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## **Making the Impossible, Possible – Overcoming the Design Challenges of In Wheel Motors**

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### **Abstract**

For many, in wheel motors offer a panacea for vehicle design. However history shows the delivery of an acceptable in wheel motor is a deeply challenging task which is dedicated to understanding aggressive torque and speed requirements behind demands on vehicle performance such as high speeds or sustained hill climb, and even aggressive driving, all of which are allowed by delivery of high continuous torque; limited in wheel packaging space, harsh environment, and safety requirements. Protean Electric is entirely focussed on overcoming these challenges and believes that, with its novel technology, it has delivered a product that will allow vehicle manufactures to exploit the benefits of in wheel motors. Protean's in wheel solution is based on a direct drive, permanent magnet brushless machine with an outer rotor. High torque is delivered from a space envelope based on high ratio between the motor radius and axial length and the key to maintaining this high continuous torque is effective thermal management of the motor. Power electronics together with control circuitry is integrated into the motor architecture, while the wheel bearing provides the mounting point for the motor. This paper offers a holistic view of an in wheel motor design with special attention to overcoming the design challenges presented by harsh operating environments, high performance demands and safety aspects.

*Keywords: in wheel, electric motor, safety, thermal transfer, unsprung mass*

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### **1 Introduction**

When considering a design of an in wheel electric motor for an electric vehicle, it is of utmost importance to fully understand all operating, as well as environmental, requirements. These requirements often present themselves as design challenges on a scale not tackled through traditional motor design experience and encompass the conventional electromagnetic motor sizing, power electronic drive design and mechanical packaging.

Aggressive torque and speed requirements are determined by the desired vehicle performance. Packaging space 'in-wheel' is limited, the environment is harsh, and safety requirements are of a paramount consideration. This narrows down the design choices and provides a logical direction towards a motor design which:

- works on a largest possible air gap diameter with a space for a wheel bearing within a given electric motor space envelope;

- is segmented into individually driven and controlled sub-motors to minimise the single point failure impact on vehicle stability;
- is a direct driven machine to minimise the total motor volume, as well as minimise the cost and complexity of an assembly;
- integrates power electronics drive to provide a more practical solution through higher efficiency and smaller coil inductance, as well as enabling easier on-vehicle packaging by minimising the number of connections to a number of sub-motors in a segmented design.

The logical design which presents itself at this point is a direct driven, radial flux, outer rotor motor, with a high diameter to length ratio, liquid cooled and sealed to the highest standards to ensure the integrity of all sub components. A key and sometimes controversial outstanding issue is unsprung mass. However, in full understanding of these challenges, and driven by Protean Electric's focus on designing an in-wheel motor for adoption by vehicle manufacturers for their mass markets, the added un-sprung mass has been researched and shown to have easily manageable impact on vehicle dynamics [4]. Aforementioned design aspects of motor cooling to deliver high torque, integrated electronics, sealing, unsprung mass, as well as segmented motor architecture, are discussed in this paper. Figure 1 shows exploded view of the Protean's latest motor architecture.



Figure 1: Protean's in wheel motor

## 2 Safety Aspects

The safety concept of the Protean in wheel motor is based around the basic philosophy that no single point failure requires any mitigation at the vehicle level. An intelligent approach to ensuring

that impact of a fault in any part of the electric motor has minimal effect on the overall operation and torque delivery is to switch off and exclude the region of the motor affected by the fault. This is achieved by segmenting the overall motor circumference into separate, individual, sub motors, each one of them separately powered and controlled. A fault-affected sub motor is then effectively switched off and the rest of the sub motors act to compensate for the lost portion of the torque. Dynamic response of the vehicle to such an event would cause an unintended yaw moment resulting in a vehicle course deviation. Such a scenario is preventable with a segmented motor architecture, making this approach to fault management one of the strongest points of Protean in wheel motor design. The details of Protean's safety concept including control inputs, vehicle responses, and driver modelling, are widely discussed in [2].

The key to actual delivery of this safety goal is design process which at Protean adheres to ISO26262 [1] requirements. However, to ensure effective fault management the issue of understanding the actual multitude of failure mechanisms within the in wheel electric motor drive is paramount. Only through full understanding of single point failures and their effects on the vehicle and consequently the driver, can a safety case be soundly built. It is the process of analysing and discussing these failure mechanisms during design stages, which allows engineers to account for the potential fault scenarios and tackle the possible causes of failure through effective and innovative design solutions. Effective management of such analysis is handled through the Design Failure Modes and Effects Analysis process, efficiently run at Protean.

## 3 Integrated Electronics

The Protean in wheel motor assembly carries in-built power electronics and controls modules. The case for having integrated electronics is a straightforward one, easily justified through simplified cabling and connection strategy, as discussed extensively in [3]. Operating in a spatially limited envelope with a plug-in strategy, the Protean in wheel motor demands compact design with the smallest number of cables which would be routed through the vehicle body and along suspension components. By positioning power and control modules within the motor assembly and in close proximity to the motor windings, the connecting cables become

redundant. All the losses associated with connecting cables such as high resistance and inductance of the routing travel path no longer feature in the system. Nor is EMC shielding of such cables necessary, which would otherwise adversely affect the machine efficiency. This elegant solution does, however, impose additional design constraints on the electronics. The operating temperature of the electronics components has to be effectively managed to ensure life time. This puts a demand on additional surface area within the motor assembly to cool the power modules. Also, the space occupied by integrated electronics now has to be effectively sealed from moisture to prevent any potential electronics failure modes associated with ingress.

Not forgetting that being within a road vehicle, the motor and its subcomponents must survive repeated shock loads of up to 50g with continuous vibration spectra of up to 20g RMS for severe rough roads. The cabling to the motor must be able to survive repeated bending and articulation with suspension. The design methodology to minimise the cable length increases the resistance to vibration.

#### 4 Sealing

The case of sealing Protean's in wheel motor unit is, above all, a matter of ensuring the operational integrity of the electronics. However, the integrity of other major operational subcomponents must not be neglected, such as stator windings and also of all other materials used in the assembly. Two possible ways of addressing this issue presented themselves during the design stage. Some degree of sealing would be implemented while at the same time implementing the following protection strategy: at first instance subcomponents like electronics modules and windings would be fully coated with waterproof material which protects against any potential ingress. Second protection instance would be to increase the specification requirements of these materials to include the material properties to withstand harsh environment particles, like salt or magnetic particles which could potentially damage windings and electronics components. While this solution offered several stages of protection, its main drawback was the fact that it essentially allowed ingress of water and particles into the motor unit. Such strategy would compromise the lifetime of subcomponents by stressing the wear of the internal components. The cost of acquiring

high specification materials would also result in soaring overall cost of the unit. A safer and a more reliable solution in protecting the internal subcomponents of the motor unit had to be found. Such a solution has been found in designing a seal which would offer complete protection against ingress of water and particles, with a breather which would allow moisture to escape. In such a solution, subcomponents are still coated and sealed at the level below the main V seal level, as can be seen in Figure 2. Electronics modules are encapsulated in their separate sealed enclosure, and within that enclosure, modules are further protected from moisture and vibration by a gel substance. Stator windings are fully potted with a substance with highly thermally conductive properties to aid the thermal performance of the machine as well as act as secondary insulation. The main V seal acts as a main line of defence against water and particles through the full operating speed range and is backed by the second line of defence by integrated electronics encapsulation and stator winding potting.

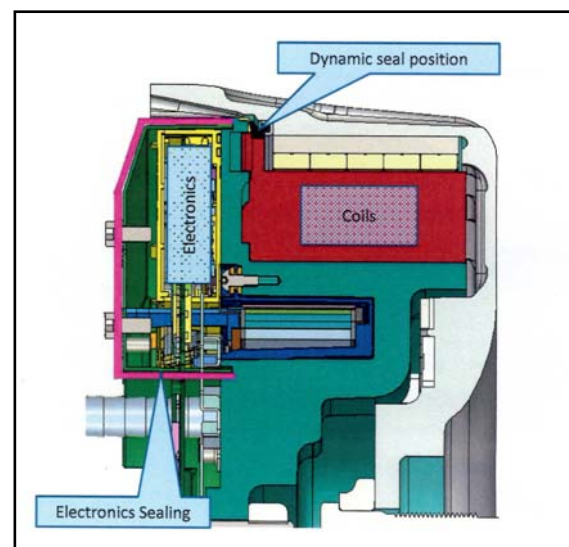


Figure 2: Sealing solution in Protean's in wheel motor

Magnets on the rotor are protected by V seal and against moisture by their surface, epoxy based, coating. To ensure the full product life, the motor assembly design allows for seal servicing, warranting integrity of the sealing process.

This solution satisfied the design specification call for the motor to be sealed to IP6k9k and IP 68 compliance, or in other words allowed high pressure jet wash and use of motor in 1m of water.

## 5 Thermal Management

One of the most important aspects in the design of Protean's in wheel motor and a key to the success in achieving high continuous torque is the thermal management of losses.

After having considered all above mentioned aspects of limited space within a wheel, harsh environmental conditions and demanding operating temperatures, sizing of the machine is to be approached with great attention to high performance material selection and efficient thermal path design, not forgetting effective cooling strategies.

Liquid cooling is the strategy chosen for Protean's high power dense machine. The heat from copper losses is effectively channelled into the cooling liquid via a thermal path which consists of potting material surrounding the copper wire, slot lining, stator tooth, stator back iron to cooling jacket interface and eventually cooling liquid. Selection of thermally high specification materials for stator potting and stator slot lining enables effective thermal transfer. However, it also limits the operating temperature within the stator slot, as currently, the operating temperature of the potting is significantly lower than operating temperatures of surrounding components.

The positioning of the cooling jacket and the layout of the cooling path within it is also of great importance and issue constantly looked at and reviewed at Protean. The main cooling path consist of two main channels: the first is positioned axially parallel to the length of the stator. The second section of the cooling path is positioned orthogonally to the first and runs below the power electronics modules to provide the cooling for them at first instance and as a secondary instance, cooling for the stator end winding section. The sketch of the cooling path can be seen in Figure 3.

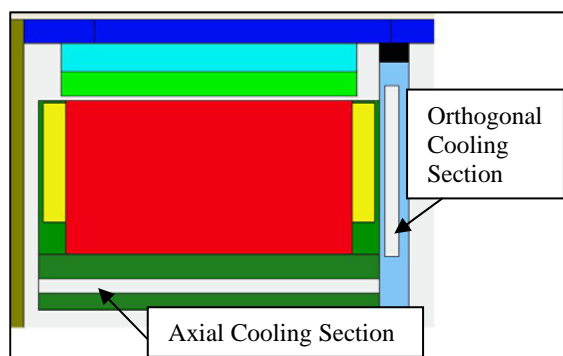


Figure 3: Sketch of Main Cooling Paths

Thermal losses of the machine are effectively channelled away into the coolant, while the machine's operating temperature is being monitored via a set of temperature sensors at each of the sub-motors.

## 6 Unsprung Mass

When discussing the integration of in wheel motors to a vehicle the subject of additional unsprung mass cannot be ignored. It is a widely held belief that it will have a major impact on the ride and handling behaviour of the vehicle. Protean Electric has addressed these concerns with care by commissioning two separate studies into unsprung mass effects. The two studies worked from two different perspectives and their result is extensively reported in [4]. The main conclusions of the studies are briefly summarised here, as the issue of unsprung mass does not form main design effort in achieving high performance demands of an in wheel electric motor. It rather alleviates the worries that this issue implies due to the traditional belief that unsprung mass impacts ride and handling of the vehicle.

The above mentioned studies were carried out on numerical models and using real vehicles with an aim to address primary concerns of degraded road holding and degraded ride comfort. The indicators against which the analysis was scored were split into categories of ground vehicle dynamics were given as follows from [4]:

- "Ride: the ability of the vehicle to absorb disturbances
- Refinement: the ability of the vehicle to attenuate noise and vibration
- Active safety: the ability to stop and steer in emergency situations
- Driveability: the response of the vehicle to the controls – steering, braking and drive – in normal situations"

Exercises were carried out using subjective assessment, on a real base vehicle and vehicle modified with 30kg of additional mass at each wheel to represent Protean's in wheel motors. Subjective responses to ride, handling and steering are shown in plots below [4], where the scale refers to the VER (vehicle evaluation rating):

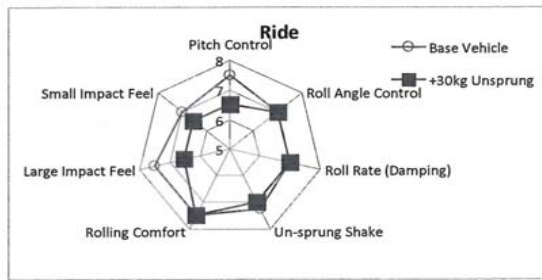


Figure 4: Subjective results for base vehicle and +30kg unsprung mass at each end - ride behaviour [4].

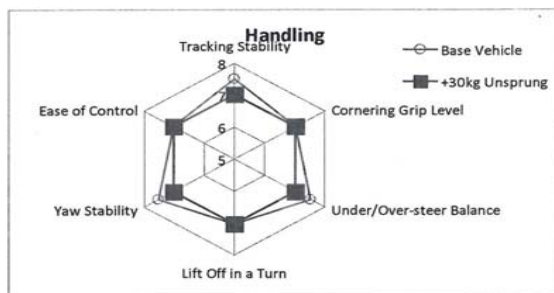


Figure 5: Subjective results for base vehicle and 30kg unsprung mass at each end - handling behaviour [4].

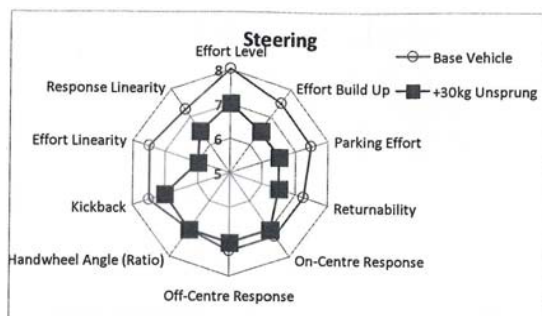


Figure 6: Subjective results for base vehicle and 30kg unsprung mass at each end - steering behaviour [4].

Numerical analysis in [4] was based around the definition of key performance indicators for ride, refinement, active safety and driveability and the main conclusions of the analyses are quoted below:

- “ride overall: difference in road roughness results in very large differences in scores compared to influence of unsprung mass
- Primary ride: no discernible difference on smooth roads, slight degradation in rough road performance
- Secondary ride: slight degradation in both rough and smooth road performance may require detail changes to seat or suspension components

- Refinement: some change in suspension component detail may be required to recover small loss in refinement behaviour
- Active safety: noticeable but not severe loss in smooth and rough road grip levels; slight increase in damping levels may be required to optimise performance
- Driveability: slight changes to suspension components may be required to restore agility”

The authors in [4] carry on concluding that although differences due to increased unsprung mass do occur, they are of small influence, if even apparent to an average driver. They believe the nature and magnitude of the changes can be overcome by application of normal engineering processes within a product development cycle and should not overshadow the benefits individual wheel motor control can offer in substantial improvements in vehicle behaviour.

## 7 Conclusions

The design of Protean’s electric motor for in-wheel application is based on a modular approach [5], which offers advantages for vehicle safety. The motor is divided into multiple sub-motors, each powered by its own power module and controlled by an independent control circuit. As a consequence, a single failure results in only a fraction of the torque loss, meaning that the induced yaw moment on the vehicle will be within the safety limits of the vehicle. The design solution is based on a direct drive, permanent magnet brushless machine with an outer rotor. High torque is delivered from a space envelope based on 3:1 ratio between the motor radius and axial length. Power electronics together with control circuitry is integrated into the motor architecture, while the wheel bearing provides the mounting point for the motor. The motor is fully seal against ingress of particles to ensure integrity during motor exposure to harsh environmental conditions and to fulfil the operational lifetime requirements of all sub components. High performance requirements and high power density are achieved with effective thermal paths, which offer space for improvement around better material selection to allow even more efficient thermal energy transfer through the machine.

The question of unsprung mass has been answered through analysis showing that the nature of the changes imposed on vehicle dynamics can be

addressed with even conventional development process, if needed.

The result of this concentrated engineering effort is a highly efficient motor unit, having a combined motor and inverter efficiency in excess of 93% and combined drive cycle efficiency in excess of 85%, high power dense and high torque machine, with output torque shown in Figure 7, able to withstand required operating and environmental conditions of vehicles, ready to be adopted by vehicle manufacturers.

## Author



Dr Dragica Kostic Perovic gained her first degree in electrical engineering at University of Belgrade, Serbia and her DPhil at University of Sussex, UK. She is a Principal Motor Design Engineer at Protean Electric with main interests in the area of electromagnetic motor design, and DFMEA as a design process.

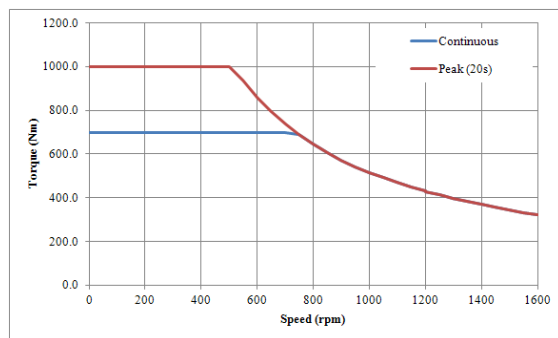


Figure 7: Performance Characteristics of Protean's In Wheel Motor

## Acknowledgments

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