DEVELOPMENT OF A NEW HYDRAULIC FREEWHEELING VALVE HCC-200

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This paper presents development of a new hydraulic freewheeling valve HCC-200, intended for activation of two hydraulic motors in rear drive axle of an agricultural combine harvester. Complete development process of the valve was supported by several numerical simulations. Before producing first physical prototypes, polymeric 3D printed models of new components were produced for initial study of production process. First physical prototypes of the new valve were produced in a specific modified version that allowed integration of main spool position monitoring sensor and additional pressure sensor to monitor specific internal chamber of the valve. Both monitored variables are important for evaluation of both valve and system behaviour. Extensive system simulation was performed prior to field test campaign. Simulation results confirmed the functionality of the valve and at the same time identified few potential weak points of the system, for which alternative solutions were provided to customer for the test.

Keywords:
combine harvester, hydrostatic transmission, freewheeling valve, numerical analysis, testing

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1 Intruduction

New Poclain Hydraulics freewheeling valve HCC-200 was developed for combine harvester application. Combine harvester is a self-propelled agricultural machine that is used to harvest grain crops from farm fields. With its processing system it separates grain and the waste, which is typically shredded and left on field. Grain is collected in tanks integrated into machine.

Combine harvester is operated by an operator, who controls the machine operation from the cab located high in front of the machine for good visibility of the environment. Depending on the configuration of land and harvested fields a machine could be configured for two-wheel drive (2WD) or four-wheel drive (4WD) mode operation.

Figure 1: Typical combine harvester machine
Source: own

Development of a new freewheeling valve enabling shifting between 2WD and 4WD mode of combine harvester is presented in this article. Freewheeling valve controls two motors in the rear wheels of the machine.

1.1 On hydraulic power transmission system

Typical hydraulic power transmission system consists of components, shown in Figure 2. Machines that are using such power transmission system are usually equipped with hydraulic motors, which are connected to variable displacement hydrostatic pump. Often one or more motors (typically on one axle) are intended for on-demand drive function. In this case an additional valve is required, which controls the engagement status of the motor(s).

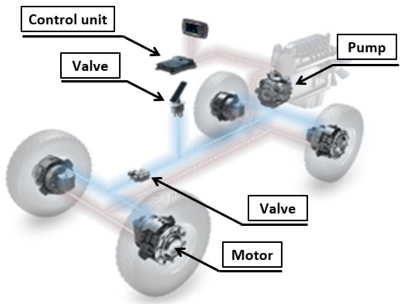

Figure 2: Hydraulic power transmission system
Source: own

Hydrostatic transmission drive is a typical drive type on combine harvester machine. While primary drive is on the front axle, some machines have an option of powered rear axle as well. This is an on-demand feature that utilizes hydraulic motors integrated into wheels of machine rear axle by sharing the same pump flow. Shifting from two-wheel drive mode (2WD) to 4WD mode is done using freewheeling valve.

1.1.1 Freewheeling valve

Freewheeling valve controls engagement status of hydraulic motor in rear driving axle. The name comes from its function, which enables almost free rotation of motors (and wheels respectively) with minimal losses or dragging torque. This is done by draining motor working ports to tank. At the same time motor case is slightly pressurized, which keeps motor pistons retracted and separated from the cam. Hydraulic schematic of basic configuration of freewheeling valve is shown in a Figure 3.

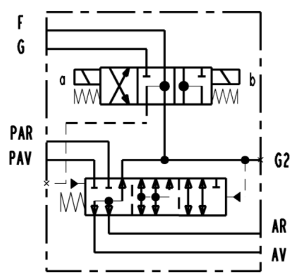

Figure 3: Hydraulic circuit of freewheeling valve (basic configuration)
Source: own

Ports PAR and PAV connect valve to the pump while ports AR and AV connect valve to the motor(s). Port G is fed from charge pump, port F is drained to tank line. G2 port is optional and carries pilot pressure information. Freewheeling valve consists of two main sections; a high-pressure section that connects a main drive pump with the motors and a low-pressure section that allows release of pressure in motors when not being activated and controls motor engagement and disengagement phases.

Figure 4: Freewheeling valve HCC-200
Source: own

While high-pressure section of HCC-200 valve is functionally identical to basic configuration of freewheeling valve there are some differences in low-pressure section of the valve. It features hydraulically piloted directional spool valve and additional solenoid operated directional valve to control pilot pressure for displacement change on hydraulic motor. Valve provides the ability to engage and disengage rear motors regardless of vehicle travel speed, i.e. stationary or on-the-fly shifting.

1.1.2 Radial piston hydraulic motor

Poclain radial piston motor is a high-torque low-speed hydraulic motor that works on cam lobe principle.

Typically for combine harvester application, a dual displacement motors are integrated in the circuit, with control spool valve that shifts between both displacements values when pilot pressure is applied to port Y. Motor ports as shown in Figure 5:

– A, R: Working ports (feed and return)
– F: Motor case port (leakage drain and case pressurisation)
– Y: Displacement control spool pilot port

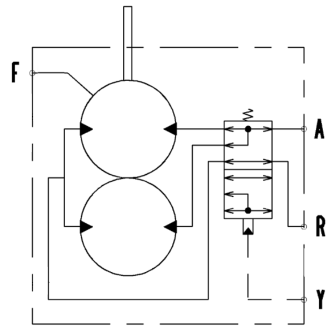

Figure 5: Hydraulic circuit of dual displacement hydraulic motor
Source: own

Two main modes of the motor in 4WD application are:

– Working mode
Ports A and R are connected to hydrostatic pump in a closed-loop configuration. Pistons are extracted out of cylinder block and are pressed against the cam. Motor is generating output torque.
– Freewheeling mode
Ports A and R are connected to tank line. Slightly pressurized port F sustains certain pressure in motor case that keeps motor pistons retracted inside the cylinder block. Motor can be rotated with minimal dragging torque.

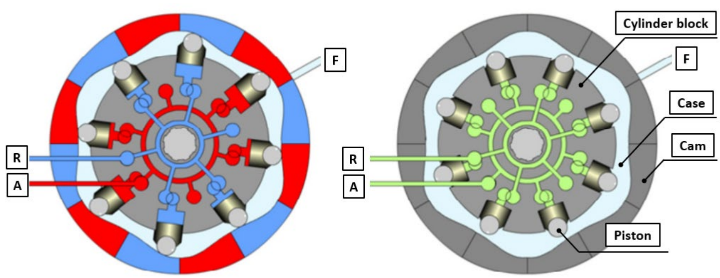

Figure 6: Hydraulic motor in working mode (left) and freewheeling mode (right)
Source: own

2 Valve design and validation process

During the project with combine harvester manufacturer a new freewheeling valve had to be developed because basic (catalogue) configuration of the valve did not meet given system requirements. Due to early implementation date of new valve integration, there was a tight schedule put in place for the team to complete and validate the design of the valve. Several actions were taken to minimize development time and specifically minimize risk of mistakes along the process. Due to short timeline, it was important not to introduce any delay. All common design steps were performed when preparing the design of the new valve:

- 3D concept
- DFMEA (Design Failure Mode Effect Analysis)
- Tolerance stack-up analysis
- Flow analysis (Computational Fluid Dynamics - CFD)
- Structural analysis using finite element method (FEM)
- Functional analysis (1D lumped model simulation)

Apart from usual design steps some specific actions were taken to assure that potential issues are identified and resolved as early as possible – Table 1:

Table 1: Valve design steps

Action	Description	Risk management impact
3D print	Production of new casted components in 3D technology	Early check of tools, fixtures and clamps for machining process
CR inspection	Computed radiography inspection of new castings	Detect potential issues on new parts before launching full validation campaign
Additional sensorics	Integrate spool position monitoring and main spool piloting pressure monitoring. Custom port adaptors produced for testing.	Monitoring of additional valve internal variables. Controlled flow conditions, alignment of test results and simulations.
Functional system simulation	Evaluation of valve and system performance using 1D multiphysics numerical model	Identification of potential critical points. Definition of alternative options.

3 Numerical approach

A significant part of design work was supported by numerical simulations evaluating different aspects of valve characteristics and performance. Some key analyses are presented in this chapter: Structural analysis, Flow analysis, Functional analysis and System integration.

Structural analysis: All main components of the valve were designed from scratch due to specific project requirements. Each of them was calculated for its stress and fatigue lifetime. Most of new components are non-standard and were evaluated by structural analysis using FEM, except for a new compression spring where a standard calculation procedure according to EN 13906-1 was applied.

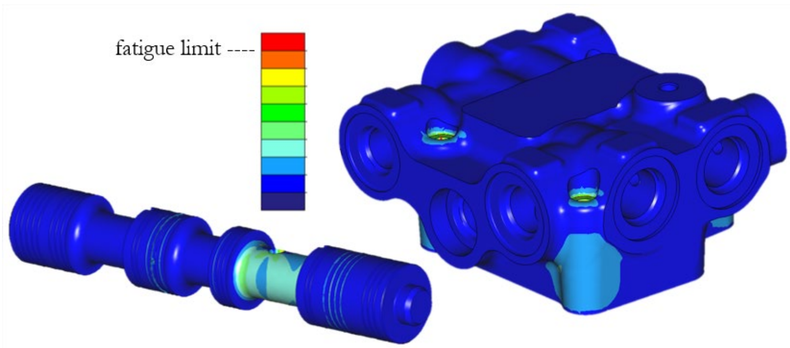

Figure 7: Von Mises stress distribution on spool and pilot housing
Source: own

Flow analysis was performed by CFD simulation tool StarCCM+. Three main focus points of investigation were:

- Pressure drop across main flow lines (main pump to motor)
  This was one of main constraints when designing the valve. Pressure drop directly affects the power consumption on the vehicle during 4WD operating mode. Valve size greatly depends on this requirement.
- Pressure drop (also local at the valve functional internal points) from valve low-pressure section to motor line ports (charge pump to motor and motor to tank)

Pressure drop in piloting lines plays an important role in dynamic 4WD mode engagement and disengagement events. Shift between 2WD and 4WD mode needs to be enabled at any vehicle speed, which requires adequate sizing for both extraction and retraction of motor pistons.

- Flow force on main spool
  Flow force can have an important impact on shifting ability of the valve, therefore its understanding is critical to predict valve operating range.

Functional analysis: Numerical evaluation has been performed by commercial simulation tool Simcenter Amesim (2021.2). In the first step, detailed 1D lumped model of a new freewheeling valve has been created and tested for its basic functionality. The model has been tuned so that its response fits the results of flow analysis in terms of pressure drop and flow forces on the spools. Shifting ability of the valve was checked under specified worst case operating conditions (pressure, flow).

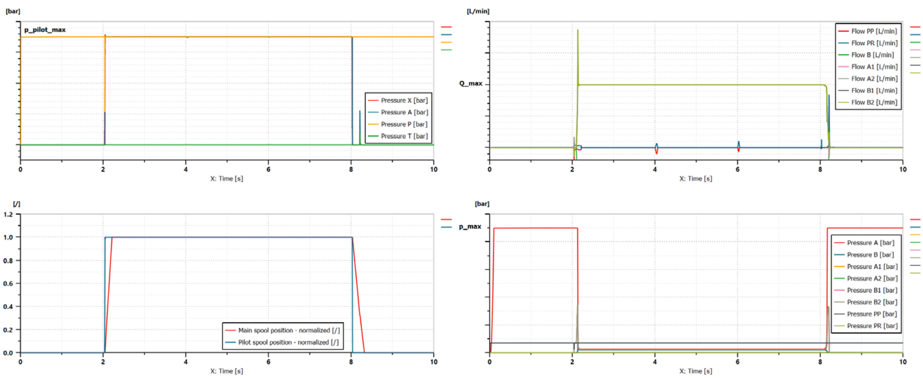

Figure 8: Simulation of valve shifting ability

Source: own

System integration: Based on available data on hydraulic circuit of the machine a system model has been built and valve model integrated into it.

Simulation of system behaviour is important, because new freewheeling valve introduces important functional change in machine 4WD circuit compared to previous circuit configuration. It was therefore deeply investigated and evaluated using functional system simulations.

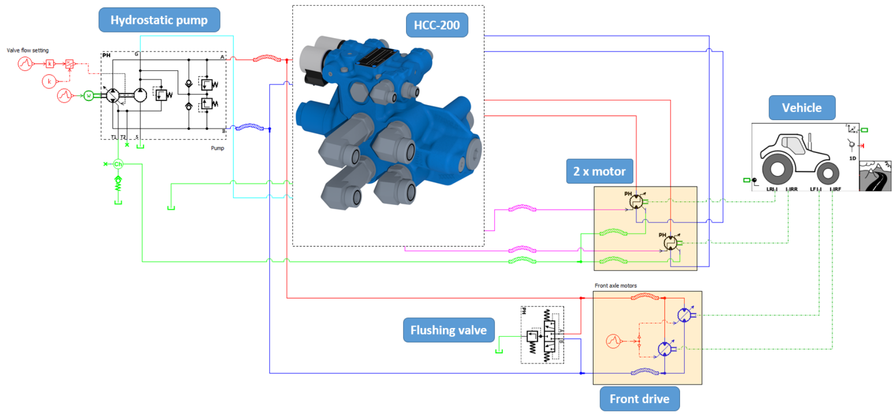

Figure 9: Numerical model of vehicle hydrostatic transmission
Source: own

Due to limited information provided by OEM, the confidence level on simulated system response is limited as well. For that matter some additional sensitivity studies were performed where critical valve parameters were modified and response evaluated for resulting trends. Such modifications were mostly evaluated for their impact on dynamic response of the system, i.e. shifting on-the-fly between 2WD and 4WD mode.

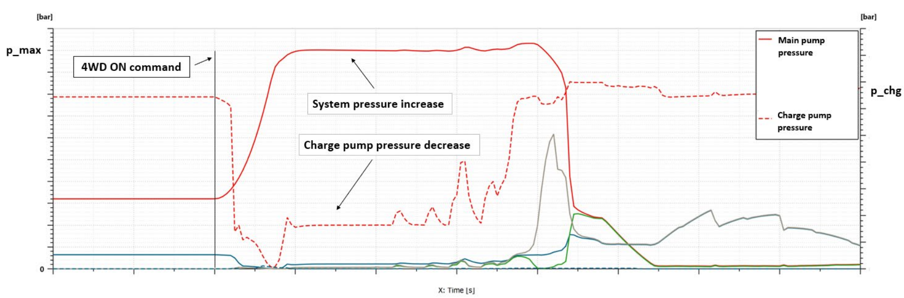

Figure 10: Baseline simulation response of 4WD activation
Source: own

Figure 10 show simulated baseline system response at activation of 4WD. It shows two points that need to be addressed to make system work properly:

– Rapid increase of system pressure at 4WD activation

- Charge pump pressure decrease at 4WD activation

Further analysis identified two important aspects linked to improvement of system response:

- Front drive control
  It is necessary to adjust displacement in front drive when transitioning from 2WD to 4WD mode and back. Timing of this change is critical for good performance and operator's comfort. Understanding the dynamics of valve shifting process is important for control tuning. Impact of valve design parameters variation was studied with simulation.
- Charge pump flow capacity
  New valve utilizes charge pump flow when engaging motors, which is different from customer previous circuit configuration. System impact was evaluated due to high instant draw of oil flow into motors during engagement.

4 Prototype build and testing

A new freewheeling valve has been developed, manufactured and tested internally by Poclain Hydraulics. The design of prototype valve included additional features that were not intended for later serial production design.

4.1 Prototype samples

Two new casted components (raw parts of both housings) were designed during the project. To enable machining of these parts also new clamping tools and fixtures needed to be designed. 3D polymer prints of components were produced for basic demonstration purpose and for an early check of fit between casted parts and the clamping tool delivered by external supplier.

A mistake in one of clamping pins height was detected by this check. With a quick corrective action the clamp has been reworked before first casted parts were delivered and available for machining. No project delay was therefore resulting from clamp issue.

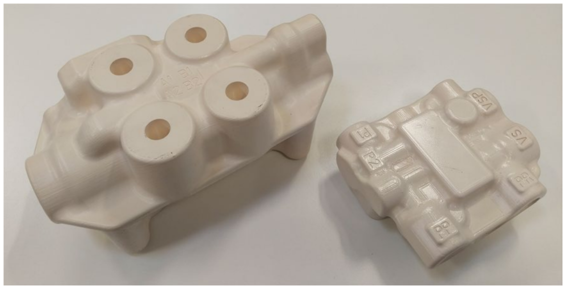

Figure 11: Samples of new castings produced by polymeric 3D print process
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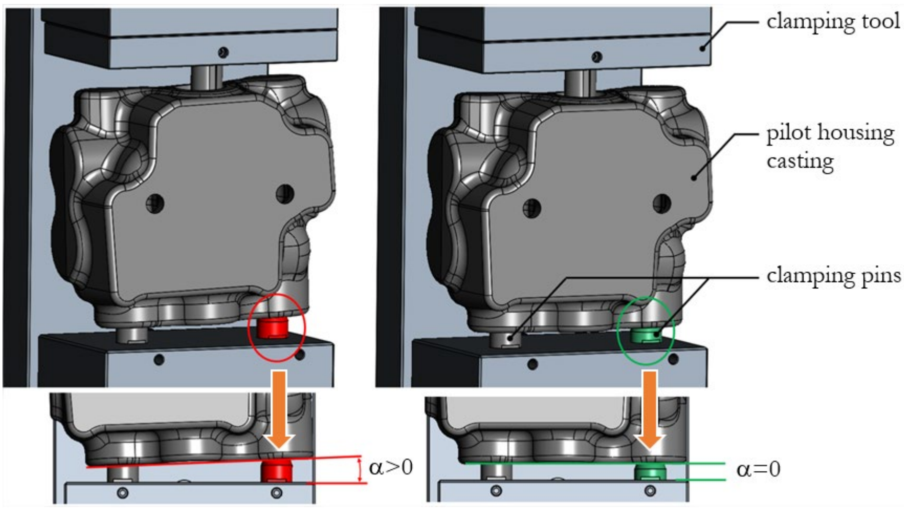

Figure 12: Wrong (left) and correct (right) clamping pin height on clamping tool
Source: own

New casted components of the valve were set for sand casting process. Casting process often requires additional modifications after initial batches in order to reduce risks of porosity, surface defects etc. Non-destructive method of CR was used to inspect the samples before building the valves and launching the validation tests. This assured there were no hidden defects that could be discovered late in testing phase and caused non-representative test results and a need for repeated testing and associated delays.

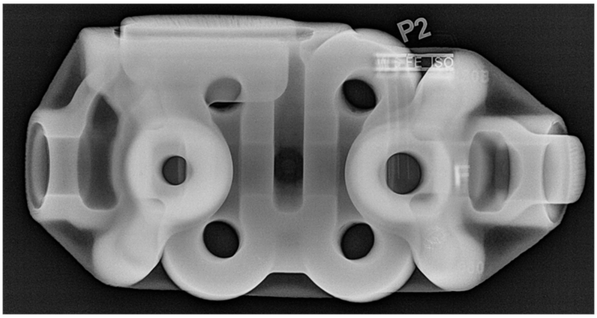

Figure 13: CR inspection of main housing casting
Source: own

Main spool position and its pilot pressure level are two internal variables of the valve that are not monitored on serial production machines. However, experience from previous projects proved that monitoring these variables gives important additional information about status and dynamic performance of 4WD system during its validation. Custom adaptor plug and associated clamps were designed to integrate both spool position sensor and pilot pressure sensor to prototype valve.

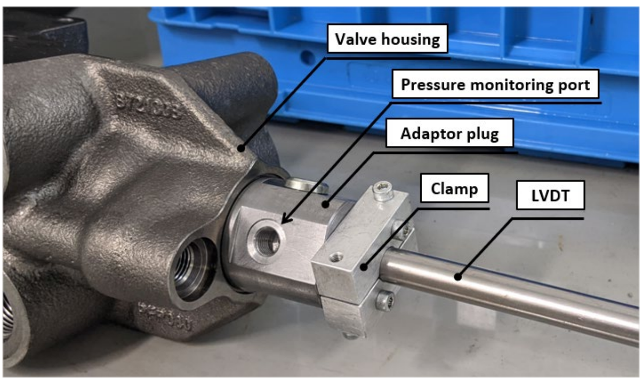

Figure 14: Adaptor plug with LVDT integration and pressure sensor port
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Custom port adaptors were designed to be installed in valve ports during bench tests. They were designed in a way to assure adequate flow section and diagnostic ports with defined position.

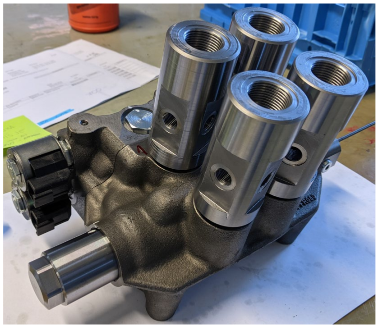

Figure 15: Custom port adaptors
Source: own

Benefits of using such custom adaptors is that they eliminate usage of various fitting types with different flow sections, reductions/expansions and possible local effects that they reflect in measurements. This gives better confidence in measured characteristics of the valve, in particular pressure drop values. 3D model of custom adaptors was used in flow analysis (CFD) as well, therefore a correlation of measured and simulated values was possible for further tuning of functional 1D numerical model.

4.2 Characteristic and endurance bench testing

Prototype samples have been tested on hydraulic test bench to check main hydraulic characteristics as well as structural integrity. Samples were built with additional monitoring features as presented in previous chapter.

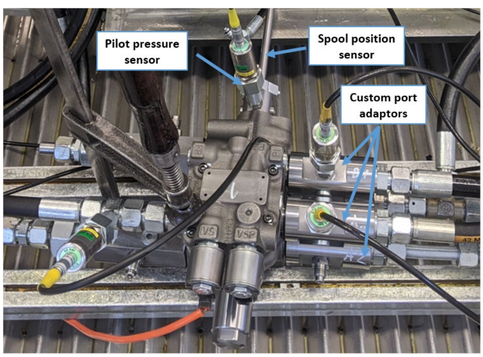

Figure 16: Prototype valve on test bench
Source: own

After in-house bench testing of valve characteristics, the valve has been sent to customer for field testing and final evaluation and validation.

4.3 Customer field testing

Customer has a standard set of procedures and operating modes to test on prototype machine. Apart from that, customer considered proposals resulting from Poclain system simulation and included them into testing plan to evaluate the circuit after integration of the new freewheeling valve. Initial field tests were done with no modification of 4WD system control. Figure 17 shows how measured response of 4WD system during engagement matches well the simulated behaviour in two critical points presented in Chapter 3.2.

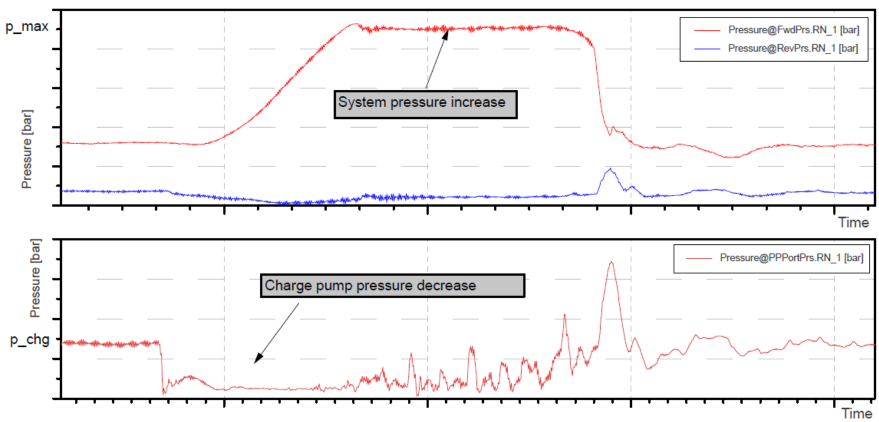

Figure 17: Field test results - initial

Source: own

System simulation suggested change of front drive displacement control to address the rapid system pressure increase at 4WD activation. Modifications were introduced to 4WD system control and the circuit. Repeated field testing resulted in an improved performance, which was detected by machine operators and approved by review of measurement results. Rapid increase of system pressure was replaced by smooth transition during activation of 4WD mode.

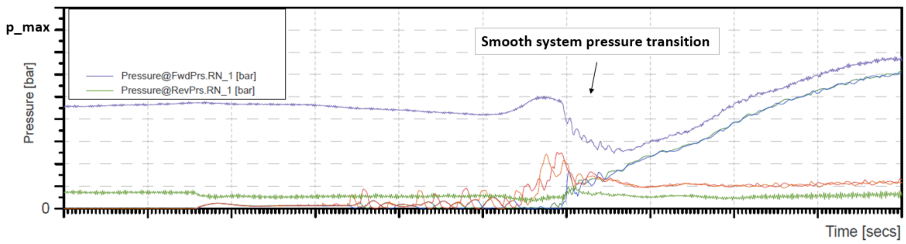

Figure 18: Field test results - modified

Source: own

Drop of charge pressure level at 4WD activation was evaluated more in detail by installing additional pressure sensor to the circuit. It indicated that charge pressure drops low at the valve due to significant distance from charge pump to the valve, but remain at sufficient level on other parts of the circuit. Therefore, it does not affect other functions of the circuit and no modification was required.

5 Conclusion

Project timeline of developing new freewheeling valve was very constrained and represented a challenge for the company. Specific steps were performed to minimize risk of mistakes and issues along the design process and preparation of prototype samples.

Several numerical calculations and simulations evaluated behaviour of the new valve prior to building physical prototypes. System simulations analysed integration of new valve inside 4WD circuit. Few main points were identified that needed specific focus during field test evaluation. Alternative design variants were prepared in case that behaviour of 4WD system would require improvement during field tests.
Eventually, new freewheeling valve was developed and validated on time for implementation on customer machine according project timeline.

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