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Research project "e performance" – Design approach for a holistic BEV

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Abstract

The development of Electric Vehicles, in some facts, is a contradictory challenge that ought to combine customer expectations, quality and price. Knowing that the prospects on the cruising range of comparable combustion-engined vehicles cannot be realized contemporarily on battery-electric vehicles, a large variety of other automotive characteristics must be redefined. The redesign of these characteristics, going along with totally new approaches in vehicle characteristics, is indispensible for increasing the customer's benefit. The resulting layout criteria are not yet sustainably verified because of their mostly unknown, multi-variant interaction. Therefore, the joint research project „e performance" is meant to demonstrate technical and economical feasibility on the basis of a re-usable module kit. This module kit should allow analysing and scaling vehicle properties, the implementation over various vehicle categories as well as the mode of driving. This publicized, integrated development approach on the basis of „E-Modules" will be exemplarily demonstrated and evaluated using a collaborative vehicle concept called „e-tron research car 2012". One of the mentioned "E-Modules" on the car is the battery system. It features an innovative concept to improve the crash safety of electric vehicles. The idea behind this concept is to avoid rigid and rather heavy battery housings by making the entire system deformable, when a certain force is applied in a crash. This can help to save weight and provide more space for energy absorption. At the same time the acceleration pulse is reduced. Due to a special shape of the so-called macrocells the energy is deployed in several directions inside the pack and gets absorbed by deformation elements between the cells. The deformation elements, for example made from aluminium, serve as cooling or cell venting ducts. Since the entire system consists of a large number of macrocells, it is very variable in size and outer shape due to its modularity. Starting with the concept idea, the development steps on the way to building up such a battery system in the "e performance" research project include the design and development, the prototyping and real life tests. In this paper design attributes of the system will be introduced and also the strategy and first results of the finite elements analysis to optimize the crash functionality together with the results of mechanical tests on batteries [1].

Keywords: battery, BEV (battery electric vehicle), finite element calculation, safety,

1 Introduction

The energy storage systems of today's electric vehicles are mostly based on Li-Ion technology. These offer the highest potential concerning energy density in comparison to other battery technologies. At the same time such cells tend to show critical behaviour under mechanical loads or if damaged. Explosions, fire and the evaporation of harmful substances can occur. To avoid that, these systems are commonly contained inside rigid housings, which cause a further weight increase to the entire vehicle added on the pure battery weight. In the research project “e performance”, funded by the German BMBF, the work packages “Body and Lightweight Design” and “Energy Storage” deal with a new approach on battery crash safety and lightweight design at the same time. Since such an innovative energy storage concept must not set limitations to the vehicle’s overall performance due to its mechanical architecture, other areas, like the thermal management have to meet a challenge as well.

2 Technical Outlines in the Research Project “e performance”

The research project addresses all the relevant topics in the battery electric vehicle (BEV) development. Due to this, special work packages, dedicated to all the development and science key aspects, got specified. Objective in the development of the battery system is the display of the following attributes:

- High energy density at system level, i.e. the lowest possible mass fraction of the peripherals and the housing;
- High overall efficiency;
- Modularity and scalability;
- Safety in operation and in a crash;
- Series production orientated concept.

In addition to these research areas a number of requirements and constraints are also defined in the design phases, which are crucial for the implementation of the demonstrator. The specification of the usable design space is always an important design variable for the development of the components, as this influences the design freedom and concept selection significantly. In the case of the described project in which the demonstrator is based on the structure of an existing sports car of the AUDI AG, two areas to accommodate the energy storage are coming into consideration. On the one hand, the space in the tunnel is identified as available. This area in the vehicle longitudinal direction from the front bulkhead to the firewall, separating the passenger cell from the engine compartment, can be used. The height of the vehicle tunnel is limited, as the driver’s steering movements must not be restricted, and the rescue of passengers over the tunnel has to be ensured. As a further location the front portion of the rear vehicle section is defined. Again, the overall height is limited to keep the center of gravity of the vehicle low.

From the specification sheet of the demonstrator important parameters are obtained for the battery system. The range within the normal cycle "NEDC" (New European Driving Cycle) is 230 km. From the vehicle’s parameters and the estimated losses in the drive train results a consumption of about 16 kWh/100km, which in turn makes a useable energy content of 36.8 kWh for the battery system necessary. At the same time the desired performance requires a system output of 195 kW, which will be available at short term. In addition to the above requirements, the integration into the high voltage (HV) intermediate circuit is an important boundary condition for the development of the battery system. With commercial electric vehicles, the battery system is usually connected directly to the DC side of the drive inverter and charger. For the research vehicle, a special HV topology is chosen. This requires two additional HV-DCDC converters in addition to the typical components drive inverter, charger and 12V DCDC converters. Due to the decoupling of the power battery systems from the rest of the DC circuit (drive and battery charger), this results in several advantages:

- Flexibility in the design of the battery structure with several electrically and mechanically independent battery systems in the vehicle;
- Optional battery systems to scale power output class and range of customer requirements;
- Different types of cells and cell technologies in the systems;
- Increased reliability of the vehicle.

A disadvantage of this approach is the additional energy conversion in the HV DCDC converters, resulting in additional losses. Since the losses in the drive inverters can be reduced using the adaptable traction voltage in part load, the overall efficiency of the system can be compared to the reference, see [2].

A battery system consists of the interconnection of several cells and the cell selection for the design of the system must be taken in a first development step. First, the entity of available cells in terms of the attributes of size, energy and power density, design and mass production is analyzed.

The project "e performance" uses so-called 18650 cells as a result of this process. These round cells with a diameter of 18 mm and 65 mm in length are used in various fields of consumer electronics.

Arguments for 18650 cells are the easy exchange because of standardised cell geometry and the availability of production-ready cells of various cell chemistry and manufacturers. In addition, the

low cost and consistent quality in production in large quantities can be evaluated positively as well.
The selected cell is the smallest element of the battery system shown. According the HV-topology, the entire battery system of the vehicle consists of two separate battery systems. To achieve the required performance, a number of 5200 cells was selected, wherein always 52 cells are connected electrically in parallel. This produces so-called “macrocells”. They are discussed in detail concerning the mechanical structure in the following sections. They always contain one half, i.e. 26 of the 18650 cells in parallel.
Due to the space given, the two battery systems can be designed asymmetrically, so that 2080 18650 cells in the tunnel system and 3120 cells in the rear system are installed. By the series connection of 40 and 60 cell blocks the systems reach their nominal voltage of 148 V and 210 V.

3 Concept Idea of a Crash-deformable Battery Pack

The basic idea behind the presented battery principle with regard to the mechanical design is the use of the battery pack as a deformable member which can absorb deformation energy in a crash. It exploits the fact that with the 18650 cells geometrically very small battery cells were selected for the project. If a certain quantity of these cells is combined as a mechanical unit, its design can relatively free be selected. The concept of macrocells is therefore the smallest and undeformable unit in the deformable battery pack. It should be noted that the concept was worked out for 18650 cells due to project constraints, but an implementation is possible with other cell types. It is only important that a trapezoidal unit is created, see Figure 1.

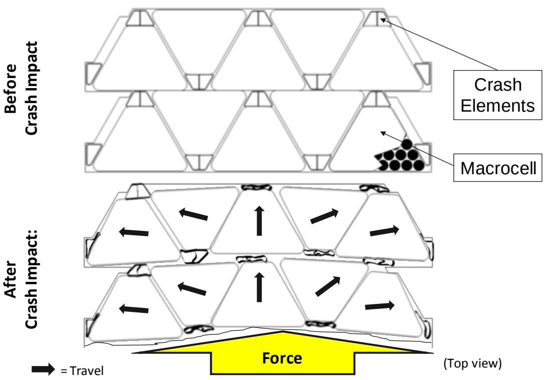

Figure 1: Principle of the deformable battery pack

This form ensures the transmission and distribution of occurring deformation forces by shifting the macrocells into different directions. The energy is absorbed in deformation elements between the macrocells. These elements are in this case made of aluminum profiles with a certain wall thickness. For larger production numbers they can for example be made as extrusion profiles. The profiles can also perform other functions and serve as channels for example, cooling fluid, or for degassing and ventilation of cells. Advantages of such an approach, in addition to the primary weight savings through the elimination of a rigid housing, are savings to the body structure as adjacent load paths must be designed less massive. By the deflection of the forces in other directions in areas with relatively small deformation zones (e.g. vehicle tunnel in the side impact) sufficient energy is absorbed and the acceleration of the occupant is reduced.

4 Mechanical Tests on 18650-Cells

To realize the above concept with 18650 cells, at first insights into the mechanical properties and possible failure modes of the cells are necessary. Figure 2 shows the test bench, where this is examined.

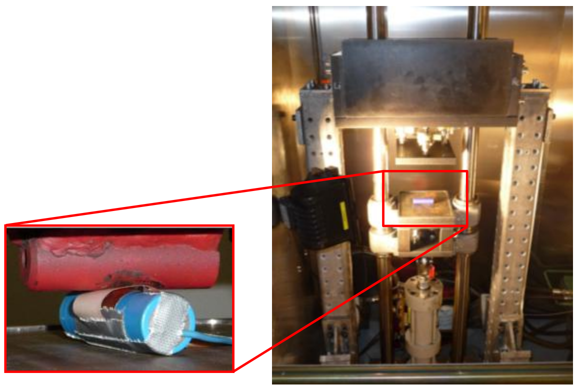

Figure 2: Cell test bench

Therefore different impactors with different loads act upon single 18650 cells. Values such as force, deformation, stress state of the cell, temperature, etc. get measured. The test bench also includes a suction and adequate ventilation. Chemical reactions with flames and smoke occur. Also cell explosions can be noted.
The force and displacement curves from the tests show, that the force level of cells that are specific to this project, is very high with a maximum value of about 30 kN. The associated deformation at these levels however, is already at 6 mm to 8 mm.

For such deformations explosions and fires in the cells can already happen. For the battery's structural design concept the aim must be to exclude the cell deformation. Given the expected loads in the event of a crash, based on the test results structural reinforcements to the macrocells are required.
Besides this important finding, the experiments also provide data for the simulation of 18650 cells using the finite element method, described in Chapter 6.

5 Battery Pack Design in Detail

In the design of the battery system, the design of the trapezoidal macro as mechanically very robust elements, which includes 26 18650 cells, can be regarded as the greatest challenge. An approach here may be metal structures that do offer advantages in heat dissipation, but at the same time bring much weight to the system. The use of fibre reinforced plastics, however, could mean savings in weight, but bring with it more challenges in terms of mass production.
The chosen way in the development of the macrocell is the use of a structural foam which is injected into the spaces between the cells and hardens there. Materials of this type are usually used to reinforce vehicle body structures. It is a 2-component epoxy material. It offers high strength with low density, which is both needed in this application. The outer shape of the macrocell is formed by an injection moulded container with the 18650 cells inside. This assembly is filled with the foam. Also integrated in each macrocell are the electrical conductors for contacting the cells and a liquid cooling duct by which the cell is kept within a defined temperature range. Electrical connectors and those for the coolant are also integrated into the container. Figure 3 shows a macrocell.

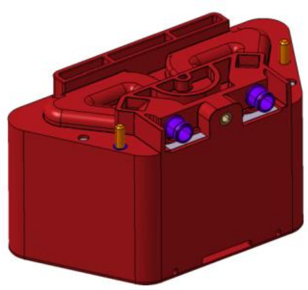

Figure 3: Macrocell

By the alternating and layer-wise arrangement of macrocells on a base plate made of carbon fiber, the battery pack is generated. The bottom plate is designed to be carrying the weight of the battery, but also allows the system's crash deformation when force is applied in the vehicle transverse direction.
Between the individual stacks of macrocells there are aluminum profiles for energy absorption. At the same time the macrocells are bolted to the profiles and these are fixed to the base plate and a cover plate (also made of CFRP), which gives the entire battery structure the necessary stability during driving. Parallel to the profiles in vertical direction, the cooling hoses to the individual macrocells are running. They are fed by supply and returning pipes at the top of the battery pack. The ends of the battery in longitudinal direction are formed by large aluminum profiles that have a higher wall thickness of 5 mm on the outside. At the side facing the macrocells the wall thickness is only 1 mm. So the cells located at the pack's ends can carry out an intrusion into the end profiles, caused by the deflection of the crash load.
The battery pack in the rear of the vehicle is completely independent from the tunnel pack and has got the same assembly structure, but with two double rows of macrocells in line. The tunnel battery is housed by an adapted tunnel structure, made of sheet aluminum and the pack at the rear by one made of CFRP. The battery system for the tunnel is shown in the following Figure 4.

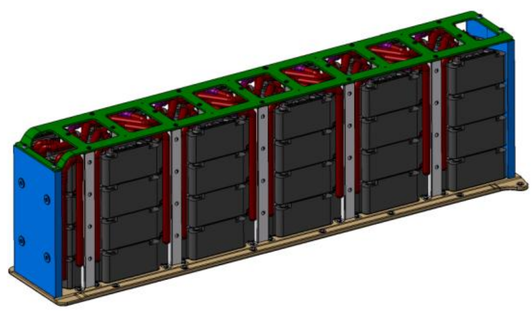

Figure 4: Tunnel battery system

The deformation profiles in the battery take the additional function of exhaust ducts, which is a benefit to the battery safety. They are connected via openings to the adjacent macrocells and end over holes in the floor plates. This allows the escape of gases, released from faulty or overloaded cells in operation for example.

6 Virtual Development with the Finite Element Analysis

For the functional validation of the deformable battery concept in terms of crash safety, the finite

element analysis (FEA) is used. The forces acting in a total vehicle crash on the macrocells are initially unknown. In addition, a sufficiently detailed modeling of macrocells in the overall vehicle model, which describes the deformation behavior and stiffness, is not possible. For these reasons, a parallel approach is used. In this approach, on the one hand simulations of the mechanical behavior of the individual components, i.e. 18650 cells and macrocells, are carried out. The resulting force and displacement curves are compared to those occurring at the contact surfaces from the overall vehicle simulation. A deformation of the macrocell in the entire vehicle model is excluded to reduce the computation time. Only displacement of the macrocells relatively to each other is permitted.
In particular the electrochemical components contribute to the complexity of the mechanical system in the 18650 cell battery. When the 18650 cell deforms under a force applied the individual layers of the separator which is rolled up inside the steel outer shell slide relatively to one another or dissolve partially from each other. The friction forces in this influence the deformation behavior of the cell. Since the short circuit time can be determined by the experiments only without sufficient accuracy, a tolerated maximum deformation is set with the load case under consideration. Furthermore, it is assumed that the internal friction up to the allowable deformation only has a minor influence on the tolerated level of force.
The simulation model of the 18650 cell, consisting of the stainless steel outer shell and the inner core, is compared with the experimental results of the tests with two different impactors. In this case the adjustment of the force-displacement curves of the simulation is done by varying the material parameters of the core. Within the maximum allowable deformation (flat impactor: 1.5 mm, half-shell: 0.9 mm), a good accordance between experiment and simulation is recognizable. The simplified simulation model of the cell and the load cases are shown in Figure 5.
Based on the single 18650 cell model a model of the macrocell is generated. As described in Chapter 5, the space between the cells in the casing is filled with foam. When modeling with "Mat_014: Soil_and_Foam_Failure" of the used FEA solver LS-Dyna, a homogeneous and isotropic distribution of material behavior is assumed.

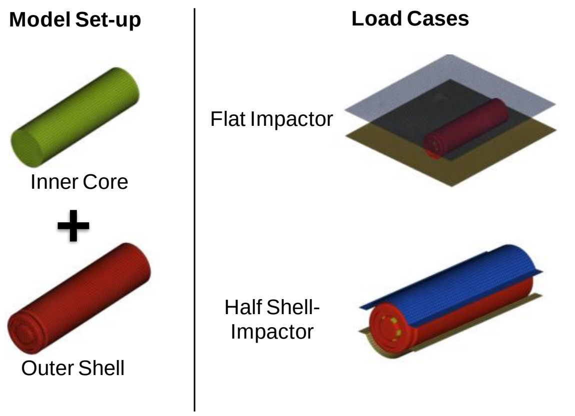

Figure 5: Simulation model and load cases

In a vehicle crash multiple macrocells collide with each other inside the battery pack, slide sideways, or are blocked between adjacent parts. The critical load case here is the compression of individual macrocells and the associated possible deformation of the battery cells. As a dummy load case, the macrocell between two ideally rigid plates undergoes a force in the y-direction, see Figure 6.

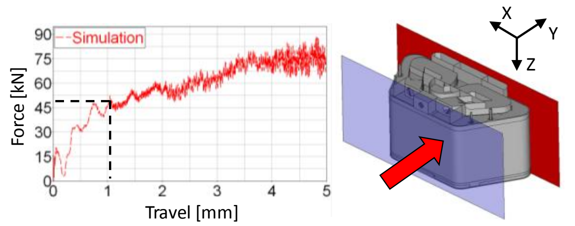

Figure 6: Dummy load case for macrocell

In an initial estimation the deformation of the 18650 cells depending on the overall deformation of a macrocell and the applied force is evaluated visually. Based on the maximum allowed and specified deformation of the 18650 cells, a maximum power level of about 50 kN is obtained for the macrocell.
Using this model, the macrocell is not feasible in a complete vehicle simulation. Due to the element size and amount of resources required, the calculation time would increase by far too much. That is why in the entire vehicle undeformable macrocells are used and their force level is compared with the single macrocell simulation, described above. If the load in the entire vehicle crash model is below the one from the single macrocell subcase, the cells in the vehicle crash are likely to withstand the occurring forces.

The load cases for the entire vehicle, that are simulated, are:

- Side pole impact according to EuroNCAP;
- Frontal impact according to ECE-R 94 ODB;
- Rear impact according to ECE-R 32.

The following Figure 7 of an early full vehicle model in the pole impact is already showing the potential of the concept.

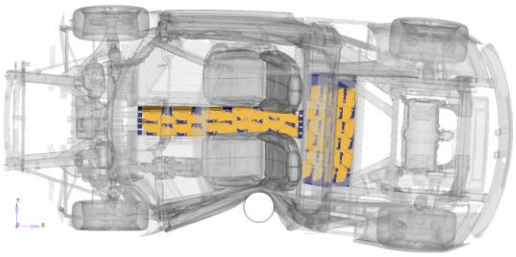

Figure 7: FE model in pole side impact

Another project goal in this work package, in addition to the development of optimized deformable battery pack, is to create a realistic FEA model for the macrocell used in the entire vehicle. This will allow drawing conclusions for both deformation and potential damage to the cells.

7 Summary and Prospect

During the electrification of the powertrain of motor vehicles the energy storage is an important component, on which research and development must focus intensively. This applies, in addition to the functional side in terms of guaranteed performance and energy storage capacity, particularly to high reliability and also safety in the event of a crash. This is done in the BMBF-funded research project “e performance", where the electric vehicle is considered as a whole and at the same time intensive research is done on its various components. The traction batteries and a crash-safe and high quality lightweight design are a central part of the development activities that lead to the build-up of a fully functional demonstrator vehicle, called the “e-tron research car 2012”.

For the battery a new concept is being developed, which allows it to be deformed if a mechanical load from a vehicle crash is applied. This offers advantages in reducing the acceleration pulse to the passengers and, almost as important, it saves weight, because solid battery housings are not required.

To realize such a system in hardware, the virtual development process with many complex simulations, such as finite elements analysis is prosecuted. One main aim of the interdisciplinary cooperation of different departments in industry and science in the project “e performance” is to build up and evaluate this deformable battery concept.

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