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ABSTRACT

For the first time, the BMW Active Steering system allows driver-independent steering intervention at the front axle with the mechanical link between the steering wheel and the front axle still in place.

The system is primarily comprised of a rack-and-pinion steering system, a double planetary gear and an electric actuator motor.

This new level of freedom enables continuous and situation-dependent variation of the steering ratio and therefore adaptation of the transmission behaviour between the steering wheel and the vehicle's reaction to the relevant driving situation. Comfort, steering effort, handling and directional stability have been extensively optimised as a result of this.

In addition, driver-independent steering intervention also guarantees vehicle stabilisation in critical driving situations.

As a world exclusive, the new Active Steering system will be available for the first time as an option in the new BMW 5 Series.

INTRODUCTION

The importance of the steering system as an interface between the driver and the vehicle is generally known. Steering transmission behaviour and feedback extensively influence the extent to which the driver is able to master his task in the driver vehicle environment control loop.

Development of steering systems in modern motor vehicles is characterised by the introduction of hydraulic power assistance throughout all vehicle classes and the substitution of recirculating ball and nut steering with the lighter and less expensive rack-and-pinion steering system in nearly all passenger cars at present. Recently, electromechanical power steering systems have begun to displace hydraulic power assistance, particularly in small and light passenger cars.

All of these developments are aimed at making vehicle operation as simple as possible, reducing steering forces to a reasonable level and ensuring the best possible feedback regarding frictional adhesion conditions between the tyres and the road surface.

Together with ZF Lenksysteme GmbH, BMW AG has developed a new steering system which is able to influence not only the steering forces, but also the driver s steering wheel input. As a result of this, the front axle steering angle can be specifically modified with respect to a given steering wheel angle.

This new degree of freedom makes high demands on the technical design because, in addition to taking safety-technical aspects into consideration, it must also be guaranteed that any new functionality which can be realized with this system is plausible from the driver's point of view and does not supersede him.

The system, its functionalities and its development are described in the following.

SYSTEM STRUCTURE

Basically, the structure of the steering system and therefore the driver's mechanical intervention into the steered front wheels are always maintained in the Active Steering system. This is the major difference between this and "steer-by-wire" systems.

Accordingly, the steering system is still comprised of the steering wheel, steering column, steering gear and tie rods.

MECHANICAL SYSTEM LAYOUT

The difference between this and conventional steering systems is a planetary gear, which has been inserted between the steering wheel and the steering gear. In order to achieve a compact layout, this planetary gear has been flanged onto the steering gear.

Fig. 1: Front Axle featuring Active Steering

The flow of power in the steering gear runs from the steering spindle to the rotary valve, then via the planetary gear trains, the steering rack and the tie rods to the steered front wheels. The planetary gear carrier has external toothing, and can be rotated by an electric actuator motor via a worm gear stage. Arbitrary actuation angles can therefore be superimposed on the driver's steering wheel input.

The advantages of this layout are numerous:

- Regardless of the function of Active Steering intervention, mechanical intervention is always retained as a safety circuit. The system can be made safe simply by shutting the actuator motor off.

- From the driver's point of view, the frictional and stiffness conditions between the steering wheel and the steering valve have remained unchanged in comparison with conventional steering systems. Like interference caused by the road surface, reactive torques arising from the planetary gear are primarily suppressed by means of conventional steering torque control.

- The patented double planetary gear train operates at low speeds, and therefore generates low tooth intermesh frequencies, with the result that the system is acoustically and haptically inconspicuous.

- Integration of the planetary gear into the normal steering gear enables a compact design which is not sensitive to tolerances.

- In the package in vehicles with the steering gear located in a low position in front of the front axle, necessary extension of the steering gear housing is possible with comparatively little effort. Thanks to this, acoustic problems in this system are easier to solve due to the great distance between the actuator motor and the passenger compartment than those which arise in a layout in which the planetary gear is positioned higher up in the vehicle (e.g. on the firewall).

The additional steering degree of freedom is actuated by means of a brushless DC motor, whose actuation angle leads to a steering angle at the front axle via the planetary gear and the steering rack. The entire actuator drive is designed in such a way that actuation intervention can be carried out in the whole frequency range relevant to vehicle lateral dynamics without significant phase lags.

Fig. 2 shows the power flow from the electric motor via the worm drive to the planetary gear carrier and the sun gear on the output side.

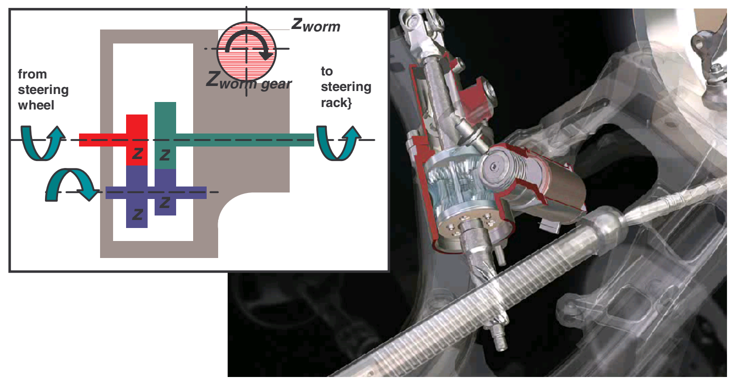

Fig. 2: Mechanical layout

This layout enables various operating states:

When the actuator motor and therefore the worm drive are stationary, the steering angle is transmitted from the steering wheel to the output-side sun gear via the drive-side sun gear and the two planetary gears. This corresponds to the driver's normal intervention into the steered front wheels. Torque feedback from the front axle, which is vital as regards the steering and driving feel, follows the same path in reverse.

If the steering wheel and therefore the drive-side sun gear are stationary, the front wheels can be angled in an arbitrary manner via the worm gear and the planetary gears, which are then supported by the sun gear facing the steering wheel, and via the output-side sun gear.

Both the drive-side sun gear and also the actuator motor, in a normal driving situation both, generally rotate. Hence, the driver's and the actuator motor's actuation angles will be superimposed and result in a front axle steering angle which comprises of both inputs.

HYDRAULIC POWER SUPPLY

In principle, the superimposed steering function requires hydraulic power assistance in order to limit manual forces to a reasonable level.

Commercially available open-centre steering has been selected for this system; however, this had to be adapted to the increased output requirements. In certain driving situations, the addition of the driver's and the actuator motor's actuation speeds may lead to a steering rack displacement at a speed which is far higher compared to conventional steering systems. These situations accordingly necessitate a higher volumetric flow of oil, in order to keep the hydraulic assistance operational.

As, however, increased volumetric flow is not required in the majority of driving situations, a general increase in volumetric flow would not be sensible, because it leads to both higher pump power consumption and power loss, which is dissipated as heat. This results in both increased fuel consumption and increased cooling capacity requirements for the steering circuit.

In order to resolve these conflicting aims, it was decided to use a vane-type power steering pump with a flow control valve on the high pressure side, whose geometrical delivery volume is designed for the maximum, theoretical actuation speed of the steering system.

In the majority of driving situations, the recirculated volumetric flow of oil can be significantly lowered in comparison with the theoretical, maximum value, with the result that the recirculation pressure and therefore the pump's power consumption and oil circuit heating are considerably reduced.

The full volumetric flow is only provided when required; this is achieved by accordingly actuating the flow control valve depending on the vehicle speed, steering wheel angular speed and actuation activity.

Pressure-side flow control offers a very dynamic and acoustically inconspicuous power supply for the Active Steering system.

ACTUATION

For the very first time, the layout described in the above enables intervention into the steering degree of freedom at the front axle without impeding the driver's steering activity. Both the functions which can be implemented as a result of this and the safety-technical relevance of driver-independent actuation intervention at the front axle necessitate a complex control concept.

A separate controller unit with two processors has been designed for the Active Steering system; these communicate with one another via a dual-port RAM. Both processors are assigned with specific tasks: one processor is responsible for actuating the electric motor and one for calculating the correct actuation angle with respect to the actual vehicle dynamics.

The status of the steering gear's movement is sensed by one angular sensor on the steering pinion (this corresponds to the steering wheel angle in conventional vehicles) and one on the actuator motor. Added to this is the steering wheel angular signal representing the driver's steering input, and sensors for yaw velocity, lateral acceleration and wheel rotational speeds, which are used together with the DSC controller unit.

Active Steering system ECU networking in the vehicle is carried out via the powertrain CAN already introduced in previous vehicle generations and via the new chassis CAN, which interconnects all chassis system ECUs (Active Steering system, DSC, sensor cluster for yaw rate, lateral acceleration and steering wheel angle) with the required, high data rate.

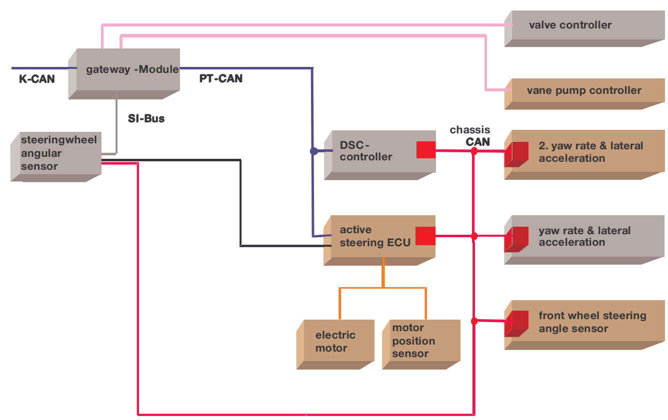

Fig. 3: CAN network including Active Steering

In contrast to other new chassis control systems such as, e.g. the electrohydraulic brake (EHB), the Active Steering system does not require any inherently safe and therefore complex electrical power supply, as it independently becomes inherently safe on failure of the electric power supply.

The solution which is depicted enables a multitude of innovative functions; only driverless operation with automatic lateral guidance is not available, because the actuator motor is only then able to trigger steering movement if the torque which it applies is able to be supported on the drive-side sun gear and therefore the steering wheel (which is held by the driver), (compare Fig. 2).

As the introduction of fully-automated vehicle operation is not anticipated in the medium-term, however, this functional limitation does not really restrict the operating range of the Active Steering system.

FUNCTIONS

Basically, the required value for the actuating angle to be set is formed in the Active Steering system's control module that contains all functionalities. They can be divided into two groups depending on whether they require feedback information from the vehicle (forming a control loop) or not.

The most obvious function that does not require a feedback loop is the variable steering ratio. On the other hand, any vehicle stabilisation function requires vehicle feedback information. Conseqently, these functions require differents processes in order to ensure stability and driveability under all circumstances.

The common feature of both groups of functions is the fact that they modify the vehicle's reaction to the driver's steering wheel inputs. In this case, steering intervention is generally continuous, and unlike brake intervention, for example is not perceived by the driver, or is at least not perceived as annoying.

As the driver is unable to see or otherwise sense the steering angle actually set at the front axle, he ascribes what he regards as a change in transmission behaviour to the vehicle, although the steered part merely modifies his steering wheel angular input.

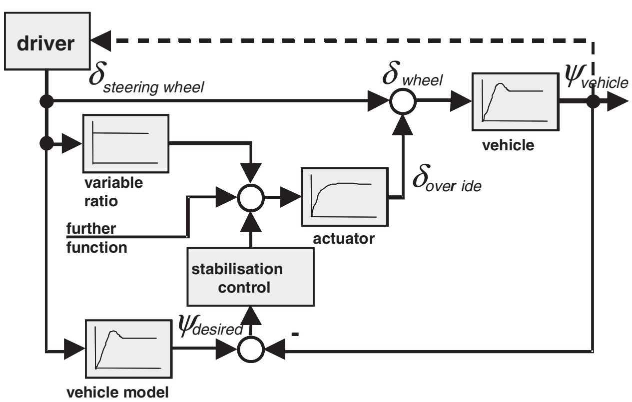

Fig. 4: Active Steering functionalities

In contrast, a controlled partial nominal value which, in accordance with its definition, has access to additional control loop information, forms a control loop inferior to driver control. The vehicle's behaviour in the closed control loop differs from that of the original vehicle.

STEERING RATIO VARIATION

The basic design conflict faced by conventional steering systems involves choosing a suitable, geometric steering ratio, as this does not only define steering effort in the manoeuvring range, but also significantly determines the vehicle's yaw and lateral acceleration transfer behaviour at higher speeds.

The desire for a direct steering ratio at low speeds, which improves handling, is therefore opposed by the demand for an indirect ratio at higher speeds, in order to ensure comfort, driveability and directional stability in the high speed range.

The Active Steering system is able to resolve these conflicting aims by enhancing steering slightly proportionate to the steering angle to the driver's input at low speeds and, accordingly, by counter-steering slightly at high speeds. The result is an increase in the front axle steering angle at low speeds and a reduction of the same in the high speed range. From the driver's point of view, this results in the impression of a steering ratio which varies according to the vehicle speed. One direct result of this function is the fact that the steering effort primarily remains constant over a wide speed range.

On the basis of an exemplary layout, Fig. 5 demonstrates that with a variable ratio the steering wheel angles that are required for all driving situations above the manoeuvring range are clearly less than 180 . Thanks to this, shuffling the steering wheel is no more requried when driving, while at the same time it is easier to operate the control elements positioned on the steering wheel (e.g. multifunctional buttons or shift paddles for automated manual gearboxes).

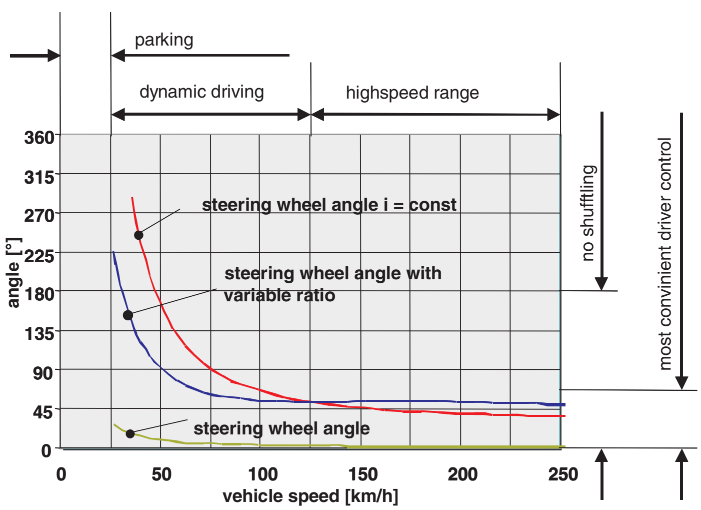

Fig. 5: Variable Steering ratio layout

On closer examination, three characteristic steering angle ranges can be defined:

- Feedback is perceived in a sensitive manner via the steering wheel in an ergonomically optimum **range 1 (±60°)** around the centre position; the driver is able to finely control the vehicle in this range. Ideally, this range should be sufficient, in the medium to high vehicle speed range, to regulate the course up to the medium lateral acceleration range. Due to the fact that it makes up the vast majority of vehicle operation, this range is characteristic of the vehicle's reaction to the driver's steering input.

- In the case of a correct seating position and steering wheel position, **range 2 (±90)** can be covered very rapidly with the correct steering technique. In this range, vehicle operation should be possible in the medium vehicle speed range up to the handling limits. In this range, lane-change manoeuvres and counter-steering in oversteering situations must be possible at maximum steering speed. The vehicle's reactions to steering inputs should harmoniously continue the "usual" range 1.

- **Range 3 (±180)** is limited by the steering wheel-arm system's movement space without shuffling the steering wheel. In urban traffic, all curve radii and turning processes should fall into this range.

However, an analysis of the useable steering wheel angle ranges is not sufficient to completely design a steering system. Fig demonstrates that no further purposeful criterion for designing a variable steering ratio can be derived from the steering effort at vehicle speeds above approx. 80 km/h.

A sensible steering system design in the medium and high speed range therefore necessitates distancing oneself from the term steering ratio. Rather, analysis of the vehicle speed-dependent yaw transfer behaviour and, at high speeds, also that of lateral acceleration transfer behaviour, is necessary.

VEHICLE STABILISATION

By manipulating the driver s steering wheel input, the vehicle can be specifically stabilised and its reaction can be approximated to the anticipated vehicle behaviour. As a result of the principle involved, stabilising intervention is limited to situations in which the vehicle oversteers; further increasing the front axle slip angle when the vehicle understeers is not helpful.

In order to calculate the correct, stabilising steering intervention, the vehicle dynamics properties such as yaw velocity and lateral acceleration are fed back and compared with the driver's input depicted by the steering wheel angle and the vehicle speed in the stabilisation controller.

In comparison with the familiar method of vehicle stabilisation via individual wheel braking, vehicle stabilisation via steering intervention at the front axle reveals a different characteristic profile:

Steering intervention is less noticeable to the driver than brake intervention, which is also more acoustically perceptible. This results in the possibility of earlier steering intervention and further linearisation of yaw transfer behaviour throughout the entire frequency range.

Steering intervention is faster than braking individual wheels, which requires a certain period of time to build up pressure. This results in advantages for steering intervention, particularly at higher speeds.

Brake intervention stabilisation performance particularly with respect to low friction surfaces is superior to steering intervention.

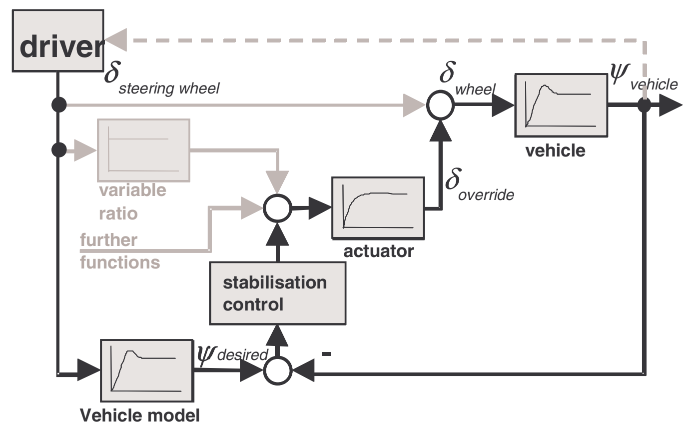

Fig. 6: Stabilization control loop

Comparison of the different characteristics reveals that optimum vehicle stabilisation is achieved by combining the Active Steering system (steering intervention) and DSC (brake intervention). However, the prerequisite of this is that the DSC controller uses the Active Steering system's summarized steering angle, not only the steering wheel angle, as its input variable. This avoids controller nesting.

In comparison with brake intervention alone, combining both systems can be used to reduce comfort-impeding brake intervention. As an additional effect, a higher pass-through speed may also be achieved in the case of certain driving manoeuvres (e.g. ISO lane change), as less vehicle speed is dissipated as a result of stabilising steering intervention.

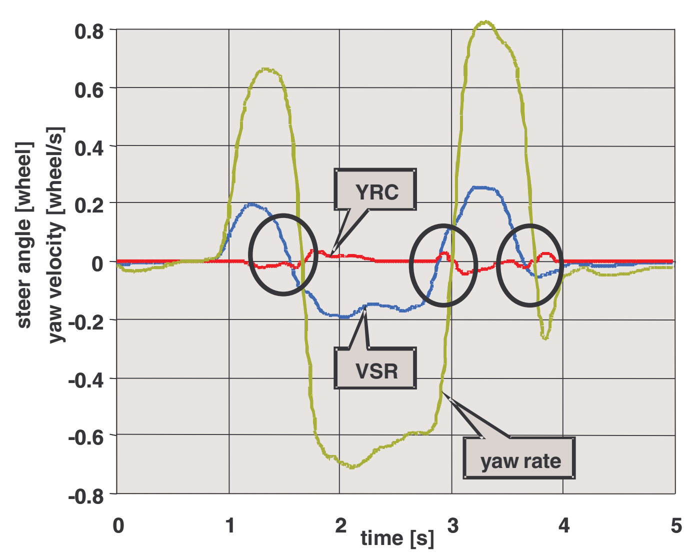

Fig. 7 Severe lane change with Active Steering

By way of example Fig. 7 shows the stabilising steering interventions in the event of a double lane change.

The reduction in steering effort is also obvious; this is a result of both the more direct steering ratio and the lower stabilisation requirements.

Control & Display

Active Steering does not require any additional control elements, as all sub-functions are automatically activated on starting the engine. When the combustion engine is not running (e.g. during towing), the Active Steering system is deactivated in the same manner as the conventional power steering system. Like customer-relevant functional limitations, such situations are indicated by a control light in the instrument cluster.

In special situations such as, e.g. operation on a race track, Active Steering system vehicle stabilisation can be deactivated. This is carried out, together with DSC deactivation, using the existing DSC button. However, the variable steering ratio remains active.

SAFETY CONCEPT

One significant aspect of the Active Steering system's safety concept is the mechanical link, which is always present and always engaged. When the actuator motor is stationary and locked, this ensures that the driver always has full control of the front axle steering angle. This enables the Active Steering system's fail-silent design. A redundant system design is therefore only required to rapidly detect faults or to increase system availability.

The safety concept is shown schematically in Fig. 4. All relevant input signals are validated using redundant sensors or measurements. Calculation of the nominal signal in the controller unit is carried out redundantly by two different processors; the driving programme is calculated by implementing the functional logic redundantly on different processors.

The selection of a BLDC motor prevents any undesired actuation movement relevant to vehicle dynamics. Any electrical failure will immediately stop the electric motor.

The safety concept is enhanced by an adapted de-activation concept. Maximum possible availability of all sub-functions is guaranteed by means of situation-dependent functional degradation. Functional de-activation ranges from the temporary or permanent deactivation of vehicle stabilisation (e.g. if the oil supply is insufficient) to limited vehicle operation with substitute values (if, e.g. the vehicle speed is not available) and complete deactivation of the entire system.

State changes which exert the greatest influence on vehicle behaviour have been analysed by independent institutes in numerous voluntary studies. It has been proved that the influence on vehicle guidance is comparable with familiar and accepted course disturbances, i.e. cross-wind or longitudinal grooves in the road surface.

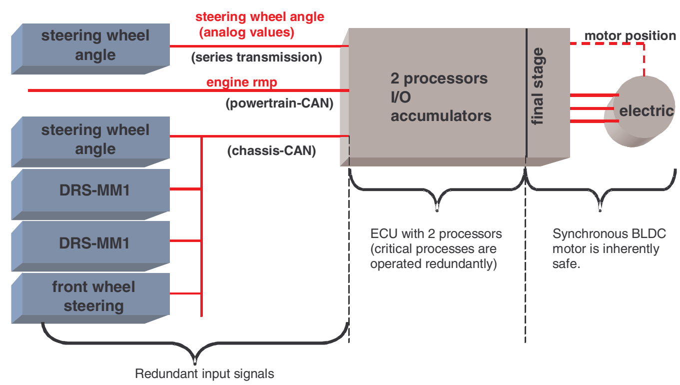

Fig. 4: Active Steering safety concept

CONCLUSION

With Active Steering, BMW has introduced a completely new steering system and herewith many new functionalities that improve the well-known BMW driving performance.

However, Active Steering avoids the typical dis-advantages of steer by wire systems and it maintains an authentic steering feedback. In the near future, Active Steering will enable even more functionalities that further improve driving pleasure.

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