design and dimensioning of an optimal eBike drive unit, it is crucial to examine the chain of effects in the overall system in more detail to consider the interactions between the drive unit and the entire bike. In this context, the focus is primarily on the optimized design of the drive unit regarding durability. As the drive unit is directly connected to the bike frame, it can be assumed that the frame has a relevant influence on the load situation of the drive unit and especially its housing.

The aim of this study is hence to characterize the influences of different bike frames on the loading of the drive unit housing. Therefore, it is necessary to study these effects for different load types and driving situations, in accordance to already defined load collectives of the rider and the existing normative requirements for frame. However, the loading and design of the actual bike frame by dynamic or static loads are not considered in this study. These are already covered in existing studies on the bike frame and its optimisation for static and dynamic loads [3,4,5].

2 State of the art

In the case of the eBike middle engines, the drive unit is installed as a standard component at a suitable interface and mechanically coupled to the frame (in the present case: bolted connection). This integration of the drive unit into the frame implies that loads of the drive unit are transmitted to the frame and therefore are dependent on the frame stiffness and the boundary conditions of the overall system. Likewise, loads on the frame are transmitted to the drive unit via the interface.

Despite this connection between the eBike subsystems, current norm specifications only prescribe loads and tests for a separate consideration of the frame and the drive unit. With regard to the bike frame, several load situations are defined, such as forces on the saddle, pedalling forces and loads on the wheel axis due to uneven surfaces or braking manoeuvres [2]. Simplified boundary conditions are also given for the bearing of the frame on the wheel axles. These

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can be derived from the counter-torque of the rider on the handlebars and the two contact points of the tires with the ground (see Fig. 1.). Regarding these specified loads, the comparison with the measurements in [6] shows that the assumptions for loads during braking and when riding over uneven surfaces are properly specified. Investigations of the real pedal forces in different riding situations revealed complex multi-axial load collectives, which are not covered by the simplified standard load case of a fixed pedal and chain force [7].

However, for the frame independent norm test of the drive unit and its chain and pedal loads, a bolted connection with a rigid body is specified and the reaction forces of the chain are absorbed by a separate fixation [1]. As a result of this separate consideration, the respective stiffnesses of the bike frame as well as the real boundary conditions of the bike during the pedalling load are neglected. Instead, a fixed boundary condition with constant stiffnesses at each attachment point is obtained. Furthermore, loads acting on the frames that are considered for the normative durability test of the frame are not examined with respect to the drive unit as an embedded sub-system in the frame.

By transferring these separate norm requirements to a combined consideration of the frame and the drive unit, the influences of the frame on the drive unit can be shown for loads acting on the engine as well as for loads applied to the frame. In this case, the two load situations and their specific boundary conditions shown in Figure 1 can be defined for the combined system.

In this context, the following research questions arise from the perspective of the drive unit design:

- Does the bike frame and the real boundary conditions have to be taken into account for the design of the drive unit?
- What influence does the different frame types have on the load situation of the drive unit?
- Are relevant loads transmitted through the frame to the drive unit?
- Which influence does the variable multiaxial loading of the real pedal load have on the frame connection?

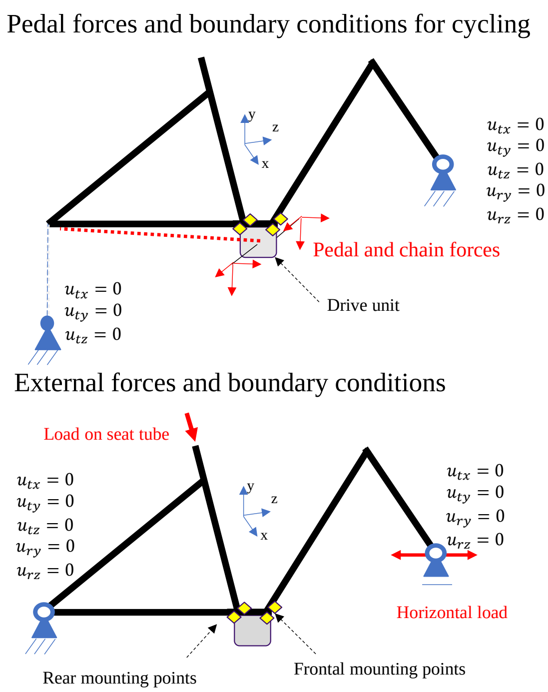

Figure 1 Load Cases and boundary conditions for the combined consideration of an eBike frame and drive unit

3 Simulative study

3.1 Modelling the frame

In order to identify and characterize the influence of the frame on the engine, FEM simulations of the two load scenarios described in Figure 1 are carried out with different frame types and geometries. To determine the specific influence of different bike and frame types, examples of the frame types shown in Figure 2 are varied in the simulations.

When selecting the frames, special emphasis was placed on having a similar mounting angle of the drive unit to avoid the results being biased by this parameter. For the same reason, only aluminium frames were used to ensure comparable material parameters.

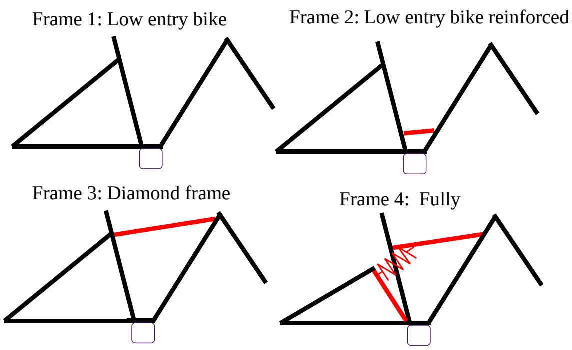

Figure 2 Frame types for the investigation

For the modelling of the bike frames, real CAD geometries of real bike frames are used. To minimize the computational effort, frame geometries were transformed into an order reduced sub-model using the Guyan reduction [8]. Since the focus of the investigation is on the drive unit and not on the frame, the number of degrees of freedom considered for the frame and thus the computation time can be significantly reduced. As the remaining nodes, the mounting points of the drive unit, the seat post, the axle of the front wheel and the contact point of the rear wheel with the ground are selected to represent the boundary conditions and loads on the frame. In case of the suspended fully frame, a separate condensation was carried out for both parts of the frame and the retained nodes were extended by the anchor points of the damper.

Due to the static linear elastic simulation and relatively low deformation of the frame during loading, this model simplification can be considered permissible [9]. Additionally, a comparison with an unreduced model was calculated and no relevant deviations were found.

3.2 Simulation of drive unit loads with frame

One objective of this study is to characterize the frame-dependent change of load for the drive unit at common loadings on the drive shaft. Since real measurements of the pedal and chain forces have resulted in complex multi-axial load spectra, the investigation will examine and combine several load types to capture the influence of the frame over the real load spectrum.

Therefore, load points were defined in a DOE representing basic pedal and chain forces combinations from elementary driving situations. These were subsequently simulated with setup 1 from Fig. 1 for all frame types. Here, it is important that the chain force at the drive shaft of the motor as well as its reaction force at the rear axle of the bike were considered. For comparison, a model was also calculated for a drive unit mounted on a uniformly stiff boundary condition according to the normative requirement for the drive unit.

An evaluation of these calculations was performed using the vertical and horizontal bolt transverse forces at the interface of the bike frame. Figure 3, 4 and table 1 show the defined load points and the results of the horizontal and vertical transverse bolt forces. These were analysed separately to correctly evaluate the orientation of resulting forces.

Table 1 DOE for the loads on the drive unit

Number of the loadcase	Vertical right pedal force [N]	Horizontal right pedal force [N]	Horizontal left pedal force [N]	Vertical left pedal force [N]	Chain force [N]
1	-1800	0	0	0	0
2	0	0	0	-1800	0
3	-1800	0	0	-1800	0
4	-1800	0	0	0	3000
5	0	0	0	-1800	3000
6	-1000	-400	400	-1000	0
7	-1000	400	-400	-1000	0
8	-1500	400	0	0	3000
9	-1500	-400	0	0	3000
10	0	0	400	-1500	3000
11	0	0	-400	-1500	3000

Overall, the results show a clear influence of the bike frame on the load of the drive unit's screws. This is particularly evident for the amplitudes of frame 1 compared to the frameless norm setup for the drive unit mounting. For the other frames, amplitudes with smaller but still significant differences to this uniformly stiff norm setup are determined. For frames 3 and 4, a similar development of the screw forces can be determined. Noticeably, the influence of the bike frame varies depending on the load. Another interesting point is that a comparable but differently scaled behaviour can be determined for the examination of the vertical forces. For the horizontal forces, on the other hand, different characteristics can be observed.

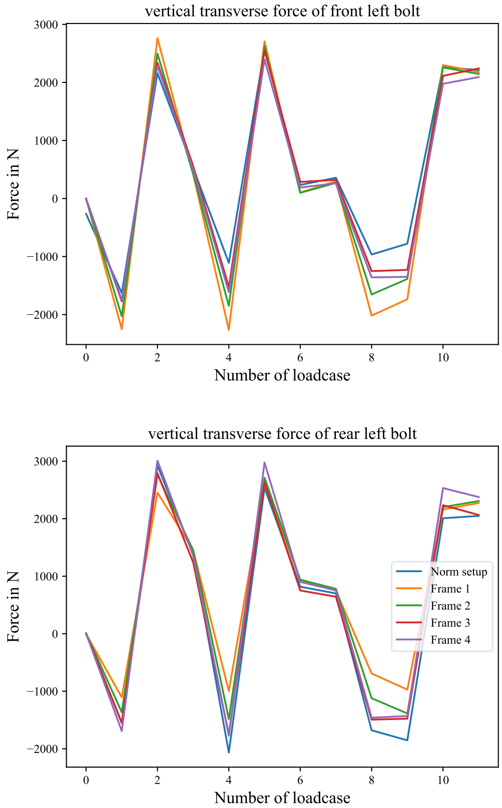

Figure 3 Vertical transverse force of the front and back left bolt connection the interface of the frame

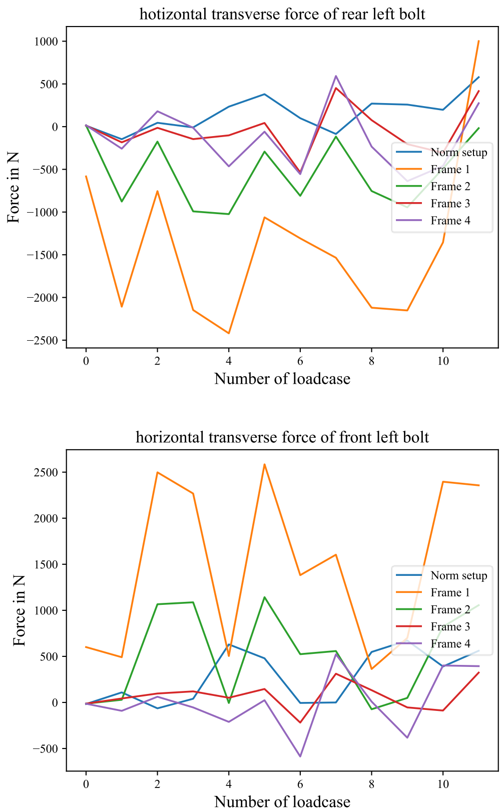

Figure 4 Horizontal transverse force of the front and back left bolt connection the interface of the frame

In general, these results can be explained by the stiffnesses of the individual frame geometries and their boundary conditions. The loads on the drive unit and its crankshaft result in bending and torsional moments that can only be absorbed at the front axle with the given boundary condition.

In case of a low stiffness of the frame, the load on the drive unit is mainly transmitted to the frame via the front screw. However, no comparable force can be absorbed at the rear screw due to the free rotation of the rear axle. In simplified terms, the proportion of the forces transmitted here is defined by the ratio of the stiffness between the mounting points of the motor and the bearing point of the front wheel, which is why this can be regarded as a critical factor. Due to the dependence on the load type, it is important to consider the resulting stiffness for all degrees of freedom between the frame interface and the respective boundary conditions.

For the two frames without a top tube (frames 1, 2), the overall stiffness can be assumed to be low in comparison to the frames 3 and 4. Therefore, this results in strong differences in the front and rear bolt loads, especially in comparison with the uniformly stiff bedding of the norm test. In this case, an increased load on the front and a lesser load on the rear mounting point can be observed. For the two diamond frames (3, 4), a minor deviation of the bolt forces and thus a behaviour similar to the rigid norm test can be observed. Here, the connection of the top tube helps to stiffen the seat post and the rear part of the frame and couples the forces introduced there to the boundary condition of the front axis. To visualize this effect, the following figure 6 shows the scaled deformation of the frame1 for the example of a load on the right pedal. Here, a stress concentration and torsion on the down tube as well as the resulting displacement of the rotationally not limited rear axis can be observed.

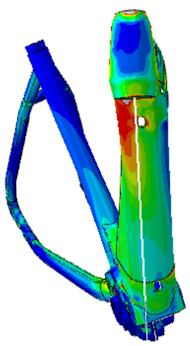

Figure 5 Deformation of frame 1 for a right pedal load of load case 4 (scale factor= 20, colours represent the mises stress)

For such a deformation of the frame due to a lower effective stiffness at the rear mounting point, forces at the drive unit are mainly transmitted via the frontal screw. In addition to this modified force flow, this also causes a torsion of the interface, which results in the horizontally oriented forces at the bolted connection, as the drive unit is blocking that deformation.

At this point, it should also be noted that the modelling of the reaction force of the chain on the rear axis has a decisive influence on the load situation of the housing. This is because the moment applied by the chain to the rear axis as well as the tensile load of the chain stays have a strong effect on this behaviour and the deformation of the frame.

Finally, from the perspective of the housing optimization, the question arises how this frame dependency affects the actual loading on the housing of the drive unit. For this purpose, various points of the entire housing were calculated for a larger set of real field loads in a subsequent calculation. For good comparability with the previously determined bolt forces, the most critically loaded points at the front and rear left mounting points are displayed in figure 7.

These results show an enormous influence of the different frame variants on the actual stresses of the housing, confirming the observations of the previous investigation. Dependent on the respective load, a variable local influence of the frame stiffness arises due to the complex geometry of the housing.

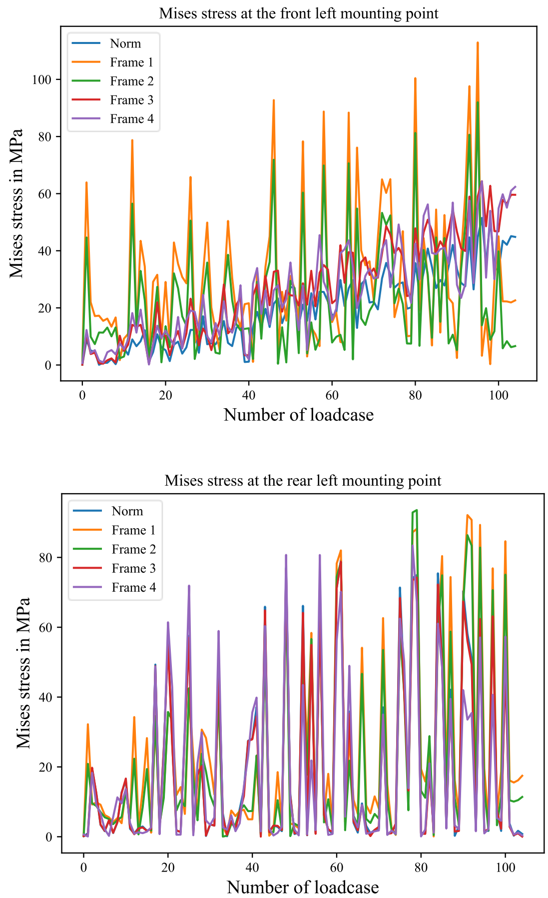

Figure 6 Mises stress at local parts of the drive unit housing for different loads of a real load collective

The fact that the difference between the mises stress values for each frame varies across the selected load points indicates that there is in fact a load dependent influence of each bike frame. Thus, it can be stated that the influence of the frame on the loading situation of the housing must be evaluated locally for each section of the housing and regarding the real load collectives. Since deviations from the norm setting can also be observed for frames 3 and 4, it can be stated that not only low-entry frames, but all frames must be taken into account in the design.

3.3 Simulation of the frame loads

For this second part of the investigation, the loads of the second setups in Fig. 1 were simulated for each frame type with the drive unit mounted. To determine the influences, again the bolt forces at the frame interface are evaluated. Since the amplitudes of the bolt forces were similar at all four bolt points, only the maximum values for each load are listed in table 2.

Table 2 Amplitude of the transverse forces for bolts during external loads on the frame

		Frame 1	Frame 2	Frame 3	Frame 4
Load on front axis (1000 [N])	vertical Bolt forces [N]	15	12	13	15
	horizontal Bolt Forces [N]	90	71	16	100
Load on seat tube (1200 [N])	vertical Bolt forces [N]	57	35	25	2
	horizontal Bolt Forces [N]	1100	710	72	4

Based on these results, it can be concluded that only for the low entry frame geometries significant forces are introduced into the engine through external loads on the frame. These results can again be explained by the low stiffness at the interface. For the external loads, the horizontal forces result from the deformation of the interface, which makes the drive unit a load-carrying part of the frame.

An examination of the actual stresses in the housing showed an increased mises stress value of up to 14 MPa for the load on the seat tube of frame 1 and at the locations considered in figure 6. For the same load on frame 2, 9 MPa could be determined. All other load and frame combinations showed only very small effects.

4. Conclusion

Overall, the investigations revealed a non-negligible influence of the bike frame on the load and stress on the drive unit. The influence of different frame stiffnesses at the mounting points was obvious and therefore needs to be considered for the calculation, design and testing of the eBike drives. This means that for the design of the drive unit, a sufficient selection of loads and frame stiffnesses must be considered and varied to identify the most critical points. The external load on the frame had a lesser influence, but this load case should not be completely disregarded for frame geometries comparable to frame 1 and 2.

At this point, it should be pointed out once again that only certain mounting positions and a small section of the frames available on the market were considered in this study. Other mounting angles, materials and differently designed frame interfaces may lead to other results for both load cases.

In general, these results show that the simplified frame-free analysis of the present norm requirements for the drive unit is not sufficient to cover loads in real eBike applications. Especially regarding the load collectives determined in [7] and their interaction with the frame stiffness, it cannot be assumed that the normative load case defined in [1] allows a robust design or reliable testing for all possible loads and system configurations. Likewise, from the perspective of frame design, it must be examined whether the norms defined there also enable a safe and robust design for eBike frames. Due to the enormous influences and increased loads for low entry bike frames, constructive adjustments to stiffen the interface could be a reasonable option.

The sub-modelling method used in this study enables a computationally efficient inclusion of the bike frame for the simulative investigation of the drive unit. Here, it is important to also model the reaction force of the chain at the rear axle in order to represent the real loading.

Due to the large number of bike frames and frame geometries, a simulation of each bike frame is impractical. In a first step, similar to the present study, example frames for the different types of bikes and frames can be defined and considered for the simulation.

As an extension, a characterization of the frame types based on defined tolerances for individual stiffnesses would be conceivable. This would allow a target-oriented design, a specific classification of the frames as well as a defined requirement for the frame builder. For example, the bending and torsional stiffnesses between the mounting and the pivot points could be determined and used as a tolerance and release criterion.

For further investigations, the simplified choice of boundary conditions must be reconsidered and investigated in more detail, since it is not realistic to assume that there is a clearly fixed rotational boundary condition for the frontal axis. For a more accurate analysis, the driver-controlled system and its forces in relation to the pedal load and the driving situation have to be defined.

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