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Identification of root cause based on simulation approach

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Abstract The paper shows and explains customer claim regarding improper functionality of hydraulic brake valve integrated into harvester machine. Further, the paper also presents simulation-based approach to understand and solve the issue. In the first step, fully detailed one-dimensional (1D) lumped model has been made in order to reproduce customer issue. Here, it is essentially to mention that (simplified) customer environment/machine was also part of detailed 1D numerical model – customer engagement in root-cause analysis is important. Thanks to detailed simulation model, deep understanding of the key parameters that affect the machine malfunction was possible in the second step. Model allows performing sensitivity study on key parameters with high fidelity. Lastly, based on detected key parameters, harvester brake valve has been updated/redesigned and sent to customer for final validation. Customer satisfaction along with short and effective response time of Poclain development team convert challenge situation to success.

Keywords: • harvester • brake valve • numerical analysis • accumulator charging sequence • cut-in • 6. cut-out •

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1 Introduction

Harvesters are self-propelled cutting machines (1). They are able to both fell and process stems. Wheeled or tracked (2), they feature a cutting head (3) that fells, delimbs and bucks trees to specific lengths. Harvesters also have a front or rear cab (4), which is either fixed or rotating. Attached booms may be telescoping (5). [8] A forest harvester is typically employed together with a forwarder that hauls the logs to a roadside landing [3]. Harvester machine works mainly with hydrostatic braking (6). See Figure 1 for details.

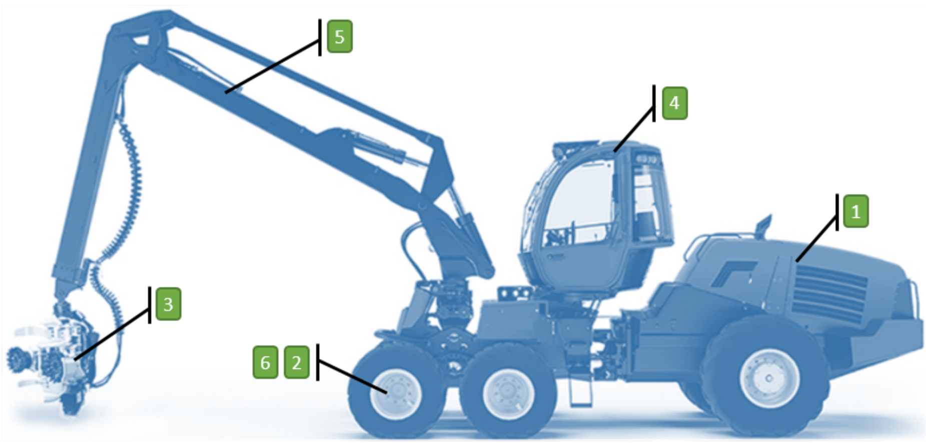

Figure 1: Typical harvester machine.

1.1 On hydraulic braking system

Machines that using such a braking system are usually equipped with spring applied hydraulically released (SAHR) brake, which is activated via parking/emergency brake valve. Hydraulic applied spring release (HASR) brake is activated when operator presses brake pedal. Service brake (HASR) can be also activated by master cylinder.

Typical hydraulic brake system consists of components, shown on Figure 2.

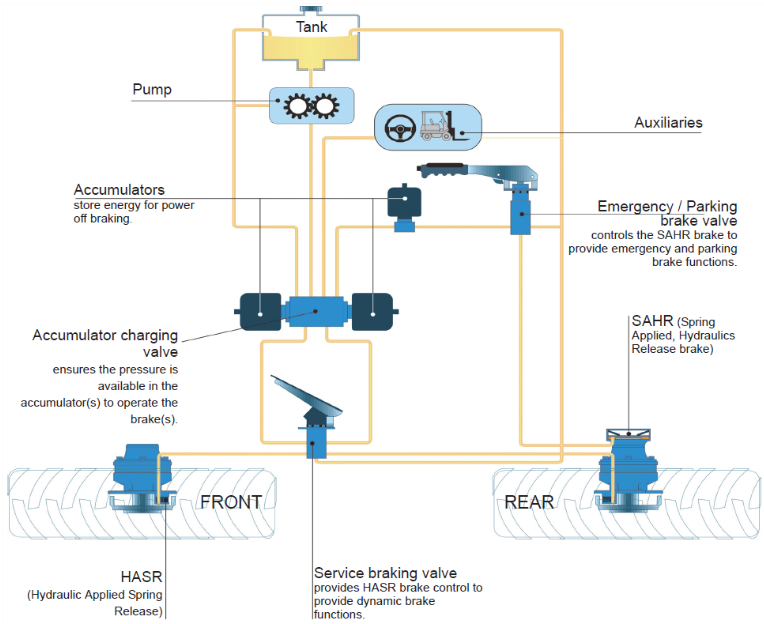

Figure 2: Hydraulic brake system.

1.1.1 Accumulator charging valve

Accumulator charging valve (ACV) charges the accumulators in a braking circuit (i.e. single or dual circuit) and maintains their pressure while supplying an auxiliary circuit (Figure 3). It consists of different parts: divider spool (1), cut-in/out spool (2), poppet isolating valve (3) or ball isolating valve (4).

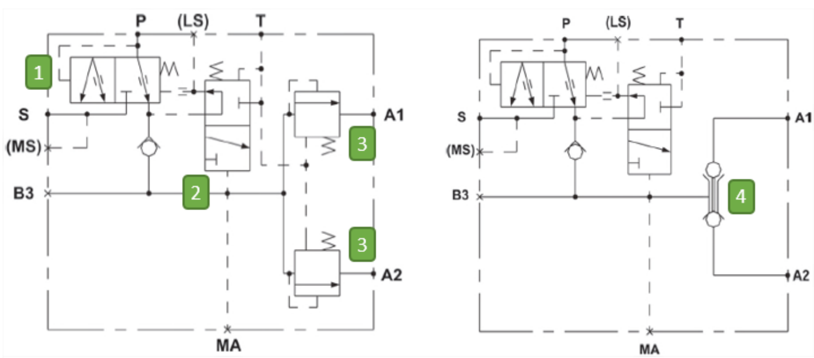

Figure 3: Hydraulic circuits of VB-200: with PRV (left) and IBV (right).

1.1.2 Meaning of underlap

In hydraulics, the parameter underlap (in its general meaning) is used to adjust the initial position of the spool. Figure 4 shows a positive and a negative underlap at zero displacement. Applying the positive value (in Amesim terminology called underlap), there will be a leakage in the central position. With the negative value of underlap (called overlap), there will be a dead-band effect.

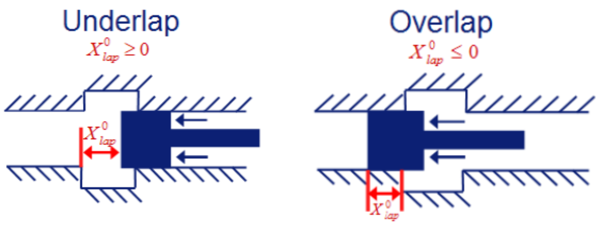

Figure 4: Graphical representation of underlap.

1.1.3 Service brake valve

Service brake valve (Figure 5) is a mechanically controlled, three-way, graduated release double pressure reducing valve. Single (i.e. VB3-010) or double (i.e. VB3-020) service brake valve provides precisely controlled output pressures (at F1 and/or F2) proportional to the pedal stroke and therefore to the force applied to the pedal. This provides the feeling of braking. In a braking circuit, VB3-010/020 is usually associated with VB-100/200 accumulator charging valve.

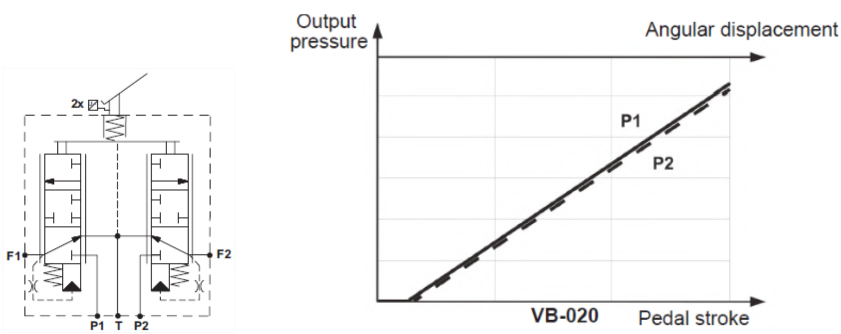

Figure 5: Hydraulic circuit of VB3-020 (left) and characteristic curve (right).

1.2 On harvester braking system

In general, harvester braking valve consists of accumulator charging valve (e.g. VB-200) as well as of service brake valve (VB-020), combined into single (i.e. compact) solution VB-220 (Figure 6). The modular approach of brake valve components enables several different design solutions.

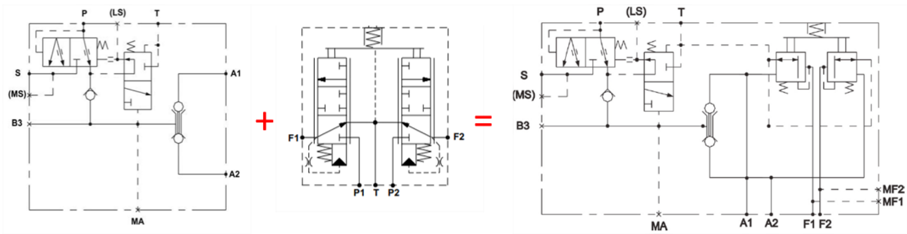

Figure 6: General schematic of VB-220 brake valve.

Actually, according to customer requirements, standard ACV valve (VB-200) and service brake valve (VB3-020) have been modified (Figure 7). Consequently, working principles of modified VB3-220 is a bit different compare to the catalogue one. One of the main difference is that harvester brake system has load-sensing pump (8) and port X is supplied by pressure upstream the divider spool (1). This could be seen on Figure 7.

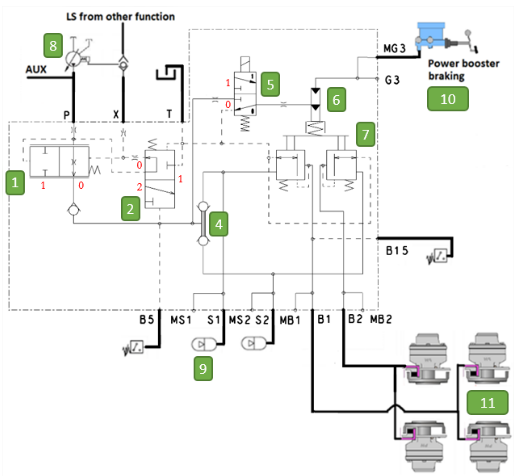

Figure 7: Harvester brake valve

Modified service brake valve (7) is piloted in two ways: either hydraulically (contrary to the standard version, which is mechanically piloted) by the special pilot valve (6), supplied by the accumulator pressure via directional control valve (5) in position 1; either hydraulically thanks to a boosted brake valve (10).

In case, that directional control valve (5) is set in position 1, maximal braking pressure is applied to HASR brake (11). Contrary, boosted brake (10) allows to gradually increasing braking pressure – proportionally to pedal stroke and therefore proportionally to the force applied to pedal.

1.2.1 Basic functionality of cut-in/out spool

Referring to Figure 7, accumulator charging sequence is performed if cut-in/out spool (2) is in initial position 0 and consequently divider spool (1) is in its initial position 0 as well. LS pump (8), which is controlled via supply on port X, charges the system. When maximal charging pressure is achieved, cut-in/out spool (2) shifts to position 2, which allows to release back pressure on divider spool (1) to T port. The divider spool (1) is then piloted to position 1. Along with cut-in/out spool (2) movement to position 2, link from port P towards port X is disconnected. This state is called "cut-out”.

As soon as accumulator pressure decreases below critical value, cut-in/out spool (2) shifts back to its initial position 0 and so the divider spool (1); then, the whole charging procedure is repeated. This state is called "cut-in”.
Isolating ball valve (4) assures that damaged braking circuit is isolated and therefore braking of harvester is still possible thanks to the pressure in second accumulator.

2 The scope of investigation

Based on customer feedback, the harvester valve worked according to specifications. However, there are some (random) situations that accumulator charging is not performed or last abnormal time (dozens of seconds).

Typical situation when such a valve malfunction appears is shown on Figure 8. Observing the P curve, issue appears just after 32 s and last up to 76 s (i.e. pressure on P channel increases slowly, which is not accepTable). Then, charging sequence continues normally (i.e. sudden increase of pressure on P line). It needs to be noted that customer could not define conditions when this malfunction appears. Deep investigation needs to be performed in order to find the root cause of valve malfunctioning.

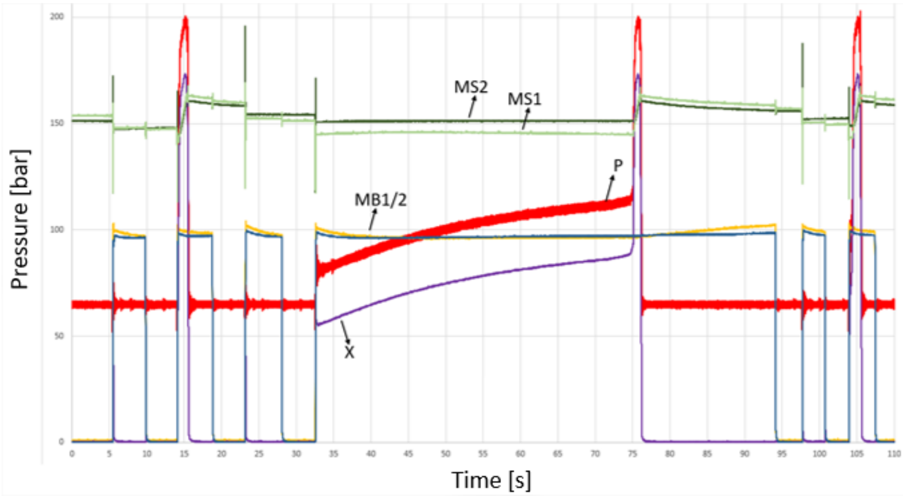

Figure 8: Measurements on customer machine.

The meaning of legend on Figure 8 is as follows: MS1 – accumulator 1, MS2 – accumulator 2, MB1 – brake 1, MB2 – brake 2, X – LS signal, P- pump. Channels refers to pressure [bar].

3 Numerical approach

Numerical evaluation has been performed by the commercial simulation tool Simcenter Amesim (2019.1). The primary goal of simulations is to (better, deeply) understand the model itself; then, it is essentially to reproduce customer issue; further, the focus has been made to discover key (design) parameters that impact the valve behavior - in particular the accumulator charging sequence. Numerical approach serves also as a first (and main) step towards further improvements of brake system which in the end could lead to customer satisfaction.

3.1 1D Amesim model

In the first step, detailed 1D lumped model has been created and shrank to a supercomponent (Figure 9) in order to allow easier manipulation and more user-friendliness for design team.

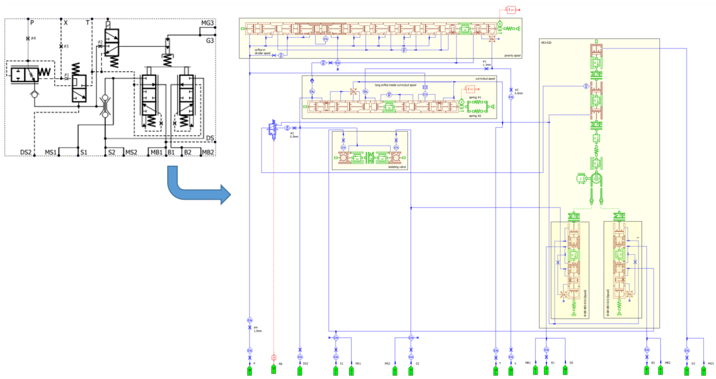

Figure 9: Detailed Amesim model of the VB3-220.

Besides the detailed modeling of problem in hand, it is very important to put the 1D simulation model into realistic environment – this means to prescribe the proper boundary conditions. Figure 10 shows the integration of detailed numerical model into simplified customer-like environment (similar to Figure 7).

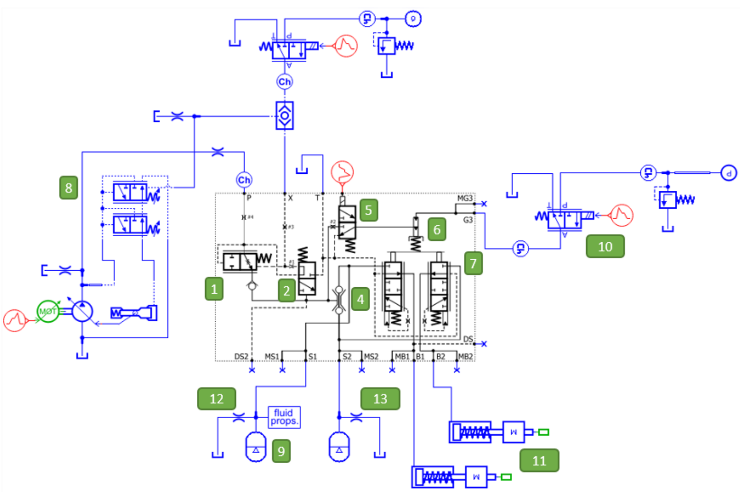

Figure 10: Simplified customer-like environment.

The environment refers to pressure and flow sources (e. g. load-sensing pump, piloting pressure and accumulators), consumers (e. g. brake cylinders) and other auxiliary components (e. g. shuttle valve and orifices).

On this step, it is essentially to have tight relation with customer in order to: understand his environment, get realistic parameters of components and other details needed for simulation purposes. Without customer involvement, it is very difficult to reproduce/evaluate customer machine behavior solely based on component-level simulation.

The initial numerical model is (usually) parameterized according to the nominal parameters. In this particular case, the initial model works according to customer specifications – no issue detected.

3.1.1 Basic model understanding and consistency

Basic consistency of numerical model has been checked in order to verify that the model was built correctly and that parameters were prescribed appropriately. Here, several different scenarios have been tested. Only few of them are explained below.

One of the most fundamental characteristic is flow rate toward accumulators (Figure 11). It can be seen that (in this particular case) maximal flow is approx. 7 l/min (on P port) and drop down to zero when accumulators are full.

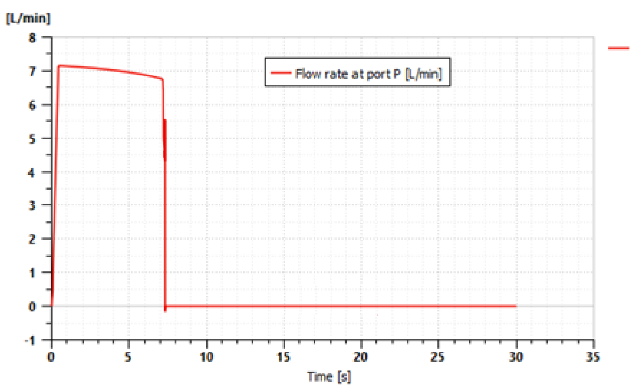

Figure 11: Flow rate on P.

Another important characteristic is pressure on accumulators (Figure 12). Initially there is a pre-charge pressure on accumulators (approx. 55 bar). Then, gradual increase of pressure could be seen up to 160 bar (from zero to approx. 7th second). Maximal charging pressure is defined by spring(s) of cut-in/out spool.

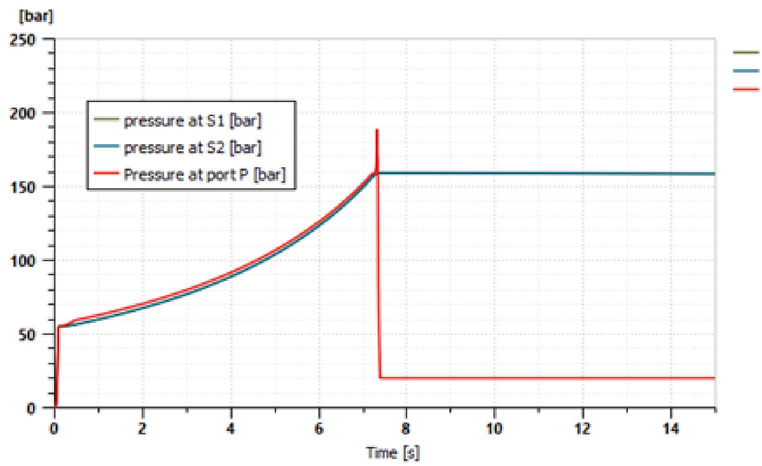

Figure 12: Pressure curves.

3.1.2 Accumulator charging sequence

Accumulator charging and discharging sequences are depicted on Figure 13.

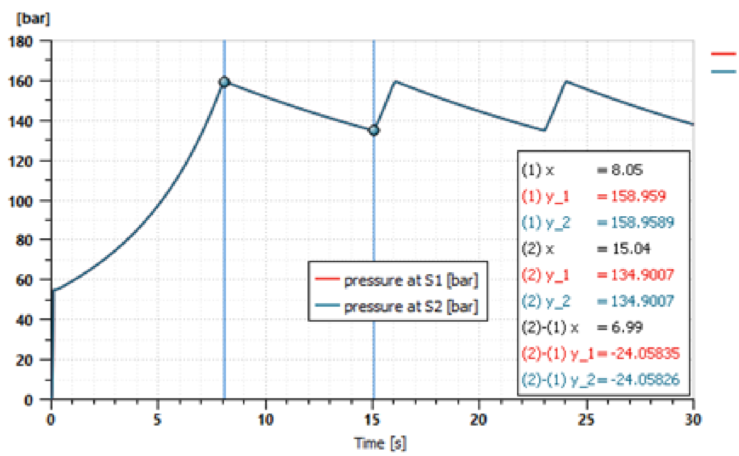

Figure 13: Accumulator filling sequences.

In order to speed up the discharging sequences, orifices (12) and (13) on Figure 10 are set to small value – which enables to simulate leakage flow out of accumulators. In reality, discharging appears due to the leakage on VB3-010/020 as well as on pressure relief valve or isolating ball valve (Figure 3) and last much longer time (from minutes to hours).

3.2 Sensitivity analyses of key parameters

Further, deeper investigation has been performed in order to detect main influential parameters on accumulator charging issue (i. e. for cut-in and cut-out states).

Note that for the purposes of decreasing computational effort, several simplifications have been introduced into the detailed model, without the cost of accuracy (e. g. complex sub-systems have been replaced by equivalent orifices/volumes or taken as simplified representation – mass, spring, damper – from software hydraulic library).

Based on extensive sensitivity study, it has been found out that main influential parameters are cut-in/out spool underlap (i. e. on metering edge from P to X and metering edge from X to T), as seen on Figure 14 and cut-in/out spool leakage (due to radial gap and spool eccentricity).

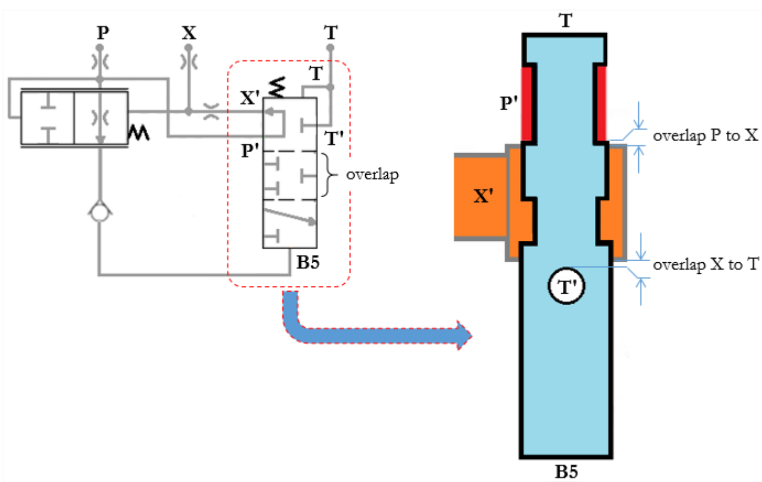

Figure 14: Cut-in/out spool symbol – explained.

By specific set of influential parameters, it was possible to reproduce accumulator charging issue (Figure 15). The cut-in and cut-out issues are clearly observable. While cut-in/out spool with given underlap and given diameter is relatively easy to produce and control, it is not true for spool eccentricity. It depends on several parameters (on spool and housing) and predicting its effect by the simulation tool (or analytical calculation) is the only feasible approach.

Along with this study, some other improvements have been proposed in order to make system more stable as well as to reduce overall pressure loss in the harvester brake valve.

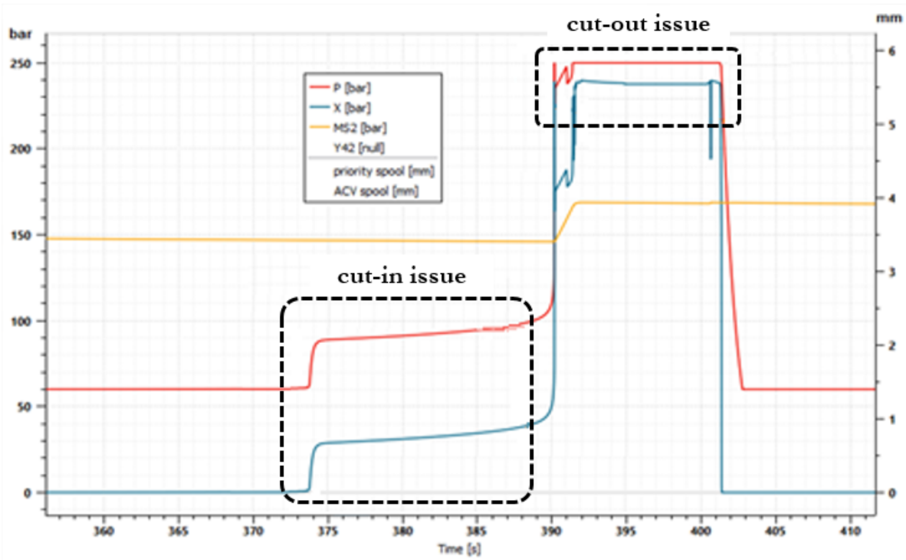

Figure 15: Reproducing customer issue.

4 Experimental approach

The harvester brake valve (VB3-220) has been developed, manufactured and tested internally by Poclain. No valve malfunction has been detected so far (Figure 16).

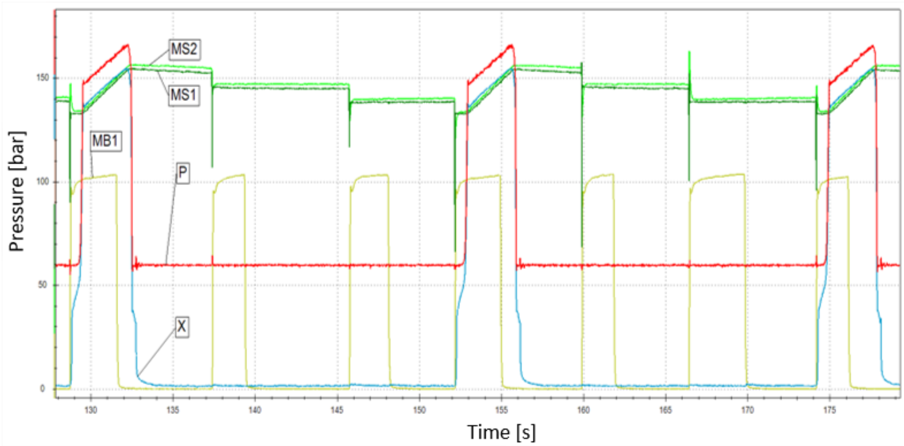

Figure 16: Initial measurements from the laboratory.

Then, the valve has been sent to customer for final evaluation and validation. As already explained, customer claimed that there were some situations that accumulator charging sequence did not work properly. The harvester valve has been recalled to Poclain test lab in order to try to reproduce the issue and to define conditions for the valve malfunction.

4.1 Root cause analysis

Although extensive experimental investigations have been performed, it was not possible to reproduce the issue in the lab. This was somehow expected, because the customer system (i.e. harvester machine) is much different compare to the simplified system in the lab (e.g. different pump, different piping – material stiffness/length/diameter, different braking cylinders etc.).

For that sake, numerical approach was the only solution to find the root cause. As explained in chapter 3, numerical model has been tested under different boundary conditions, different design parameters of valve components etc. Fully relying on the numerical model (which indeed reproduce customer issue) and simulation-based solution, new cut-in/out spools with different overlaps have been machined and then tested in the lab (Figure 17).

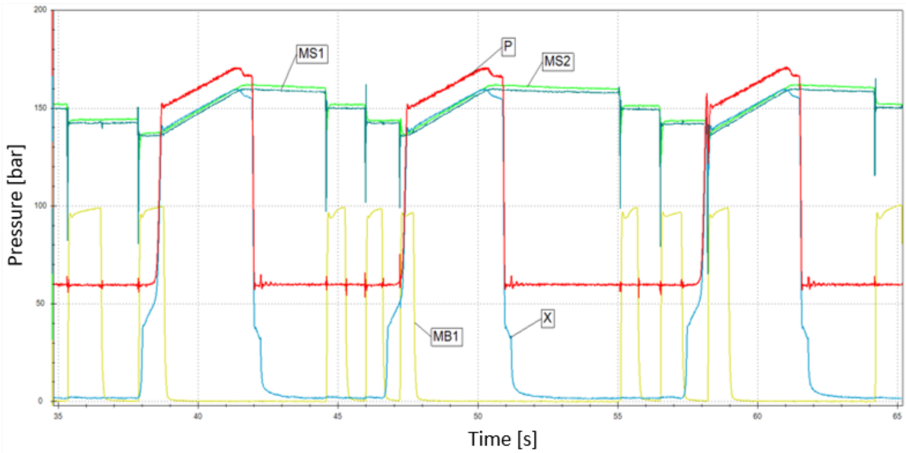

Figure 17: Additional measurements from the laboratory.

Despite that numerical analysis was able to reproduce customer issue and further proposed new spool design, additional in-lab tests of the harvester valve did not show (almost) any difference compare to initial measurements (comparing Figure 16 and Figure 17, some minor differences could be observed only on P curve). Note that shorter charging cycle on Figure 17 is due to shorter/more frequent actuation of working brake (pos. 5 on Figure 7).

For that sake, the only solution to confirm acceptance of new spool was to send the valve directly to customer. He performed several additional tests but the charging issue did not appears anymore (charging pressure raise up quickly). He treats valve as accepTable.

The meaning of legend on Figure 17 and Figure 18 is as follows: P – pump, MS1 – accumulator 1, MS2 – accumulator 2, MB1 – brake 1, X – LS signal. Channels refers to pressure [bar].

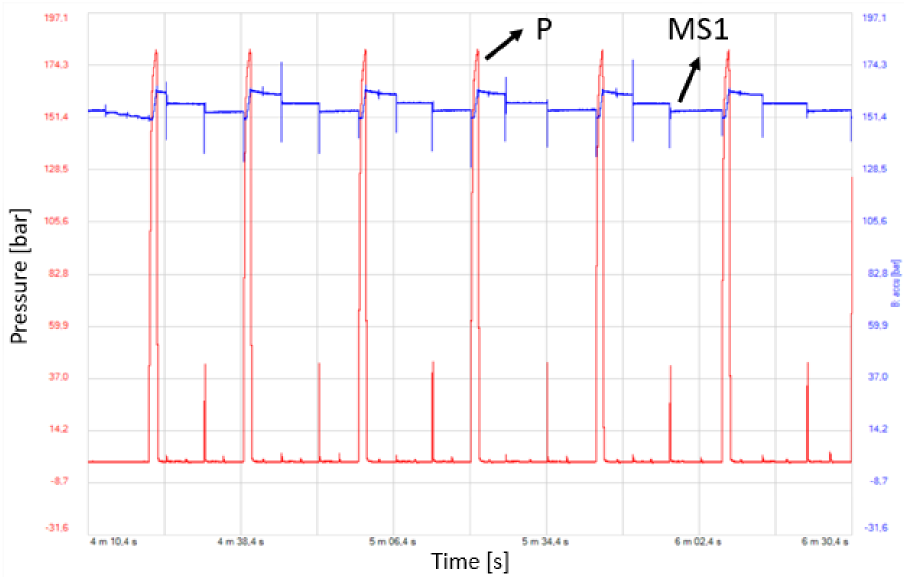

Figure 18: Additional measurements on customer machine.

5 Conclusion

The main goal of investigation is to find a root cause for harvester valve malfunction and to deploy better design solution. This was possible thanks to numerical approach (I .e. high fidelity numerical model) and customer proactivity.

In the numerical approach, in the first step, detailed 1D lumped model has been created. Preliminary simulations confirmed that model is fully functional and can be used for further investigations. The latter show that cut-in/out spool underlap and cut-in/out spool leakage are the main influential parameters that affect charging issue. Thanks to additional sensitivity analyses, it was possible to define suiTable set of those parameters that should prevent valve malfunction.

The numerical approach was followed by an experimental approach .Due to the system complexity and limitation of laboratory equipment (not possible to setup customer-like environment), charging issue was not reproduced neither it was possible to evaluate and validate new design proposals. Thanks to tests performed directly on harvester machine, new spool have been successfully tested and solution confirmed by the customer himself.

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