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Schaeffler active *e*Differential

The active differential for future drive trains

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Preface

The development of drives for electric vehicles is coming increasingly to the fore in the search for new mobility concepts, motivated by global warming and the scarcity of fossil fuels. The Federal Government wants to make Germany a leading market for electromobility in the coming 10 years. One million electric vehicles capable of being recharged from the electricity supply system and so-called, plug-in hybrid vehicles should be driving on German roads by 2020.

Because development work in the last few decades, above all in terms of individual mobility, was primarily focused on drive concepts based on internal combustion engines, there is currently an enormous lot of catching up to do in the development of electric drive trains. Not only the technical aspects must be highlighted, the industrial structure and supply chains must also be created in order to enable the manufacture of electric drive trains for large-scale production. A wide range of existing expertise at suppliers, research associations and universities must be bundled and further developed in a network. This interlinking will enable efficient and effective use of existing resources, which will benefit all involved, as they develop future-proof systems technology for vehicle drives.

Irrespective of the topic electromobility, the number of registrations for road vehicles is rising continuously and the density of traffic is also increasing as a result. Nevertheless, in order to reduce the number of accidents, the eSafety Campaign was started with the ambitious target of halving the number of road deaths in the European Union within only 10 years by 2010. This task cannot be achieved just by improved road conditions. The drive train of the vehicle with its corresponding control system must be so intelligently designed that human error in road traffic can be corrected. The development of relevant driver assistance systems has already been initiated. The actual hardware, which also enables the use of such systems in electric drive trains, is, however, new territory that holds opportunities for innovation.

Introduction

History

The idea of arranging the differential coaxially in relation to an electric motor arose at a very early stage during development of the spur gear differential at Schaeffler. The very first designs indicated that an extremely compact drive train could be produced in this way. It was solely the innovative, Schaeffler-specific idea that was lacking, because prototypes with similar arrangements had already been built by other companies.

The idea was finally developed in cooperation with the FZG Munich to combine the transmission with a superimposing stage, in order to also integrate the electric, lateral distribution of torque within the range of functions.

Along with the significantly improved drive performance and higher energy efficiency, a fundamental advantage of this innovative drive system, which was given the name “active electric Differential” (active *e*Differential), is the possibility of integrating a driver assistance system in order to prevent accidents and to actively intervene in the control of the vehicle.

The drive axle is, therefore, the actual tool with which lateral and longitudinal control of drive torques can be realized in a purely, electrically-driven vehicle. Emergency avoidance and braking maneuvers can be realized later using these functions in test vehicles.

State of the art

Direct wheel drive using wheel hub motors

Wheel hub motors were used around the turn of the century in many passenger cars, but fell into obscurity when fossil fuels started being extracted on a large industrial scale and wide use was made of internal combustion engines.

In view of dwindling oil reserves, the development of wheel hub motors has been pursued again more intensively in recent years. For example, a concept vehicle from Volvo (Volvo Recharge Concept) has four wheel hub motors with an overall peak power of 480 kW. If the energy content of the batteries, which is sufficient for a range of approximately 100 km of pure electric operation, is exhausted, they are recharged by a range extender.

Mitsubishi has also developed a wheel hub drive for a prototype of the Lancer. This vehicle was equipped with four wheel hub motors with a maximum power of 200 kW. The motors selected were permanent magnet synchronous motors which provide a maximum torque of 518 Nm per wheel. The maximum speed is approximately 180 km/h.

Direct wheel drive via a transmission

Mercedes-Benz has presented a concept for the “SLS” super sports car, by which each wheel is driven by an electric motor via a transmission (with the ratio i = 5.5). The total power should be 392 kW. It is planned to install a high-voltage battery with an energy content of 48 kWh in the vehicle. The range should, therefore, be between 150 km and 180 km based on current perspectives.

While the wheels of the Mercedes-Benz concept study are driven via prop shafts, Michelin integrates the electric motor and transmission in one unit in the “Active Wheel”. The transmission and further chassis components are mounted along with a 30 kW motor in the wheel. This includes the brake disk, the brake caliper, an active, electromechanical spring damper unit and an additional mechanical chassis spring.

Final drive with differential

Mitsubishi is currently aiming to start volume production of a purely, electrically-driven vehicle. The four-seater “MiEV” is driven by a permanent magnet synchronous motor which has an output of 47 kW. The drive is via a final drive unit and differential to the rear wheels of the vehicle. A maximum speed of 130 km/h is specified and the range should be 144 km in the EU driving cycle.

Further examples for electric final drives with a transmission stage and differential are the Lexus RX 450 h, which is driven on the front axle by a hybrid drive and on the rear axle by an electric motor with 50 kW output, or the Tesla Roadster which is already in volume production and is a pure battery vehicle with two 168 kW electric motors that drive the wheels of the rear axle via a planetary gear.

Lateral distribution of torque (without electric drive)

The first clutch-based systems were presented in the Mitsubishi Lancer. Comparable systems are produced in volume for the BMW X6 and Audi S4. These specially-developed final drive units have additional transmission elements and controllable clutches for actively distributing torque between the wheels.

Figure 1 Rear axle differential of the BMW X6

Both driving dynamics and driving safety are increased with this system. Mechatronic systems with electric actuators and mechanical distribution of torque are only known from a concept study and have not yet been realized in hardware. The use of the system as an active system, to perform emergency avoidance maneuvers for example, has not yet been envisaged. The main focus until now was on the aspects driving dynamics and driving pleasure.

The active *e*Differential

Basic principle

A conventional, simple bevel gear differential is initially considered in order to describe the function of the active differential. The arithmetic mean of the wheel speeds corresponds with the final drive speed due to the specified kinematic conditions. When the vehicle travels round a bend, the differential speed on the wheels is compensated by a rotary motion of the differential pinion in the differential. The torque (disregarding the locking rate) is also evenly distributed to both wheels by this differential pinion. The split can be symbolized by a scale beam which is represented by the pinion and ensures that the same circumferential forces and, therefore, the same torque is applied to both axle drive bevel gears of the differential.

If the rotary motion of the differential pinion, as shown in Figure 2, was coupled directly with an actuator, the actuator would be driven by this differential motion. Conversely, a differential motion could be induced on the differential pinion and a differential speed generated between the wheels by specifying an actuator speed. Because the scale beam is unbalanced externally by the drive torque of the actuator, the torque split in the differential also changes. This means the desired effect of being able to specify any theoretical torques and speeds on the wheels would be achieved.

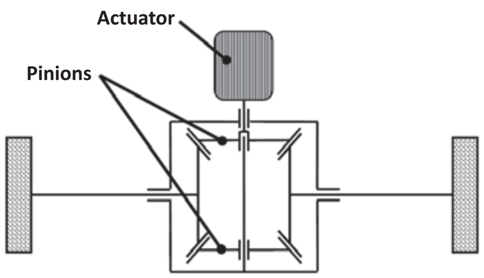


Figure 2 The principle of the active differential

A fundamental advantage of the active differential design is that no additional assemblies are required because the torque distribution is influenced directly in the differential. The actuator remains stationary when the wheels are rotating at the same speed, and only supports torque if there is active redistribution.

A disadvantage of the design shown in Figure 2 is the low ratio between the actuator torque and the differential torque, as well as the co-rotation of the actuator around the wheel axles. In order to benefit from the advantages without suffering the above mentioned disadvantages, a significantly modified differential design was selected and is described below.

The principle of lateral torque distribution

Transmissions, as shown in Figure 1, enable the torque to be individually distributed to the wheels of a drive axle. Due to different circumferential forces on the wheels, a yawing moment can be generated about the vertical axis of the vehicle with which the driving dynamics and driving stability can be influenced directly. In contrast to ESP, the vehicle is not braked by intervention of the control system. These so-called torque-vectoring transmissions, which are used on the rear axle, can in contrast to current ESP systems effectively prevent driving situations, in which the vehicle tends to drift over its front wheels (understeer), and, therefore, increase vehicle safety and vehicle dynamics.

The control of wheel torques is always carried out using speed control of the wheels. The prevailing slip conditions generate the differential torque between the wheels. Figure 3 shows the relationship between wheel speed and drive torque. It is initially assumed in State A that the vehicle is travelling straight ahead, and both rear wheels are rotating at the same speed and are driving with the same torque.

There is equal drive slip on both wheels. The left wheel is now braked and the right wheel is simultaneously driven so hard that the total drive torque on the vehicle remains constant. State B shows the relationship between the braking torque of the left wheel and the required brake slip. The drive torque on the right wheel must be increased to State C in order to keep the drive force as constant as possible despite the braking torque on the left rear wheel. Figure 3 shows the operating point required on the slip curve of the right wheel.

It can be deduced from the operating points of both slip curves that the distribution of drive torques on the driving axle requires a change of wheel speeds and vice versa. Therefore, it is necessary for one wheel to accelerate in relation to the other in order to generate the differential torque for the torque-vectoring function.

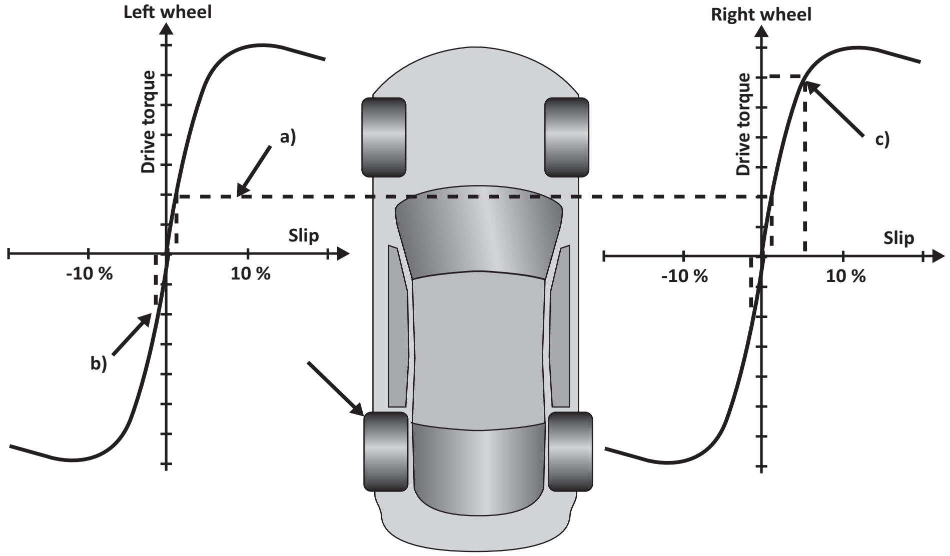


Figure 3 Relationship between wheel slip and drive torque

The design of the active differential

Overview

The electric, active differential differs fundamentally from current axle differentials. A final drive unit as in the design described below is not previously known. The selected combination of planetary gear sets in the associated transmission is also new. There are many transmission designs, which could be used to implement the design of the active differential, each offering specific advantages depending on the application.

The final drive unit shown in Figure 4 was designed for a mid-size vehicle in which each axle is driven by one main electric motor and one electric control motor, which generates the differential torques between the wheels of the relevant axle. The active *e*Differential can be basically subdivided into the assemblies “planet stage with the final drive ratio”, “differential” and “superimposing trans-

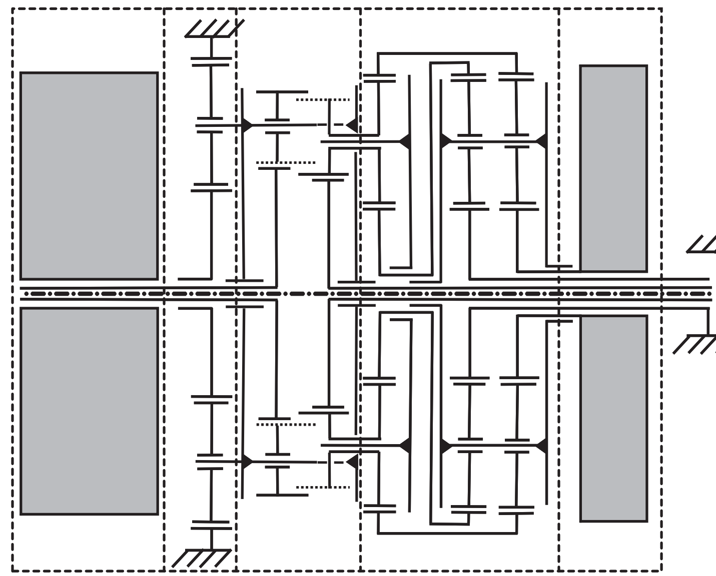


Figure 4 The design of the active differential

mission”. The assemblies are arranged together with the traction and control motors coaxially in relation to the output shafts of the differential.

The differential

A spur gear differential distributes the wheel torques evenly [1] when the control is inactive. This can comprise, as shown in Figure 4, a planetary gear with two suns and three planet pairs which mesh with each other, but other differential designs are also conceivable. The drive power of the traction motor is fed to the transmission via the final drive ratio, which can be designed as a planetary gear. The center bars of the final drive transmission and the differential are connected. The planets of the differential mesh with both suns which are each connected to one wheel. It is of elementary importance that spur gear differentials in the form described here can be combined with additional planetary gears. The three pairs of differential planets in the spur gear differential in principle fulfill the function of the axle drive bevel gears in a bevel gear differential. They compensate the speed difference between the wheels and roll against each other.

Conversely, a differential speed can be generated between the wheels by inducing a relative movement of the planet pairs in the spur gear differential in accordance with the principle from Figure 2. This task is performed by the superimposing transmission in the presented transmission concept. When a vehicle is travelling straight ahead, there is no relative speed difference between the differential planets of the spur gear differential.

The superimposing transmission

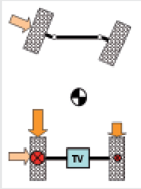
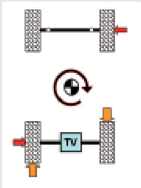
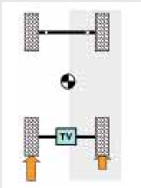
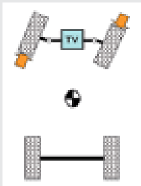
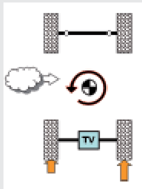
The superimposing transmission comprises three planetary gears, two of which are of identical design. In Figure 4, the left planetary gear in the superimposing transmission shares the center bar and one planet with the differential. This design, which allows an additional, planetary gear to be integrated comparatively easily, is usually called a “reduced coupling gear”. The coupling gear is used to reduce the high wheel torques, which can be generated with lateral distribution, to lower torques for the control motor. If the sun is rotated relatively to the internal-geared wheel, the planets of the spur gear differential are forced to rotate at a relative speed, whereby a speed difference occurs between the wheels. The speed of the radial, inner planet of the spur gear differential corresponds to the speed of the differential pinion in accordance with Figure 2.

Both identical sub-transmissions of the superimposing transmission share a common center bar. The sun of one planetary gear is fixed to the housing, the other sun is connected to the control motor. The internal-geared wheel of one planetary gear is connected with the sun of the coupling gear, the internal-geared wheel of the second planetary gear is connected with the internal-geared wheel of the coupling gear.

If a torque is generated by the control motor, the superimposing transmission rotates both internal-geared wheels of the identical planetary gears towards each other, i.e. an opposing torque is applied to the sun of the coupling gear relative to the internal-geared wheel. If the control motor is stationary, a differential motion of the differential planets is not possible, because in this case the sun and the internal-geared wheel of the coupling gear rotate at the same speed. The wheels also have the same speed as a result. If the superimposing transmission is not actuated, no differential torque is applied, the wheel torques are identical (if transmission losses are neglected) and the control motor does not support any torque. The control motor is also passive when the vehicle travels round a bend, where the control motor rotates without a load. If the transmission (e.g. in case of a defect) is deactivated, it operates like a conventional differential with a slightly increased lock value.

Range of functions of the active *e*Differential system

The development goal for the “active eDifferential” system is to combine the functional advantages of direct wheel drive with the benefits of a final drive via a differential, without incurring the corresponding disadvantages. The realization of lateral torque distribution, in particular, leads to a range of decisive advantages.

	**Efficiency and range** The amount of braking torque that can be regenerated on the drive axle is increased by selectively allocating torque to the wheels. If the braking torque of a wheel is limited, for example, due to insufficient vertical tire forces (wheel on the inside of the curve), an increase of the braking torque on the other wheel is still possible by distributing the torque within an axle. This means the full potential for regeneration is used, which improves the efficiency and the range.
	**Driving dynamics** Different drive torques and braking torques on the wheels of an axle result in a yawing moment about the vertical axis of the vehicle. This yawing moment is actively used to increase dynamics during rotary and steering motions. The more agile drive performance not only results in increased driving pleasure, it also improves driving safety, for example, in the case of avoidance maneuvers or when the vehicle breaks away.
	**Traction** A normal drive axle controlled by a differential does not achieve maximum traction on road surfaces that have different non-skid properties (µ-split), because the torques of both wheels must always be equal and the lowest torque is decisive. Selective allocation of torque maximizes the drive torques of both wheels and at the same time prevents individual wheels spinning.
	**Assisted steering** Different driving forces on the wheels of a steered axle generate torque about the axle’s steering pivot when the axle kinematics are designed appropriately. This allows steering lock or assisted steering to be realized by targeted lateral distribution of torques. The objective is to replace other assisted steering systems and to also enable emergency avoidance maneuvers to be carried out automatically.
	**Comfort** Negative effects such as the influence of side winds and sensitivity to lane grooves can be controlled using dynamic lateral distribution of torque. Furthermore, the generation of corresponding yawing moments allows the uniform drive performance to be set, for example. With a constant curve radius for a specified steering angle irrespective of the load or vehicle speed, as far as this is physically possible.

The transmission concept shown in Figure 4 was developed to meet the specified requirements. The direct wheel drive can perform the desired function of laterally distributing torque, but in a comparison, the innovative Schaeffler final drive unit can impress with the features described below.

The drive power is generated solely by a traction motor, and only one power electronics system is required as a result. Optimization of the electric motor with regard to efficiency and/or weight is benefited by selection of a favorable final drive ratio.

In contrast to the wheel hub motor, the unsprung masses are not increased due to the fact that the drive unit is firmly connected to the vehicle and the drive to the wheels is via side shafts. This has an advantageous effect on driving pleasure and driving dynamics.

The control motor and the superimposing transmission are able to generate the required differential torques of approximately 1000 Nm at any time. The power of the relevant electric motors for the direct wheel drive must be scaled accordingly (e.g. 80 kW per wheel to enable the normal differential torques to be generated in the normal speed ranges).

Significantly less electrical system power is required to enable the distribution of torque than with drive systems which have one electric motor per wheel. The sum of the drive torques on the wheels is not dependent on the superimposing system, i.e. the differential torque between the wheels. Therefore, the control system can be comparatively simple.

In the case of two wheel hub motors, the throttled power of one motor cannot be used by the second, unthrottled wheel hub motor. This function is possible with the superimposing transmission. The electric motors can be optimized separately with regard to their functions (e.g. the traction motor for high efficiency, the control motor for precise controllability).

The use of the innovative final drive unit is conceivable both in purely, electrically-driven vehicles and hybrid vehicles or in combination with a range extender. In addition, the transmission could also be designed without a control motor and a superimposing transmission as a conventional final drive without further modifications.

The design of the drive train for the test vehicle is planned so as to ensure the greatest possible freedom with regard to testing the torque distribution and the retention of the greatest overall level of variability. This is achieved by fitting a final drive with an active differential as shown in Figure 5, both on the front and the rear axle. This means the vehicle can be tested and compared both as a front-wheel-drive, rear wheel-drive and as an all-wheel-drive variant. It is also possible to make a comparison with a conventional drive without a superimposing transmission.

Figure 5 Vehicle design

A Skoda Oktavia of the current series was selected as a platform for the test vehicle. This is available as a four-wheel drive vehicle which makes modification significantly simpler. The Oktavia also has advantages compared to vehicles in the same class due to the available space and payload.

In recent years, numerous prototype electric vehicles have been produced on the basis of compact cars. However, compact and mid-size vehicles, which can also be used as family vehicles, have not been designed as electric vehicles until now. This is also an innovation in this project.

Schaeffler is setting up a network of recharging stations for electric vehicles with three stations in the Nuremberg metropolitan area to enable testing of the vehicle under realistic and customer-oriented conditions. Initially, this vehicle will be used as a test and courier vehicle at Schaeffler until approximately 2012. It will be subsequently made available to regional public services.

Technological risks

Overview

Newly developed systems in the automotive sector must meet high requirements from the start. In order to gain customer acceptance, unobtrusive acoustics and the use of all system advantages are expected without restrictions in the function or comfort. Low operating and maintenance costs, as well as high driving safety must also be achieved and, last but not least, driving pleasure should not fall by the wayside. In addition, the safety requirements demanded by legislators must be observed. Along with the general competitiveness of the product, aspects that are important for manufacturers are low manufacturing costs, the ability to manufacture with consistent quality and a high degree of maturity at the SOP.

The development of the drive concept, therefore, involves a considerable technological risk in many respects. All in all, the risk lies in the unfamiliarity of the overall system, whereby the individual challenges for each system component can be substantiated.

Transmission concept and design

The transmission design shown in Figure 4 was developed by Schaeffler in cooperation with FZG and is designed in hardware as a function carrier for the test vehicle. With regard to volume production, the existing concept has significant potential for improvement due to the number of parts, size and the complexity of the design. The finished solution should be simpler, more economical, smaller and of lighter design. Experience shows that several optimization loops must be carried out according to the findings, which are obtained during the project, for example, in order to find the ideal ratio in the final drive unit and the superimposing transmission. This can in turn lead to fundamental changes in the design and even a revision of the concept which always corresponds to the diagram in Figure 4.

Mechanical system

The basic mechanical design is straightforward. However, it has not been produced in this or a similar form until now. Figure 4 shows that the transmission has many tooth contacts, whereby not every tooth contact is in the main power flow and efficiency is impaired as a result.

Above all, the components of the planet stage with the final drive ratio must have the highest possible efficiency while having favorable acoustics over the entire operating range. This is particularly demanding with battery-operated vehicles which have a lower overall noise level than conventional vehicles. Highly efficient gear teeth must be developed here, which only have low sliding contact over the tooth contact area and which at the same time have constant tooth rigidity and produce low excitation in the entire transmission.

The efficiency of the superimposing transmission plays only a minor role in the overall energy balance due to the relatively low power flows. It should be imperceptible in terms of acoustics and capable of being produced economically. The decisive factor for the lateral distribution of torque is a low-clearance design in combination with the differential. A large clearance would lead to juddering in the transmission or to a slowdown in response behavior with highly dynamic control systems and rapid changes in the torque direction of the control motor. Control of the force flow path is also simpler with the clearance-free design. It is unclear to what extent a clearance-free design is possible and necessary, in order to prevent function impairments on the one hand, and

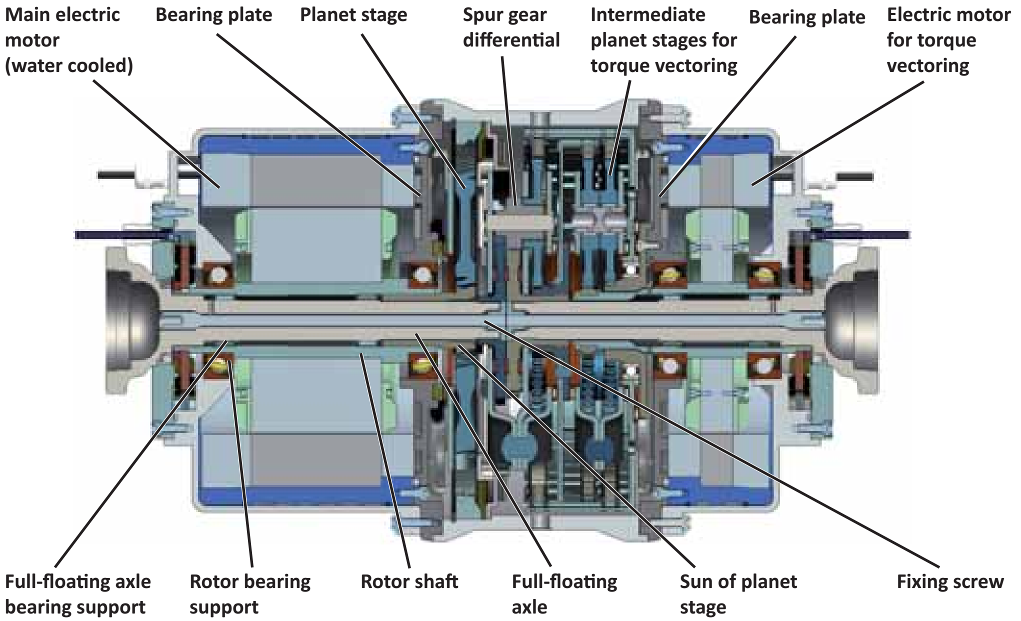


Figure 6 The design of the prototype

not to end up with uneconomically high quality requirements on the other hand. A doctoral thesis is planned about this very subject at the FZG Munich.

The development of new manufacturing technologies is required to enable particularly economical production. New and innovative lubrication concepts must be developed with regard to product functionality, which enable both cooling and lubrication of the components, while keeping losses to a minimum.

Electrical engineering, control and software

As explained at the beginning of this paper, there are different control strategies for the lateral and longitudinal distribution of torque, depending on the driving condition, which must be harmonized appropriately:

- Efficiency and range: Maximization of the regeneration phases
- Driving dynamics and driving safety: Implementation of the "active *e*Differential"
- Traction
- Assisted steering
- Comfort functions

Although there are existing control strategies for conventional drives with torque vectoring (BMW X6, Audi S4, Mitsubishi Lancer Evo) which have clutch actuators, there are no existing, state-of-the-art controls for systems with electric motors. Furthermore, a priority control between the above mentioned control strategies must be intensively developed.

The vehicle reaction must be clear, reproducible and easy to control for the customer. The "braking feeling" for the driver must be reproducible irrespective of the level of regeneration. Other vehicle dynamics control systems such as ABS or ESP must not be impaired. The safety systems must be combined in an appropriate manner.

With regard to electrical engineering, high sensor scan rates are required than with vehicle stabilization to enable the system to operate in a higher cycle range for controlling sensitivity to lane groove and side winds. To enable precise conclusions about the differential torque to be provided on the wheels, it is feasible to either calculate wheel torques based on wheel speeds and stored characteristic curves, which appears disadvantageous in view of the uncertainties, or to carry out direct, torque-sensitive recording of the required information, for which, however, a system must be firstly developed.

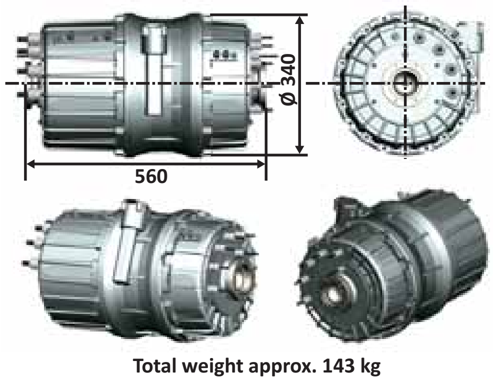


Figure 7 Dimensions and weight of the prototype

Furthermore, a suitable traction motor with the necessary key data must be developed which interacts ideally with the transmission. The control motor must operate dynamically in the low-speed range. However, it must also be economical and meet the requirements for the controllability of the transmission.

Summary

The active *e*Differential system is a drive concept which could form the optimum platform for future control strategies. The final drive unit combines the spur gear differential with an intelligent lateral distribution of torque. When used on both axles, the active differential also enables the distribution of torque in the longitudinal direction of the vehicle.

Schaeffler does not intend to become a transmission manufacturer with this innovative approach. Technologies, which Schaeffler can generally provide, are, for example, planet carriers and the previously described lightweight differential, along with the actual transmission bearing support. The components supplier must also have a core understanding about drive technology in order to contribute meaningful development work for its components and to provide the customer with optimum support.

Further motivations for implementing this transmission are future business areas which optimally combine Schaeffler and Continental technologies. At this point, reference should be made to control strategies which are being pursued by Continental and the TU Darmstadt, for example, in the "Proreta" project. As part of this project, automatic braking and avoidance maneuvers were analyzed and implemented in vehicles driven by internal combustion engines. Publications about this topic contributed significantly to the idea of the active *e*Differential.

Finally it should be noted that the active *e*Differential does not exist as a real prototype, but solely as an initial design (Figures 6, 7). Schaeffler is currently at the start of development, for which it is seeking strong development partners and customers due to the technological risks.

Literature

[1] Biermann, T.; Smetana, T.: Schaeffler lightweight differentials – A family of differentials reduced in space and weight; 9th Schaeffler Symposium, 2010

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