Eco-design and validation of in-wheel concept for electric vehicles,
EUNICE project

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Abstract

Global demand of light vehicles (A-B segment) is expected to grow, and forecasts about close future electrification of transport confirm that the A-B segment vehicles with limited range/autonomy are the most appropriate ones to initiate the general deployment of electric vehicles. In this scenario, the main objective of EUNICE project is the development and validation of an in-wheel motor prototype based on a McPherson suspension topology, in order to address the main technical risks associated with in-wheel thermal environment, vehicle dynamics, driveability and durability. The final prototype will be based on a fully air cooled solution with power electronics integrated in the in-wheel solution.

Keywords: electric vehicle; motor in-wheel; electric motor; power electronics; air cooling; MacPherson

Résumé

La demande mondiale de véhicules légers (classe A-B) à augmenté et les prévisions concernant la future électrification des transports confirme que les véhicules de classe A-B avec rayon d'action/autonomie limités sont les plus appropriées pour initier le déploiement à grande échelle des véhicules électriques. Dans ce scénario, l'objectif principal du projet EUNICE est le développement et la validation d'un prototype de moteur-roue basée sur une suspension de type McPherson, afin de relever les principaux défis techniques liés à l'environnement de la roue thermique, à la dynamique du véhicule, à l'agrement de conduite et la durabilité. Le prototype final sera basé sur une solution entièrement refroidie à l'air avec puissance et électronique intégrée dans les roues.

Mots-clés: véhicule électrique; moteur-roue; moteur électrique; puissance et électronique; refroidissement par air; MacPherson.

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1. Introduction

In-wheel electric motor architecture holds major advantages for the A-B segment vehicles, allowing high modularisation of the vehicle architecture, increased interior space and improved driveability. However, in-wheel electric motors have to overcome a series of technical difficulties, as the high torque demand at the wheel, the adverse effects derived from the increase of unsprung mass, and the endurance of the systems installed on the wheel when operating with high vibration levels. All these high demanding requirements have stopped this technology from being commonly adopted by electric vehicles.

The main objective of the EUNICE project is the development and validation of an in-wheel motor assembly prototype. The proposed concept will be based on a fully air cooled electric drive, including the electric motor and the power electronics integrated into the wheel, with only two complete units needed at the front axle to power the vehicle. This novel concept was selected based on simplicity and ease of integration, together with high performance. It is also a suitable approach within the forecasted evolution of the electric vehicle, for the second generation electric vehicles, as can be seen on Fig. 1.

In order to achieve the ambitious project objectives, electric motors using axial flow topology have been selected for the development of the solution, due to unmatched torque density, together with silent and very efficient mechanical transmission, ensuring a holistic approach. In this paper, the basic specification of the in-wheel solution is presented, together with the results of research activities carried out to assess the functionality of the EUNICE solution in terms of vehicle integration, driveability, performance and thermo mechanical behaviour.

![Fig. 1. Electric vehicles deployment forecast, from “adapted” vehicles to “dedicated” vehicles in 2020, and technological development evolution for EV’s, from 1st generation ready to market solutions, like the EUNICE in-wheel solution.](image)

The chosen concept will be evaluated against car manufacturer specifications. It is also necessary to carry out some studies from manufacturing and recycling points of view, in order to ensure the affordability of the solution when in series production. It has to be highlighted the advantage of the vehicle lay out with electric motors at the wheels in terms of integration. The benefits of this lay out can be seen in the Fig. 2, with an empty space at the front of the vehicle that can be used for different purposes.
2. Main targets of the in-wheel solution

In this section, the vehicle performance and the in-wheel module requirements derived for assessment are explained. Basic dimensions of a target vehicle are defined based on the input provided from several car manufacturers as well as the expertise from project partners. The defined vehicle and module specifications have been reviewed with relevant car manufacturers, in order to ensure that the development is in accordance with future electric vehicle needs.

2.1. Target vehicle performance

The longitudinal performance of the vehicle is mainly driven by top speed and acceleration requirements. In order to ensure attractive performance for customers, and after a series of benchmark activities and interviews with car manufacturers, acceleration from 0 to 100 km/h below ten seconds together with a top speed of 140 km/h has been identified as the main longitudinal dynamics requirements.

In order to derive the requirements for the in-wheel system, it has been necessary to define the weight and dimensions of B segment target vehicle. As a result of benchmark activities of the existing and future electric vehicles, considering research projects within the FP7, it has been considered that the target weight for future electric vehicle on the B segment is 1,150 kg including an occupant. (ref. SuperLIGHT-CAR, ELVA, and E-light European projects amongst others) (SuperLIGHT-CAR, 201; ELVA, 2013, E-light, 2013). This target is considered feasible for the second generation of electric vehicles, expected to reach the market on 2016, when the results of previously developed technologies are implemented.

In addition to the longitudinal performance, an adequate duty cycle has been defined in order to design the EUNICE system. The ARTEMIS Driving Cycles (ADC) are chassis dynamometer procedures developed within the European ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) project (ARTEMIS, 2013), based on statistical analysis of a large database of European real world driving patterns. The cycles include three driving schedules: Urban, Rural road and Motorway. The Motorway cycle has two variants with maximum speeds of 130 and 150 km/h.

EUNICE driving cycle has been defined based on ARTEMIS driving cycles, because ARTEMIS cycles are very close to real driving conditions in Europe. Nevertheless the NEDC (New European Driving Cycle) time distribution between urban and motorway use has been selected (66% urban, 34% motorway), in order to maintain the urban vehicle approach of EUNICE project, as can be seen on the following Fig. 3.
2.2. Target powertrain performance

The definition of the adequate powertrain specification have been carried out with “forward facing” simulations, taking into account the vehicle weight target and overall dimensions, the duty cycle and the required dynamic performance. The reduction gear ratio, has been defined taking into consideration what can be achieved by epicyclic gearing which can be installed into the wheel assembly.

In the previous figure Fig. 4, the operating points of the EUNICE duty cycle are presented, together with a maximum acceleration curve for assessment of longitudinal performance. From this graph, the following conclusions can be drawn:

- Defined duty cycle can be met by continuous motor service condition for most of the time (>95%).
- Operation points outside continuous motor service are restricted to short strong accelerations during urban driving cycle.
- A significant torque reserve exists for improved driveability and gradeability.

For this application, it is very relevant to provide an adequate behaviour regarding vehicle lateral and vertical dynamics. Different vehicle dynamics parameters relating the vehicle have been defined based on values from existing vehicles. With these values, a safe handling behaviour can be provided, but in order to ensure the acceptability of the EUNICE solution by future electric vehicle drivers, other subjective factors have to be taken into account. For the purpose of vehicle handling subjective rating the SAE Standard J1441 “Subjective Rating Scale for Vehicle Handling” has been adopted, as a common standard used by car manufacturers (SAE, 2007).

In order to meet the mentioned objectives in terms of longitudinal and lateral vehicle dynamics requirements, the following targets have been defined for the in wheel module:
TARGET 1: Competitive performance versus representative B segment internal combustion engine vehicle. Electric motor of 26 kW nominal power and 62 kW peak power (15 s).

The solution presented aims to suit perfectly the performance provided by a conventional B segment vehicle with an internal combustion engine. The modularity that can be achieved by the in-wheel powertrain solution could be easily integrated in other future platforms, thus representing a clear advantage for the car manufacturers by dramatically reducing the total development costs for the launching of new vehicle platforms and/or models.

TARGET 2: Increased total unsprung mass of the front axle vehicle below 45% over a B segment representative vehicle.

Suspension dynamic behaviour performance is critical, because ride comfort and quality are concepts of increasing importance for B segment cars. An increased unsprung weight below 45% will be a very challenging target in terms of manufacturing, and will help to avoid side effects in suspension dynamic performance related with high unsprung mass (Anderson & Harty, 2011) (Rojas et al. 2010) (Watts et al. 2012). Comfortable ride suspension system would have a dominant frequency between 1 and 3 Hz, and the increased sprung mass of the B segment EV, comparing with the conventional internal combustion engine B segment vehicle, will help and allow to maintain the suspension dynamic range within the human comfortable perceived frequency range (1-3 Hz).

3. EUNICE solution description

The longitudinal dynamic performance requires a significant amount of torque at the wheel, of more than 1,000 Nm for short periods of time. A combination of an axial flux Permanent Magnet Synchronous Machine (PMSM) with a compact epicyclic reduction gear has been considered to be the optimal in terms of torque and speed operation. One of the main advantages of EUNICE solution is the air cooling capability, which simplifies the vehicle integration removing a significant number of elements required for water cooling. Air cooling concept has been the baseline for internal combustion engines during many years, being displaced from the market by water cooling when emissions became more stringent. There are some factors to be taken into account when defining the air ventilation concept regarding in-wheel motors with axial flux technology:

- Two electrical machines are used to propel a B segment vehicle, increasing the heat evacuation path for total power.
- Axial flux technology electric machines have a significant exposed area, being easier to remove heat than in radial machines.
- Existing vehicles have significant radiator inlet for internal combustion engine.
- Duty cycles for electric vehicles are mostly urban, with constant acceleration, braking and stop times, which provide time for heat evacuation.

As in conventional internal combustion engine vehicles, it has to be taken into account that special cases, such as hot day combined with the presence of obstacles that may block air inlets, may require the implementation of forced convection devices such as fans. Other design feature of interest is the integration of the power electronics in the motor casing, attached in order to provide mechanical integrity and effective heat dissipation.

Main design solutions of the in-wheel solution are summarized in the Fig. 5:
4. Functional assessment of EUNICE solution

4.1. Modelling and simulation strategy for functional assessment

In order to evaluate the functionality of the in-wheel solution, it has been necessary to take into account several aspects related to the chassis and powertrain domains, therefore requiring a multi domain research approach. The different modelling and simulation stages are shown in Fig. 6, with the interdependencies between different research stages in three vertical blocks, and the research work packages progress below in blue colour.

Fig. 6. Modelling and simulation stages during the functional assessment of model and relation with different work packages.

4.2. Vehicle integration

The integrated in-wheel EUNICE system offers unmatched benefits in future electric vehicle platforms, as the components are integrated in the space required for wheel steering rotation and suspension operation. Note that the components used for these studies and showed in Fig. 7, are based on very preliminary volumes representing the main components comprising the EUNICE solution.
In order to validate the in-wheel system, a concept demonstrator based on an existing platform will be used. In order to allow the integration of the EUNICE model in an existing vehicle for demonstration purposes, 3D Fiat Grande Punto digital mock-up has been generated. A preliminary module configuration has been defined by the consortium. Functional aspects related to suspension, functional clearances, structural integrity and maintainability, have been taken into account to come up with an accepted configuration. Sub module locations of the in-wheel solution have been implemented in the final CAD assembly model, as shown in Fig. 8.

4.3. Suspension system definition and assessment

Starting from the top level vehicle dynamic requirements, the suspension and steering systems have been defined in detail, with steering angle, wheel travel, roll stiffness, roll centre, elastokinematic properties, attachment points, trying to meet the current B segment standards in terms of handling and comfort. It has to be remarked that an elastokinematic model has been generated and analysed (see Fig. 9) in order to assess the suitability of the knuckle, as the main structural component.

Suspension functional parameters have been evaluated, showing that even with the required geometry and additional loads, there is no appreciable degradation on suspension in terms of elastokinematic characteristics of the updated suspension. It has been seen that increased unsprung mass can be minimized by adopting upgraded suspension specifications for the elastic attachments of the suspension components with the chassis. This has been proven before with experimental tests carried out using a standard Ford Focus with stiffer suspension, with the following conclusions (Hurdwell & Anderson, 2011):
• Steering feel and response characteristics with additional sprung mass tend back towards reference when sporty suspension components are fitted.
• Steering kickback is reduced to reference level with sporty suspension.
• Improved on-centre response gain characteristics with sporty suspension.

Globally, all the main dynamic performance parameters of the suspension are similar to the Fiat Grande Punto, except some minor characteristics that will add some performance degradation to the demonstrator car prototype.

4.4. Electric drive and gearbox definition and assessment
The in-wheel system is driven by axial flux motor topology with high torque density, being the electric motor output shaft geared as input for the single stage planetary gearbox. The integration of the output shaft of the gearbox with the wheel hub is carried out with a normal splined shaft. The maximum torque is 180 Nm per motor. Maximum motor speed is 7,000 rpm, with a given DC voltage supply of 360 V.

For the development of epicyclic gearbox, helical gears have been adopted in order to minimize the noise and vibration which could be originated by the in-wheel solution, which is a concern expressed by car manufacturers relative to electric vehicle transmissions. Prototypes have been developed (Fig. 11) to experimentally validate the power electronics cooling method as this is considered one of the main technical challenges of the project. By testing the power electronics against a similar electric machine, the thermal model for power electronics have been calibrated.

4.5. Thermo mechanical assessment of EUNICE solution
Vehicle longitudinal dynamic performance assessment based on thermal / mechanic / electric model has been carried out in order to evaluate the temperatures achieved in the different in-wheel solution active components. Developed simulation module generates the instantaneous torque demand based on speed versus time profiles, which is converted into electric currents and introduced in the power electronic model. Subsequently all the losses related to switching and conduction losses in power electronic module, electric motor losses and gearbox losses are also computed. All the calculated losses are heat source inputs for the in-wheel solution thermal model. The components of the inverter, electric motor and gearbox are discretized in an interconnected group of nodes that form a thermal network.
In order to obtain the estimated air velocities at the different parts of the in-wheel system, a series of CFD analysis have been carried out. This multi-domain simulation is a powerful tool which is being used to optimise the cooling concept, allowing the evaluation of different geometries, fin patterns on components, relative locations and the addition of fans or other active cooling devices (see Fig. 12).

![Fig. 12. Multi domain thermal analysis: (1) CFD simulation to characterize the air flow in the contour of the In-Wheel motor shells. (2) Thermal model network to monitor in-wheel internal components.](image1)

The simulation evidences have shown that with the same air inlet area used in the donor vehicle that will be used for the final prototype, and simply adopting a series of cooling fins and adequate design of components disposition, the temperatures of critical components can be maintained under control during the specified duty cycle, even for an ambient temperature of 40ºC (see Fig. 13).

![Fig. 13. Motor components temperature estimation during EUNICE cycle under ambient temperature of 40ºC.](image2)

5. Conclusions

In this paper EUNICE project progresses have been presented. An innovative in-wheel solution is being developed in the project for a B segment vehicle. The main problems and goals of the solution have been identified, and they are being solved with original solutions within the project. Different phases of design have been taking place, showing so far that the concept is viable even at suspension dynamic system level. Suspension functionality is critical in relation with the subjective assessment of the future customers, and in this paper different evidences show that the increased unsprung mass will not be an unsolvable problem.

The proposed solution is based on an air cooled axial flux electric motor, with in-wheel integrated power electronics. Although this solution has different complex challenges (at integration level, reduction of the
unsprung mass, system cooling), the technical evidences so far show that the solution is feasible. The system will be integrated into a donor vehicle, and appropriate tests are going to be conducted at the end of the project. These tests will mitigate all durability and structural doubts that arise in a complex and novel solution as the proposed in EUNICE project.

Acknowledgements

This work is part of the EUNICE (Eco-Design and Validation of in-Wheel Concept for Electric Vehicles) Collaborative Project co-funded under the 7th RTD Framework Programme, Research & Innovation Directorate-General (DG RTD) (FP7-2011-GC-ELECTROMECHANICAL-STORE) – grant agreement n°285688. The partners involved in this project are the following: Fundacion Tecnalia Research & Innovation, Pininfarina Spa., Sistemi Sospensioni Spa., Fundacion CIE I+D+i, Industrias Puigianer S.A., IVL Svenska Miljoeinstitutet AB., Infineon Technologies AG., Fundacion AIC Automotive Intelligence Center Fundazioa, Austrian Institute of Technology GmbH., Hayes Lemmerz Srl., GKN Evo Edrive Systems Limited, Comite de Liaison de la Construction d'Equipements et de Pieces d'Automobiles CLEPA, GKN Driveline Zumaia S.A. For more information please go http://www.eunice-project.eu.

References


