DEVELOPMENT OF COMPETITIVE E-MOBILITY PRODUCTS: DESIGN METHODOLOGY AND MAIN CHALLENGES

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Abstract
The development of an innovative product that will be widely accepted on the market is not just a question of creating innovative ideas and providing suitable functionality but also of good timing. In the last years we have seen a substantial increase in interest into e-mobility and many producers have already recognized and ventured into this niche with high rewards. E-bikes are also an emerging product in this field, which have gained a lot of interest in the last years, and are becoming widely demanded globally. Being involved in the R&D process of a similar product, namely a central drive e-bike, in collaboration with several industrial partners we have gained deep insight into the challenges of entering a by now fairly mature market with a new, high quality and competitive product. The development methodology was first based on a thorough benchmarking process and the elaboration of a functional structure that precisely describes the technical problem. This way we could identify the main functions that such a product has to fulfil and pinpoint the areas and technologies that proved to be the most critical in achieving a robust and safe system. Following the so called golden loop approach we could implement a systematical design process, where the key functional requirements could be successfully fulfilled, enabling the formation of a fully operative technical system. We focus here especially on the mechanical part of the product, i.e. the drive system and housing as this was also found to be the most challenging part of the whole development process. Due to the very demanding requirements put forth by the customer many severe challenges emerged, which could only be solved by a structured development methodology and very coordinate iterative process between all the partners. Several cues can be outlined from the experience we gained, that can serve as a guideline for the development of competitive e-mobility products.

Keywords: E-MOBILITY, E-BIKE, DESIGN METHODOLOGY, GOLDEN LOOP, VDI 2221

1. Introduction

The term electric mobility (or shorter e-mobility) incorporates all products, technologies, infrastructures and services that provide transportation based fully or partly on electricity as power source. The main goal of e-mobility is to provide efficient and environmentally sustainable vehicles that also meet more and more stringent regulations set by governments and lawmakers as a measure to curb climate change effects and dangerous air pollution. In the last years we have seen an exponential rise in electric vehicles present on the roads globally. If we look specifically at electric cars there were only about 700k such vehicle in use commercially in 2014 [1]. By 2016 this number already rose to over 2M [2] (these figures comprise fully electric and hybrid vehicles). As noted in [3] the global e-mobility market is expected to grow to $340 billion already by 2020, which will constitute between 10 and 15% of the overall automotive market. In the report [4] the authors present a thorough overview of the electric vehicle (EV) market in Europe for 2014. Although major challenges in a large scale adoption of EVs still persist, i.e. due to the still relatively high TCO (total cost of ownership) as compared to ICE (int. combustion engine) cars and the necessity for huge investments into the EV infrastructure, they see many opportunities for established manufacturers as well as new entrants in this business.

We focus in this work specifically on a small segment of the e-mobility market, namely pedelec (or pedal-assist) e-bikes. E-bikes in general have gained a lot of traction in the last years, with China constituting the large bulk of the current e-bike market [5]. An annual growth rate of between 1 and all the way to 6% is estimated for this market between today and 2025 with the largest part of this growth attributed to Wester European countries. The current regulations in the EU limit pedelec e-bikes to a power output of 250W and a speed of 25km/h at which the assisting electric drive has to shut down leaving the cyclist to provide the full pedalling power [6]. In the work [7] the author uses a conceptual model to analyse the data from national mobility surveys conducted in the Netherlands between 2013 and 2015. It was found that the implementation of e-bikes has a positive effect on lower car usage and that car users are more willing to switch to e-bikes as compared to regular bikes. Positive findings are presented also in [8] where a trial done in the UK showed that e-bike use reduced the user's car mileage on average by about 20%, and the users in generally shown great interest to use this type of vehicle as means of transport in the future. The data presented in [9] also present realistic possibilities of the implementation of pedelecs and other e-bikes in logistics for goods delivery in urban areas.

Our industrial partners recognized the potential of pedelec e-bikes in the future of transport both as a means of commute, as well as a product for recreational use (for example as electrically assisted mountain bikes). A growing demand for these transport devices has given a good incentive to invest substantial resources into the development of a competitive pedelec product that would meet (end possibly exceed) the demands of the present-day user. Given that the market is by now already in a fairly developed stage it turned out to be a great challenge to develop a solution that would surpass existing competitors in terms of performance and quality. A structured approach to the design of a new product can be taken by following the VDI 2222 [10] and the more updated VDI 2221 [11] guidelines which outline an efficient product development procedure which is basically divided into four main phases: Definition of the task, Finding a rough concept, Designing of a basic (preliminary) solution and Elaboration and detailing of the actual solution [12]. Following the principles outlined in [13] the so called concurrent product development principle can be applied, which enables further timewise optimization of the R&D process.

2. Methodology

The industrial partners involved in the project identified the e-mobility and specifically the pedelec market segment as having big potential for growth in the future, especially in western European as well as other industrialized countries. A thorough examination of existing pedelec solutions on our targeted market served as basis for the definition of initial specifications, onto which the product development process could start.
The main focus was in our case the development of the product’s mechanical system, i.e. the drive train and its housing. Further benchmarking was carried out by our R&D team, with which the key functionalities of pedelec drives were identified. The process was narrowed down to four main competitors:

- Bosch eBike systems (Performance Line®)
- Brose e-bike System®
- Shimano Steps E8000®
- Yamaha PW® and PW-X® series

A review of existing and pending patents enabled us also to identify which technical solutions for a given function we should avoid or develop in such a way that it wouldn’t infringe any of the uncovered patents.

The VDI 2222 and VDI 2221 guidelines advocate a very structured product development approach, divided into several partially overlapping phases, which are in terms subdivided into multiple design stages. During the process we iterate back and forth between stages until a solution ready for physical realization is produced. Typically it is necessary to divide the designed product into modules that can be developed in parallel which enables an accelerated design process. These modules can be viewed as independent functional subsystems. It is however very important to precisely define what the inputs and outputs of each module are in terms of mass, energy and information flow. Along with recommendations given by the VDI guidelines, our product development phase followed also the so called golden loop approach presented in [14], [15] and [16]. Similarly to the VDI guideline the golden loop approach dictates an iterative design method where the latter is carried out as a sequence of loops. In the first loop a functional structure is defined, that fulfils the demands posed by the identified problem and the defined project specifications, the technical principles for each function are chosen and a preliminary model (typically using CAD software) is formed. Consultation with experts and project managers leads to identification of possible issues and necessary upgrades which in terms leads to a new design iteration loop. With each loop the specifications are rechecked, if necessary the functional structure is updated in case any new sub-functions are identified and the design model is suitably upgraded. In order to keep the development process in a manageable time frame and the number of iterations as small as possible we need to maintain effective communication channels between all the partners involved in the project. Efficient time and cost planning, involvement of industrial designers, technologists and toolmakers during the R&D process are also paramount for a successful and fast project completion. An indispensable tool for a quick identification of possible problems and failure modes has proven to be the established and widely used FMEA method, which was carried out several times during the process. With each iteration a more and more detailed design model emerges, until a solution ready for technical documentation and prototype production is achieved.
Along with the use of a suitable CAD software that is nowadays indispensable in any product design project our experience showed that also high quality analysis software is crucial. While standards and analytical tools enable a service life estimation of machine elements like bearings, shafts and gears, more custom load bearing components cannot be suitably dimensioned and optimized without modern numerical analysis tools like FEM or experimental testing.

3. Main challenges

The pedelec solution we aim at developing is primarily intended for integration in mountain bikes and is targeting especially Western European markets. As such it needs to fulfil first the nominal power and speed requirements dictated by the EU directives [6]. It is however also necessary that the drive provides increased power output in cases of steep climbs and off-road use for a sufficient amount of time. Furthermore we needed to provide adequate robustness of the whole system to withstand all the overloads that might occur during use. A brief summary of the main drive requirements is presented in Tab. 1. As visible the peak output power exceeds substantially the nominal power. Also the drive system and housing have to withstand high force overloads in any given direction. Furthermore specific attention must be given to elevated noise levels, housing outer surface temperatures and also suitable water tightness. The whole system also has to be enclosed in an as discrete volume as possible.

Parameter	Symbol [unit]	Value
Nominal output power	P_n [W]	250
Peak output power (5min continuous)	P_p [W]	770
Overloads	F_o [N]	4500
Cadence range	n_c [min^{-1}]	40 -120
Max. noise level	L_p [dB]	55
Max. out. surface temp.	T_o [°C]	60
Water tightness	Class.	IP 56

Tab 1. Main drive requirements

The main function that the drive needs to fulfil is efficient power transfer and a suitable transmission ratio from the battery powered DC motor in use to the output shaft connected to the bike chainring. A two stage gear transmission was chosen with the first stage consisting of a planetary gear train and the second of a normal gear pair as shown in Figure 1. This configuration was chosen due to its simplicity compactness and relative efficiency (less components means smaller aggregate energy losses). Developing a drive train design with very limited dimensions that would withstand the required service life while still providing a smooth and quiet ride and suitable price/performance proved to be a rather demanding task. Several measures were applied (some still being in the testing phase) to achieve the wanted performance. The main challenges in the design of the gear train and possible technical solutions are noted in Tab. 2. Of special concern here was the (first) planetary gear stage, which runs on much more elevated rotational speeds than the second stage and can hence produce much higher noise levels. Several measures were necessary to achieve smooth running conditions there. First of all a helical gear geometry was used, that enables an increase contact ratio and lower transmission error which in terms positively influences the noise level. Furthermore it was necessary to switch from metals to polymers as structural materials for the planet and ring gears, while retaining a steel sun gear. These changes lead to several additional performance issues that are being solved by a combination of measures mentioned in the table below.

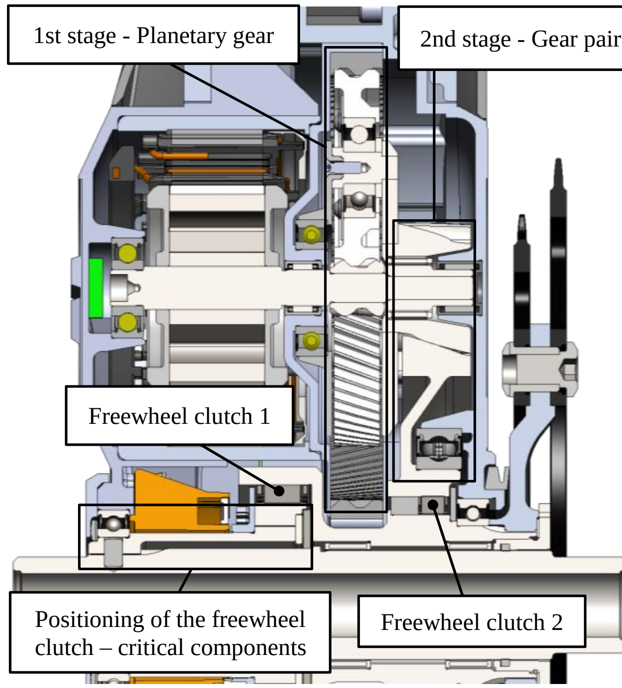

Figure 1. Pedelec drive train solution

A range of tools was necessary for the design of a suitable drive train solution. The initial geometry design and structural evaluation of the used gears was performed using software KissSoft. The latter follows available standards and established models to estimate the life expectancy of the developed drive while also enabling CAD model generation for further gear production. For metal gear design the software offers fairly reliable evaluation methods while for designing polymer gears things are somewhat less trivial. Especially for high performance plastics like PEEK used in

Performance goal	***Technical solution***	***Resulting issues***	***Further upgrade***
Suitable service life	Adequate gear sizes (module, width, etc.)	Exceeded volume limitations	Geometry optimization
	High performance materials	Higher cost	Price/performance compromise
	Lubrication	Leakages	Suitable sealing
Smooth and quiet running	Switch metals with plastics on first gear stage (for planet gears and ring gear)	Lower accuracy of the produced gears	Switch gear injection modelling with milling (more expensive)
		Lower stiffness of the gears	Use of high performance plastics (i.e. PEEK or similar) Surface treatment of the sun gear's teeth Use of wear reduction coatings
		Lower wear resistance	Wear resistance fillers (PTFE or graphite)
		Temperature sensibility	Gear geometry optimization - reduced contact stresses and sliding speed during gear meshing Lower frictional coefficient – suitable material pair choice
	Helical gear design with suitable helix angle	High axial forces	Suitable design of associated components
Reduced friction without use of oil	Grease application	Poorer frictional conditions	Appropriate grease for given running cond.

Tab 2. Gear drive train design challenges

our case for the planet gears (commercial type Victrex 650g) the available data necessary for the evaluation are very incomplete. Hence we needed to turn to experimental tests using a testing rig developed at our institute [17]. The results achievable for a simplified gear geometry can be extrapolated and projected to the running conditions present on the planetary stage to obtain a rough service life estimation. A possible and in fact typical failure mechanism present on polymer gears is the effect of wear, especially common in application where we have steel-polymer gear meshing. Wear is driven by several factors, most importantly the sliding contact conditions and resulting temperature increase due to friction which typically accelerates this process. Several evaluation tools are being developed by our team to predict the frictional thermal effects, and consequent probabilities of excessive wear. Figure 2 presents some exemplary results for the evaluation of the thermal state present during gear meshing of a POM-PA66 polymer gear pair. The overall temperature rise is a sum of two temperature components- the local flash and long term nominal temperatures. These results can help estimate whether the chose loading conditions are critical for the desired service life of the gear pair.

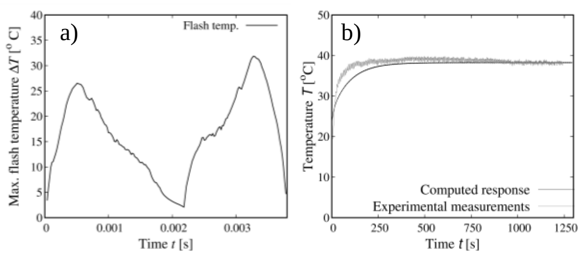

Figure 2. Evaluation of the flash (a) and nominal (b) temperature rise due to frictional effects during gear meshing (example results for POM-PA66 gear pair with 1Nm torque load and 1392rpm)

The pedelec drive also has to provide three modes of operation:

1. Simultaneous action by the drive and cyclist.
2. Independent running of the drive train.
3. Independent pedalling by the cyclist.

These modes in essence provide different types of power transfer to the frontal bike chainring. They can be achieved in a single drive mechanically by a suitable configuration of freewheel clutches as visible in Figure 1. A combination of two frictional sprag freewheel clutches was used to achieve the desired operation modes and here again several challenges emerged in achieving the desired power transfer. This type of freewheel clutch requires rather demanding preparation of the running surfaces both on the shaft and hub. A surface hardness of 700+100HV is necessary with a depth of 1.3mm and a roughness grade Ra0.4 or less. While this is achievable with different alloy steel grades, the required hardness depth can result in excessive brittleness and fracture of the associated hub or shaft. A further aspect to consider is the positioning of the clutches. Even though both the hub and shaft are produced in the required tolerances it is possible that an insufficient concentricity is achieved due to the tolerance chain of all other associated components. In our case this proved to be the case for the larger Freewheel clutch 1, with the main issue being the housing bearing seat tolerances and a spline joint used between the main shaft and the sleeve used for pedalling torque measurement (Figure 3). Initially the positioning of the sleeve was achieved by the contact of the spline teeth flanks as seen in Figure 3a which resulted in inadequate concentricity. A suitable positioning that enabled the desired functionality of the clutch was achieved by transferring the centring surfaces from the joint teeth flanks to the inner diameter of the spline.

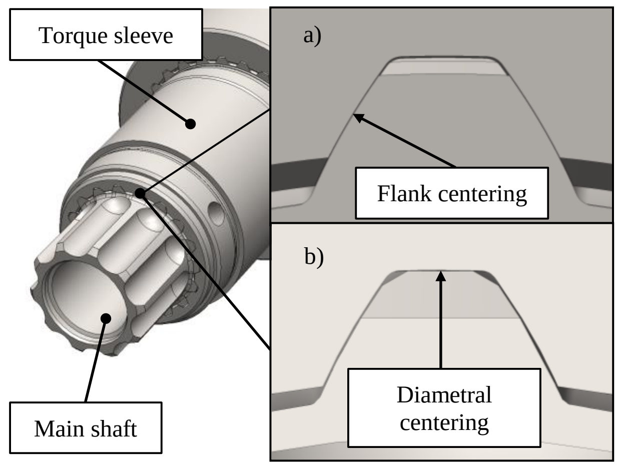

Figure 3. Torque sleeve and main shaft spline joitn: (a) flank positioning- insufficient positioning accuracy; (b) outer diameter positioning – adequate centering of the sleeve

Due to the all mentioned requirements and complications which led to rather costly upgrades we decided to switch to a simpler and more robust clutch solution where the one-way torque transfer is provided by detents and a suitably designed ratchet (Figure 4a). This custom solution was designed based on results from FEA, with which we could attest that the anticipated loads wouldn't result in too high structural stresses (Figure 4b).

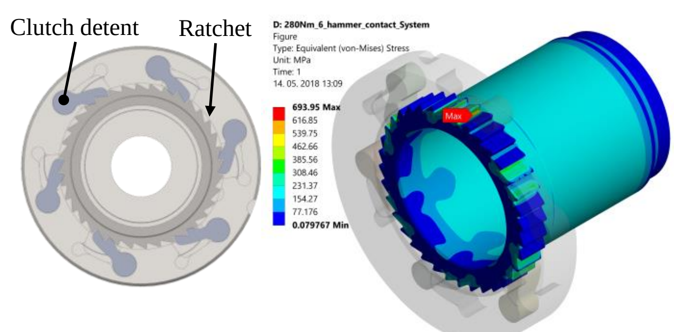

Figure 4. (a) Custom freewheel clutch solution as a cheaper and more reliable alternative to commercial sprag clutches; (b) evaluation of internal stresses due to pedalling torque transfer using FEA.

The presented problems are only a part of the challenges that were met during the design process. With them we wish to point out the fact that even with a structured design methodology it is not always possible to predict and resolve in advance all the functionality issues that might occur. Small inconsistencies like inadequate tolerance chains or inappropriate surface finishes can set back the project for weeks or even months and add to unnecessary project costs. While the use of modern design tools proves indispensable for a rapid design development, the expertise of the team members and a suitable project management with regular design checks and open communication channels between all involved parties is really crucial for a successful project completion.

4. Conclusion and discussion

A structured design process based on the VDI 2222 and VDI 2221 guidelines and following the golden loop approach is presented as was applied to the development of a novel pedelec central drive system. The process was split into several stages and the product divided into a manageable number of independent modules. Following this approach the developed product can be brought to a functional level if a team with suitable expertise is involved. However, even with expertise and modern design tools, the complexity of the system made it difficult to predict whether the service life and all the functionality requirements would be met. The production of several iterations of prototypes and extensive testing proved essential in identifying several remaining weaknesses that needed to be properly addressed and corrected. A systematic R&D approach can however substantially reduce the number of needed design iterations and lead to a much faster transfer of the product from the proverbial drawing board to the production line.

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