INTEGRATED SMART HYDRAULIC DISPLACEMENT MACHINE FOR CLOSED SYSTEMS

Werner Döhla¹, Jörg Bauer¹, Rocco Kemnitz¹

¹*RAPA Automotive GmbH&Co. KG*

ABSTRACT

The following article describes the development, validation and series introduction of a novel highly integrated smart electrohydraulic 4-quadrant displacement machine. Starting in 2012, an unique unit consisting of a hydraulic internal gear machine combined with a newly developed electric machine with integrated electronic unit was created. The developed unit aims at the application in fully active automotive chassis in combination with hydraulic shock absorbers. The very special requirements of this application resulted in a new development with numerous detailed solutions which are described below. Parallel and interacting with the product development, all new series assembly and testing devices tailored to this product was developed.

Keywords: Fully active chassis, smart hydraulics, integrated electronics, Motor-Pump-Unit

1. OBJECTIVE

The task of the project was to develop an electrohydraulic displacement machine for fully active chassis systems. The focus was on fully active chassis systems which combine the hydraulic shock absorber with an associated hydraulic displacement machine in the basic conceptual approach. In order to be independent of the drive concept of the vehicle, an electro-hydraulic unit had to be implemented. Through the combination with a hydraulic shock absorber, the electrohydraulic displacement machine becomes part of a closed and permanently pre-pressurized system. This resulted in system-related special functional requirements for the unit which had to be taken into account in the development. In addition to dynamic aspects, the machine have to be also have sufficient compressive strength.

2. TECHNICAL CONCEPT

The result of the detailed concept considerations for the given task was the use of an integrated design consisting of hydraulic displacer and electric machine in the form of an integrated design. Specifically in the form of an under oil running electric machine with direct hydraulic connection to the displacer. With this design, no sealing of the drive shaft to the atmosphere is necessary, an aspect which was given high priority, since such a seal has various

disadvantages. In addition to the entry of mechanical friction as a result of the sealing and risks to the compliance with the sealing requirements over the entire operating range and the service life, the sealing, due to the permanent pressurization of the closed system, also poses requirements that can hardly be met with currently known sealing systems. On the other hand, the electrical machine have to have the appropriate pressure resistance, a challenge whose solution is described in more detail in section 3.1.

3. COMPONENTS

3.1. Electrical motor

A comparison of different types and designs of electric motors showed the use of a permanently excited synchronous machine as the most appropriate solution. In addition to its basic suitability for a wet-running machine, the very compact design is an argument in favour of using such a design due to the high power density of the machine. To define the basic design of the permanently excited synchronous machine, numerous designs were compared with each other by means of simulation analyses. Basically, the use of a so-called 12/10 design was identified as a very suitable topology. This involves 12 stator teeth which are combined with a 10-pole rotor. For the rotor, a star-shaped arrangement of

the 10 permanent magnet stacks within the lamination stack has proven to be the most advantageous solution. The selected rotor design is shown in figure 1.

Figure 1: Rotor design

The cuboid permanent magnets are inserted into the correspondingly shaped openings in the sheet metal packet. Radially, the permanent magnets are held positively by the laminated core. In order to fix the magnets axially, the laminated core equipped with the permanent magnets is overmoulded with a thermoplastic material. The plastic overmoulding is also used to make the rotor easy to balance. For this purpose, a type of plastic disc with numerous mounting holes evenly distributed around the circumference is injection moulded onto both axial ends of the laminated core. Balancing elements in the form of metal balls are pressed into the cylindrical openings during the balancing process. This method of additive balancing is, in addition to the simple design, also ideally suited to ensure that, in contrast to negative balancing forms, no contamination is left behind in the production process. The greatest challenge in the development of the electrical machine was to find a suitable design form that combines the necessary compressive strength on the one hand with the requirement for a compact design and high efficiency on the other. Concepts with a completely hydraulically flooded motor, i.e. flooding of the stator space as well, were rejected because the surrounding housing was too large and heavy for this case. Since this variant was not the solution, an other solution had to be developed which would provide a hydraulically pressure-resistant seal between stator and rotor. There are known solutions for this task in the form of so-called can which are arranged in the magnetic working air gap between stator and

rotor. For the pressures occurring in the specific application, the market provides metallic cans. However, the electrical eddy currents occurring in the metallic can reduce the efficiency of the electric machine. Such a decrease was not acceptable under the given objectives regarding the efficiency. The only way out is to use a canned tube made of an electrically non-conductive material. With regard to an automotive series application and the associated restrictive cost structure of the individual parts, a solution made of glass fibre reinforced thermoplastic material is aimed for.

Despite the prevention of eddy currents, the wall thickness of the plastic can must be within a few tenths of a millimeter. A larger magnetic working air gap would also unacceptably damage the efficiency of the machine. Accordingly, a constructive design of the plastic can is found in numerous simulation loops, which on the one hand is supported on the inner diameter of the stator teeth with a wall thickness of approx. 0.5 mm only and on the other hand is thickened in the stator tooth gaps. The thickened area is trapezoidal in shape. Together with the correspondingly shaped counter contour on the stator teeth, this results in a supporting effect which can ultimately fulfil the required compressive strength. Due to the supporting effect of the trapezoidal thickening, the radial build-up is so low that it does not protrude into the winding space and thus does not reduce it. Figure 2 shows a cross-section of the developed can geometry.

Figure 2: Plastic can design

In this version it is finally possible to use a can made of 40% glass fibre reinforced PPA which

can withstand operating pressures up to 150 bar and 120°C temperature load. The stator is made of two several parts and consists of a stator yoke in which the stator teeth with the single tooth coils on them are inserted in the form of a stator star. Figure 3 shows the design of the stator yoke and stator star.

Figure 3: Stator assembly consisting of stator yoke and stator star

For better heat dissipation of the coils, the stator space is filled with a 2-component potting compound. In addition to heat dissipation, the potting compound fixes the motor coils and also provides additional mechanical support for the can. Figure 4 shows a typical torque vs. speed limit characteristic of the developed electrical machine.

Figure 4: Speed vs. torque limit characteristic

Maximum speeds of approx. 6,500 rpm on the one hand are opposed by a maximum torque of approx. 11 Nm on the other. To achieve high speeds on the motor, the permanent magnetic field of the rotor magnets must be counteracted electromagnetically by means of field weakening in order to be able to increase the speed further.

3.2. Displacer

An internal gear machine with a nominal positive displacement volume of 4.3 cm³ per revolution is used as the displacement principle. This principle represents the ideal solution for the application at hand. The internal gear machine is geometrically compact, is capable of delivering high hydraulic pressures, in this case up to approx. 130 bar, and allows operation in all four quadrants. As a specific design of the internal gear machine, an axial and radial leakage compensated 15/20 version is used. An internal gear with 20 teeth interacts with a 15-tooth pinion. The pinion is driven by the one-piece shaft of the electric machine. The ring gear is supported by a plain bearing in the housing of the displacer. Axially on both sides, so-called axial washers nestle against the gear set. The axial discs are pressed hydrostatically against the gear set and take over the hydraulic control of the machine. Moulded elastomer seals arranged on the rear side give the axial discs axial freedom of movement as tolerance compensation on the one hand and prevent hydraulic short circuits and thus internal pump leakage on the other. Leakage compensation in the machine is carried out radially by means of a split, hydrostatically activated filling piece. The inner segment of the filling piece contacts the pinion, the outer part of the filling piece contacts the ring gear. A sealing element is located between the filler halves. The leakage path between the pressure and suction side is thus closed. Figure 5 shows a top view of the gear unit with the intermediate filler assembly.

Figure 5: Leakage compensated internal gear machine

The leakage-compensating measures enable an almost ideal volumetric behaviour. At low pressures the volumetric efficiency is almost 100%. The volumetric efficiency versus pressure characteristic is shown in Fig. 6.

Figure 6: Typical volumetric efficiency vs. pressure and torque vs. pressure curve

The high volumetric efficiency allows a very good response of the machine in reverse operation, an important function in the present application where the machine constantly changes its operating point across all four quadrants. The internal gear machine described here is based on a solution that already exists on the market. The challenge with this component was, on the one hand, the automotive industrialization of the machine originating from the industrial sector and, on the other hand, the necessary optimization of the noise behavior. Although the principle used in industrial applications appeared inconspicuous, considerable detail optimizations were necessary to reduce the pressure pulsation introduced into the downstream system and to reduce the radiated airborne noise. No less challenging is setting up and validation of the series supply chain for the demanding individual parts of the displacer unit.

3.3. Electronics

The electronics unit to drive the electric machine is flanged directly and radially to the bottom of the motor housing on the side facing away from the displacer machine. The motor housing is used as a thermal sink for cooling the power semiconductors. A permanent magnet located at the end of the motor shaft facing the electronics serves as a position sensor for a Hall sensor on the electronics to detect the actual position of the rotor. The housing is thin-walled between the permanent magnet as rotor position sensor and the Hall sensor. The thin wall seals off the hydraulic area from the electronics on the one hand and still allows the Hall sensor to detect the permanent magnetic field sufficiently. The integrated electronics have all the contents for controlling the electric machine and thus make

the machine a smart unit. Besides the power supply, which is designed for 48V, the default signals and status variables are exchanged via a CAN bus connection. Speed or torque can be selected as target values for the motor controller. Various actual values of the machine are available as status information on the CAN connection. It is especially worth mentioning that measured actual pressures are also made available at the two hydraulic connections of the machine. The measured pressure values are determined via two miniature pressure sensors integrated in the hydraulic machine. The two sensors are integrated in the housing of the hydraulic machine, not visible from the outside, and are electrically connected to the electronic unit via a contact assembly through the motor. In addition to measuring pressure, the two sensors also record the temperature at the installation location. In addition to the functional concerns, the electronic unit fulfils an ASIL classification according to Level C for selected features that have been agreed with the customer. Mechanically, the electronic unit consists of two printed circuit boards, the power board attached directly to the motor housing and a signal board. Both printed circuit boards are mechanically and electrically connected to each other via an intermediate assembly. The intermediate assembly is a plastic carrier part in which the geometrically large and heavy electronic components of the electrical intermediate circuit and the input filter are mechanically fixed. In addition, contact bridges are arranged in the part for the electrical connection of the two boards adjacent to the front sides of the intermediate assembly. The intermediate assembly and the two circuit boards form a stacked structure which is screwed to the bottom of the motor housing. The three electrical motor phase connections pass through the bottom of the motor housing and the power board and are screwed to the power board with contact elements. The developed electronic unit can provide electrical string currents of up to 120 Arms. Figure 7 shows the developed machine without electronics housing.

Figure 7: Explosion view

Figure 8: View on the on board electronics unit

3.4. Housing and interfaces

For a compact design, the hydraulic and electric machine are integrated into each other. For this, the two components can no longer be operated as individual components. Thus the unit works with a common shaft coming from the electric machine and projecting into the hydraulic machine. As a consequence, there is only one common bearing point for the shaft between the electric and hydraulic machine. Thus the hydraulic machine forms the A-bearing of the electric machine. The two bearings near the gear set are designed as plain bearings. Opposite this, at the other axial end of the shaft, a fixed bearing in the form of a roller bearing is arranged. Aluminium die-cast parts are used as the surrounding housing for the hydraulic machine, the electric machine and the electronic unit. In

addition to accommodating the components, the housing also serves to provide or accommodate the various interfaces. Figure 8 shows an exploded view of the entire unit. Although the electrical machine is designed to be pressure-resistant, as described above, the pressure in the rotor chamber is additionally controlled by two mechanical check valves. There is one check valve each between the rotor compartment and the two hydraulic connections of the unit. With the help of this hydraulic circuitry, the leakage oil from the pump, which is fed into the rotor chamber via the hollow shaft, is drained off and can only build up pressure in the rotor chamber at the level of the lower pressure of the two connections.

4. TESTING AND VALIDATION

4.1. Functional testing

Figure 9 shows a typical pressure vs. flow limit curve of the developed machine.

Figure 9: Pressure vs. flow limit characteristic

The unit is capable of delivering volume flows of up to approx. 26 l/min on the one hand and pressures of up to approx. 130 bar on the other. The response times of the unit are particularly relevant for the intended application. It is important to influence the hydraulically coupled shock absorber of the vehicle depending on the current driving situation. **Figure 10** shows a characteristic hydraulic step response measurement.

Figure 10: Flow step response

After less than 10ms from the time the setpoint is applied to the CAN connection, a volume flow is available to build up pressure in the downstream system. The pressure response depends on the hydraulic stiffness of the downstream system. Numerous new product-specific test possibilities have been created for the developed displacement machine. At the very beginning of the project, still in the concept phase, a function test bench was put into operation in order to be able to carry out benchmark tests and concept comparisons. In addition to an overall function test bench, a further test bench for measuring the electric motor was created. The characteristic values of the electric motor are determined on the engine test bench. Numerous small test benches for measuring the unit via temperature and especially in the noise measuring chamber round off the testing possibilities.

4.2. Endurance testing

The unit fulfils all requirements which are placed on components installed in the underbody area of motor vehicles. The housing and interfaces are

designed according to protection class IP69. In the lifetime validation, the units were subjected to a load which corresponds to an operating time of 8000h operation. To apply these test loads, specially designed test benches were put into operation. In the endurance tests the extreme robustness of the developed design is demonstrated. Since the motor is designed to be virtually wear-free, the evaluation of the internal gear machine after the endurance tests is of particular importance. Endurance tests in early prototypes have already shown that the selected internal gear machine is excellently suited to the service life requirements. Here, the use of a robust component from the industrial sector pays off particularly well. As a result of the endurance tests, a slight improvement in the overall efficiency of the unit over the test period is characteristic. Such an evaluation is shown in **Figure 11**.

Figure 11: Typical total efficiency characteristic vs. life time testing

5. LAUNCH AND START OF PRODUCTION

The developed unit is completely produced at RAPA Automotive GmbH&Co. KG in Selb. The focus is on the assembly and testing processes. Primary parts as well as the circuit board set of the electronic unit are purchased from external specialists. In the course of the project, a completely new production hall with an impressive production line was built for this product. The assembly sequence is serial with buffer possibilities. Special processes such as the injection moulding of the rotor or the winding of the stator coils are arranged in the assembly flow. Product design and assembly are coordinated. For example, in a winding process two coils are wound simultaneously, a so-called coil pair. On the one hand, this shortens the cycle time in

production for the winding process and the electrical connection of the coils and, on the other hand, enables a simplified design of the connection assembly which electrically connects the coils of the stator to the three phases U, V and W as interface to the electronics unit. A vacuum potting process is used to reliably fill the stator space with the narrow gaps with the 2-component potting compound. Here, the volume to be filled is subjected to vacuum before the filling process. The End of Line function test bench was designed and built in parallel to the development of the product and was already put into operation during sample production and further optimised until the start of series production. The basis for this was the laboratory test bench, which was designed and installed at the beginning of the project. A similar approach was taken in the design of a test step for the electric motor, which was temporarily stored in the assembly line. Here, various measuring methods were first examined and evaluated on the motor laboratory test bench with regard to their suitability for integration into the assembly process before a suitable test method for series assembly was defined.

6. FURTHER DEVELOPMENT

There are already numerous approaches for the development of a further generation of the presented electro-hydraulic displacement machine. One goal is to provide units for use in HV power supplies of motor vehicles in addition to the currently operated supply voltage of 48V. In addition, there are also efforts to further reduce the size of the units by increasing the power density of the electric machine.

7. SUMMARY AND CONCLUSION

In the project presented here, a highly integrated electro-hydraulic displacement machine has been developed since 2012, especially for use in fully active chassis systems of motor vehicles. In addition to the automotive industrialization and optimization of an internal gear machine, the electric machine including an integrated electronic unit was completely developed and could thus be tailored to the very special requirements of the intended application. The first series application in a customer's vehicle started in the fall of 2018. The OEM is a German premium manufacturer that will also offer the

fully active chassis system in which the unit is installed in another model series from 2020. RAPA Automotive GmbH&Co. KG is thus supplying the pressure supply unit for the world's first series active chassis based on fully active shock absorbers. The technology is currently being used in the first premium vehicles. A further distribution in the upscale vehicle segment is possible. Completely new topics, such as measures against motion sickness, will open up further fields of application for active chassis systems in the future and thus also further potential areas of application for the presented technology.

Figure 12: Developed smart device