Investigation of diesel injection pumps prototypes' performance and redesign using Digital Twins

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ABSTRACT

An innovative diesel injection pump was created, and during the testing of the initial prototypes, the performance of the prototypes was incongruent to expectations. To investigate this, each prototype was fully measured and converted into a digital twin in the Amesim system simulation software. With the virtual prototypes at hand, their hydraulic performance was simulated under the same conditions of the physical tests. The models from each prototype could explain why they presented inconsistent results.

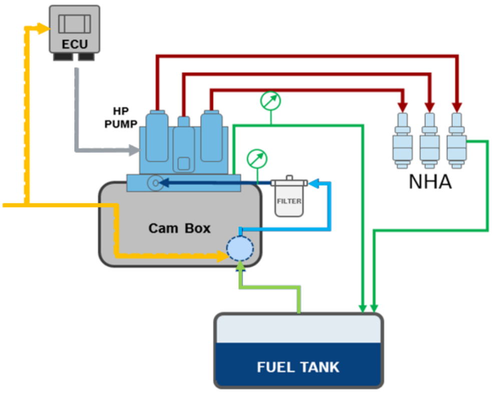
A full factorial DOE was created to evaluate the most significant geometric contributors. Then, three design proposals were evaluated and two designs were discarded with these results. A sensitivity study was conducted for the original design and the best design achieved. Design improvements to the valve were suggested using these results.

Finally, new prototypes were produced according to the new design, they were tested and measured and again converted into a digital twin. The models presented the same performance as the measurements, being considered validated. Both the nominal design as well the digital twins of the prototype presented results within the targeted performance of the design, so the issue was considered solved.

GENERAL INFORMATIONS

To address the emission regulations of the off-highway diesel engines with engine power below 19kW, the Bosch Power Solutions in Brazil (PS-LA) developed different sizes of electronically controlled diesel injection systems. One of such systems was aimed at the lowest sizes of stationary diesel engines, using an innovative design to produce a high-pressure pump for such systems with a very small footprint, to fit even the most stringent packaging requirements from the customers.

In the system in question, a camshaft rotates and displaces a plunger. The plunger movement displaces the fuel volume inside the pump. While traditional systems use mechanically controlled valves to control the fuel injection [1], to reduce pollutant emissions a new electronic valve was designed. The valve movement is commanded electronically by an Engine Control Unit (ECU), so that when the ECU outputs a current signal to the valve, the resulting current generates a magnetic field. The magnetic force will attract the valve armature, and this force is used to control the closing of the valve. The function of the valve is, when closed, to isolate the fuel inside the pump cylinder from the inlet and outlet, so that the plunger displacement compresses the fuel. The pressure increases until the pressure achieved is high enough to open the mechanical valve of the nozzle, the nozzle needle opens and the fuel flows into the engine cylinder. After the desired fuel quantity is achieved, the ECU turns off the electric current, a spring forces the valve to open and the fuel flows from the pump cylinder to the outlet, the pressure drops, the nozzle needle closes and the injection ceases. This valve is intended for unitary fuel injection systems [1], as shown in picture 1, was named Micro Unit Control Valve (µUCV).



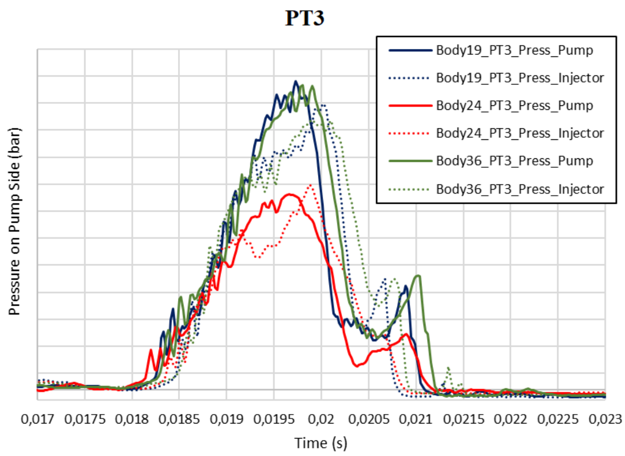
Pic 1. – System overview

During the development activities, several samples of the pumps were built and tested. The pumps could be tested on a test bench in the PS-LA laboratory. The test bench mimics an engine installation, with the entire fuel system, ECU and measuring equipment to capture the most important parameters of the pumps during operation, while the camshaft is driven by an electric engine for precise control of the operating conditions. On the A4 development round, the samples of the pumps presented, on the test bench, hydraulic behaviors that needed to be investigated.

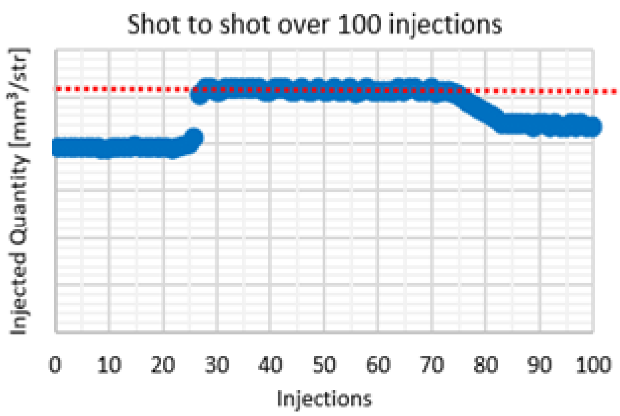
SAMPLE MEASUREMENTS

During the development activities, several samples were produced and tested. Three of the samples, identified by serial numbers #19, #24 and #36 in particular, presented conflicting results that didn't match the expectations based on similar products. The signals of pressure on the pump outlet and pressure on the injector inlet are measured, as well as the injected quantity on the injector.

Several running conditions were tested, but the picture 2 shows one condition tested, with the pressure traces measured on the pump outlet, and on the injector body. The three pumps are being actuated with the same shaft RPM and electric current profile, but the resulting pressure traces are very dissimilar. Additionally, the injected quantity of the prototypes showed signs of instability between injections, as shown in picture 3 for pump #36. Some injections resulted in higher quantities than others and could disrupt proper engine function.



Pic. 2 – Pressure traces measured at operating point 3 (PT3)



Pic. 3 – Shot-to-shot deviation between injections from #36

Conventional engineering wisdom about these systems dictate that such deviations are consequences of the valve characteristics and tolerances, the OAG _ Open Air Gap _ being the predominant setting parameter that influences the pump operation. Valves with increased OAG take longer for the valve to close, because the initial force generated by the current is lower (the magnetic force is inversely proportional to the OAG). Valves that close with delay because of large OAG result in delay on pressure peak, shorter injection period and reduced injected quantity. Also, longer OAG mean more travel for the valve pin, which can lead to other instabilities related to friction and stiction.

Interpreting the results above, they show some characteristics of each prototype: Pump #19 achieves the highest output pressures and the faster valve opening. Pump #24 shows the fastest valve closing, but it doesn't achieve the same level of pressure as the other pumps. Pump #36 achieves the peak pressure with a delay, and the valve opening is also delayed. These results would imply that the pump #19 has the lowest OAG and the pump #24, the higher OAG. However, looking at the assembly parameters of the measured samples, the OAG values were as follows:

- Pump #19 – 310µm
- Pump #24 – 237µm
- Pump #36 – 262µm

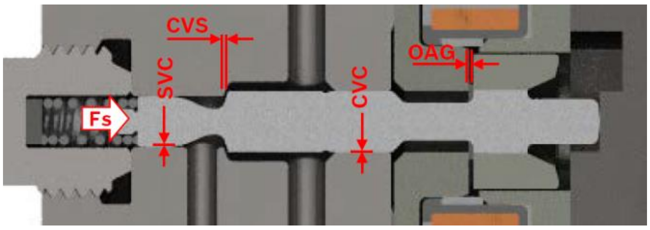
The valve from pump #19 had the wider OAG and should be the last one to close, however the pressure peak of this valve was consistently faster than the others on all tested operating points. The valve with the narrower OAG, #24, should be the fastest and achieve the higher pressures, however it always achieved the lowest outlet pressures. Valve #36 had similar OAG as #24, but its pressure output was wildly different than #24.

To clarify this inconsistency, a simulation was requested to compare the three samples and identify the design levers that caused the measured values. A system simulation model was built using the software Simcenter Amesim, which is a 1D system simulation software. In this software, a model is constructed using simplified parametrized multiport blocks, each block representing a physical energy conversion or a machine element or a hydraulic component. For example, pistons, springs, pipes and masses, represented by its simple parameters such as diameters, stiffness and preload, diameter and lengths, and masses, respectively.

The system model of the pump assembled on the test bench was already available in Amesim, having been already prepared during the development of the product. However, the base model is always based on nominal parameters, and now it needed to be adapted with parameters measured from each sample. A number of parameters of the valves were selected based on the design, and each valve was measured for all these parameters. Afterwards, the simulation model was updated with the individual settings of each pump valve, building a digital twin of each pump. was generated using the measured parameters, and each model was tested under 8 running conditions which were also measured on the test bench using the real prototypes.

The simulation was also occurring in parallel to other activities, such as additional testing of samples, Problem Solving investigations, Failure Tree Analysis and other development activities, so the authors do not claim full credit for the investigation of the problem and discovery of the solution, but the simulation played an important role. To simplify this paper, only the following valve parameters will be shown as they were directly related to the valve operation, as shown in picture 4, although there were more parameters measured in total. The parameters are:

- OAG – Open air gap
- CVC – Central valve clearance
- CVS – Control valve stroke
- SVC – Secondary valve clearance
- FS – Spring force



Pic 4 – Example of parameters used for the modelling

Table 1: Measured values for characteristics from Pic 4.

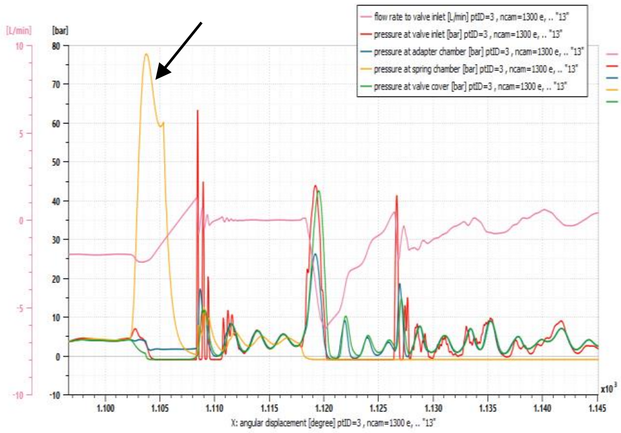
Pump #	CVS [µm]	OAG [µm]	CVC [µm]	SVC [µm]	FS [N]
19	178	310	13	32	~11
24	176	237	17	53	~11
36	173	262	7	14	~11

The simulation was conducted in several steps. Case 1, to evaluate the performance of the samples according to their production and assembly parameters. Additionally, the design limits of the valves should be analyzed through a full factorial DOE (case2). Design proposals for redesign (A) are evaluated through another DOE (case3) and compared with the standard design. Based on those results, it was decided to expand the scope and run 2 sensitivity analysis of the valves to the secondary valve clearance (SVC), one of the A4 design (case4) and a redesign (B) (case5).

As the initial simulation models were not fully validated, some of the simulated values did not reproduce the exact measured values on the test bench. A validation would also be impossible because of the instabilities on the measurements. However, a good engineer can work beyond this limitation and use the available data to interpret the behaviors of the model and relate these behaviors to the observed results from the measurements. The next section shows some of the work involved with the analysis of the simulation results and interpretation of the physical equivalent effects.

SIMULATION RESULTS

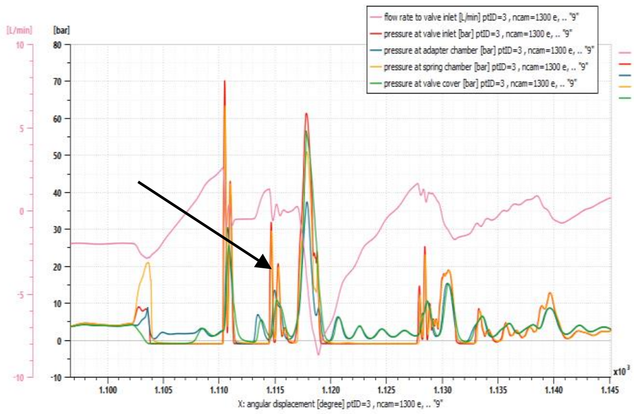
CASE1 - The results from case1 are extensive, but the following pictures exemplify the value of a digital twin of the pumps, only results from operating point 3 (PT3) are shown.



Pic. 5 – Results from pump #36 on PT3

The results from picture 5 show the pressures inside various hydraulic volumes within the pump, during one injection event. The values act like a virtual sensor inside the pump during the test and allowed the comparison of each sample with the nominal assembly. This level of measurement would be extremely difficult to make in a physical sample and would take a lot of adjustment to enable. And in contrary to a physical measurement, the virtual sample does not disrupt the behavior of the sample, and is free from noises such as vibrations, electrical noise from the grid and the signal processing hardware.

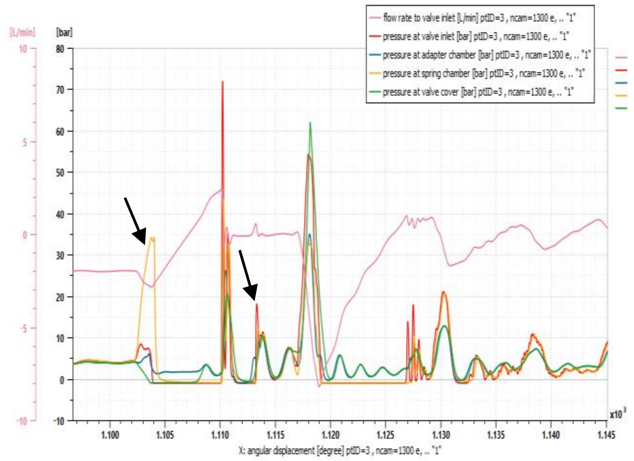
For example, the results in picture 5 show an unusual high pressure in the spring chamber during closing of the valve, before the injection begins (arrow on the plot). This increased pressure generates a force contrary to the closing of the valve and delays the valve closing and the formation of pressure. This effect could be traced to the reduced clearance between the housing and the secondary valve clearance.



Pic. 6 – Results from pump #24 on PT3

The behavior of pump #24, that generated lower pressures, could also be understood from the simulation model results. In picture 6, there is an increase in pressure in the spring chamber when the valve is closed (arrow on the plot), and this pressure event forces the valve open and releases pressure from the system.

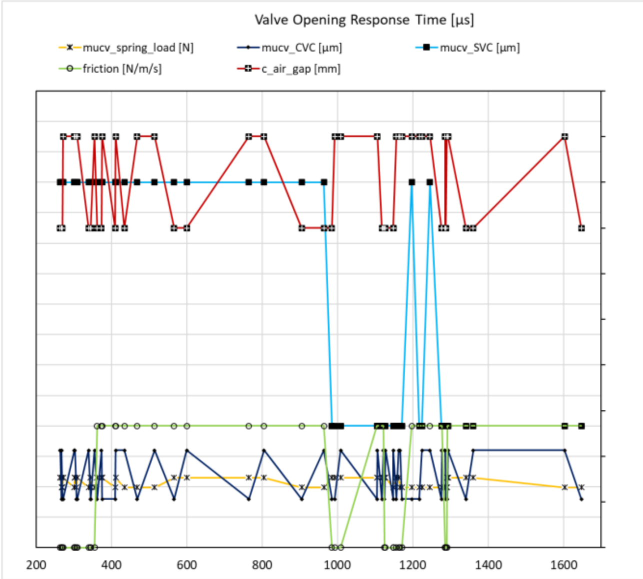
Most importantly, the results from the nominal system shown in picture 7 also show both pressure peaks occurring, but with less intensity.



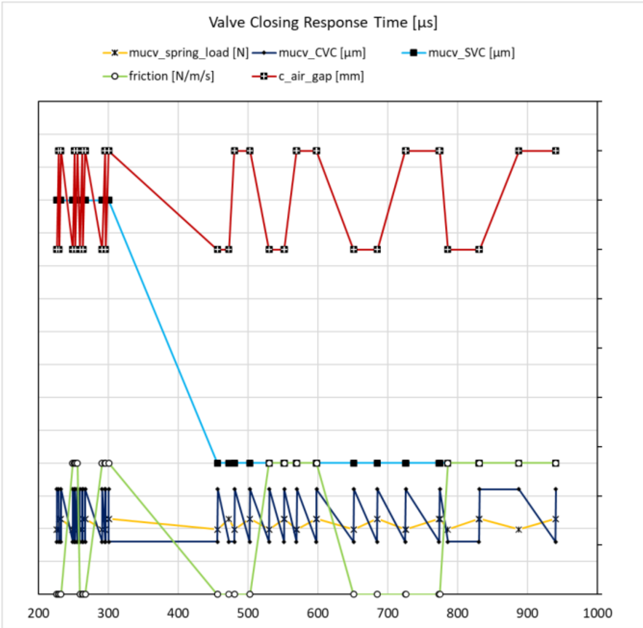
Pic. 7 – Results from nominal pump on PT3

The nominal pump did not present any disturbance on the simulation model, but the presence of these unwanted pressure peaks could mean that the design was prone to generating undesired forces on the valve that could affect the pump function. Pressure peaks on the spring chamber affected the Valve Closing Response Time (VCRT) and pressure peaks on the valve cover were found to affect the Valve Opening Response Time (VORT).

CASE2 - A full factorial DOE was carried out for all the critical parameters of the pump. Again, to simplify the paper, only the parameters from table 1 are shown here (parameter values omitted to protect Intellectual Property of Robert Bosch). Just for the 5 parameters from the Table 1, a full factorial DOE already requires running more than 50 simulation cases for each test point. In total, several thousand models were simulated and compared to understand the most critical parameters of the design.



Pic. 8 – Valve Opening Response times from the DOE

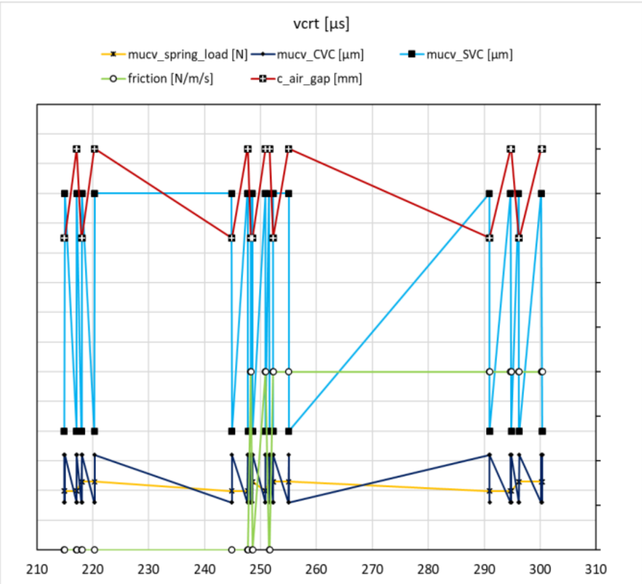


Pic. 9 – Valve Closing Response times from DOE

The plots on pictures 8 and 9 display on the x-axis the value of the opening and closing times as a function of several parameters of the pump. Picture 8 shows that the increased VORT could not be directly linked to a single parameter on the pump and the valve, and that the design could result in VORT up to 1,6ms, which was excessive. The VCRT on picture 9 show that it is highly influenced by the SVC. Only the models with SVC on the maximum tolerance resulted in VCRT below 0,4ms. For this reason, design suggestions were made to the pump and the valve, to avoid formation of pressure peaks on the spring chamber and the valve cover, so that delays on closing and opening of the valve could be avoided.

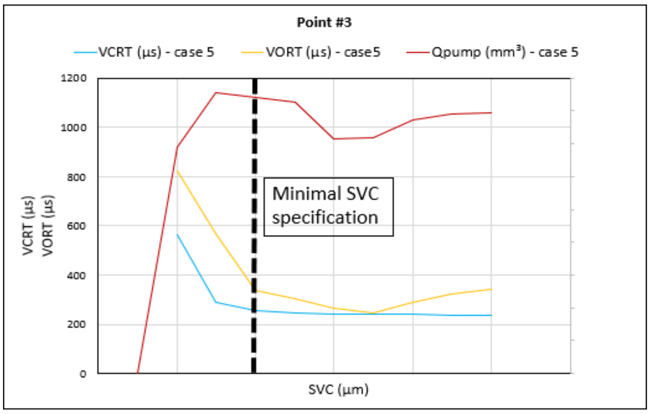
To avoid a lengthy paper not all design results will be shown, but it is a testimony to the practicality of a digital twin of a product, because each design could be modeled and tested in a matter of hours, and with some automation, the results could be post-processed in a matter of minutes. This is a stark contrast to the traditional methods of building samples and testing on the laboratory, where each sample can take days or weeks to build and test. After several designs were tested and evaluated using these models, and several DOEs were conducted to compare the design proposals, a design was selected that had potential to avoid delayed operation of the valve.

CASE3 - The picture 10 is an example of the improvements generated by the new designs that were verified in the simulation model on case3. It is the DOE simulation result of the redesign (A), for the VCRT. This design shows that all the combinations of the parameters are within a much shorter range of VCRT between 0,2ms and 0,3ms, and that the redesign (A) solved the delay in the closing of the valve.



Pic. 10 – VCRT result from redesign (A)

CASE5 - The final step was to propose a design to solve the delayed opening of the valve by elimination of pressure peaks on the valve cover. The pump body design was modified again on redesign (B) to allow the dissipation of pressure peaks on the valve cover without undesired influences over the pump function. This design was evaluated on a sensitivity analysis just to the SVC value on case5, as this design was already much stabler in respect to the pump function on the simulation. The picture 11 shows the results for VCRT, VORT and injected quantity for PT3, for the redesign (B).

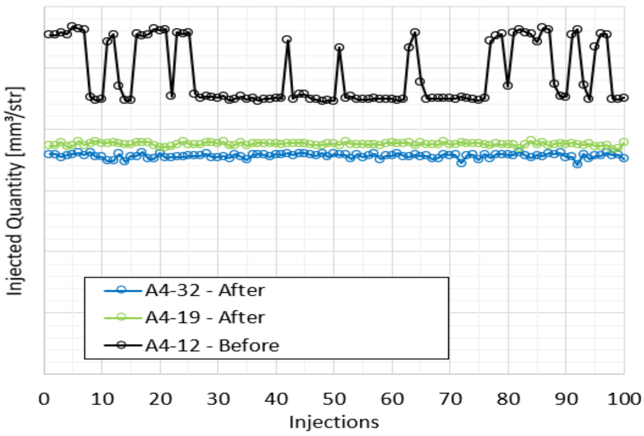


Pic. 11 – Sensitivity analysis results from redesign (B)

Based on the results from case5 in picture 11, the ranges of optimal values from SVC could be chosen, mainly by specifying a minimal value for SVC, that would avoid delays in opening and closing of the valve and stabilizing the injected quantity. A stable injection quantity is important to ensure that the diesel engine runs smoothly without oscillations, excessive noise or pollution.

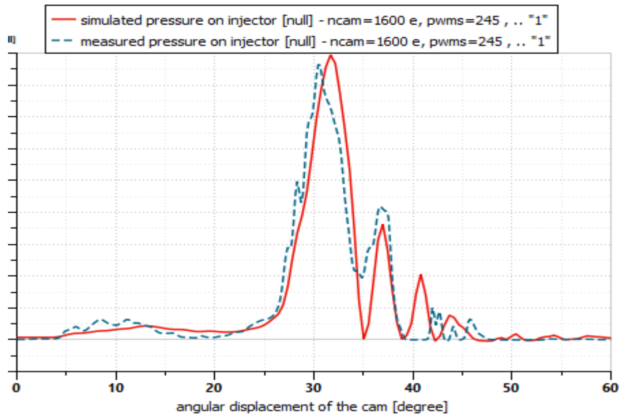
FINAL DESIGN

After the optimizations a final design was produced and tested on the test bench, and the performance targets of the pump could be achieved. The picture 12 shows the measurements of pressure stability before and after the improvements. The redesign (B) no longer presented instabilities and solved the initial problem.

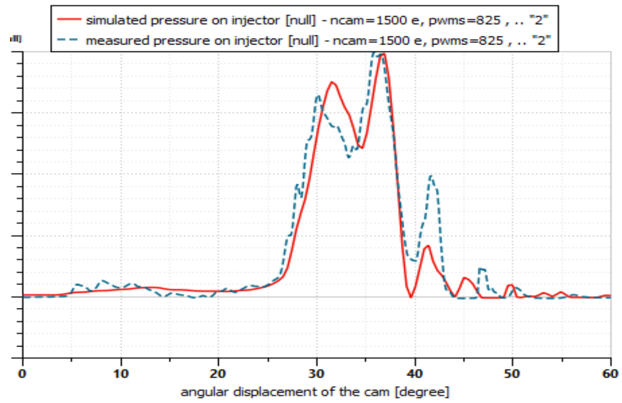


Pic. 12 – Shot-to-shot stability measurement

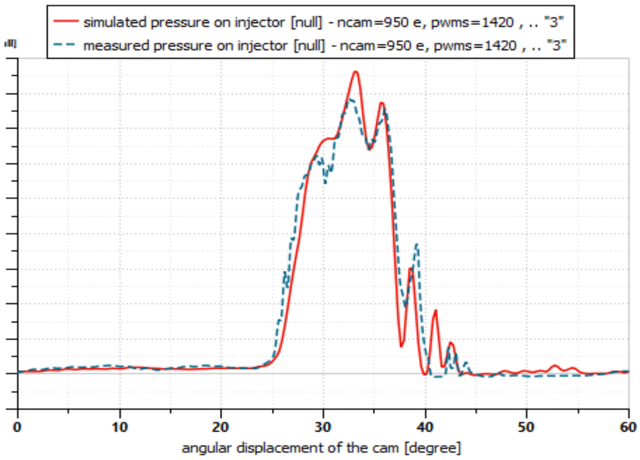
Additionally, the pump performance was mapped in eight operating points (PT1…PT8), to allow a validation of the model. The model was again updated with the measurements from the assembly parameters and compared with the measured values. The pictures 13 through 16 show the pressure inside the injector, on both the simulation and the measurements. From the simulations, each kink on the pressure traces could be related to specific physical events occurring inside the pumps and valves, giving a full understanding of the product function. This can give room to further improvement of the product in the future.



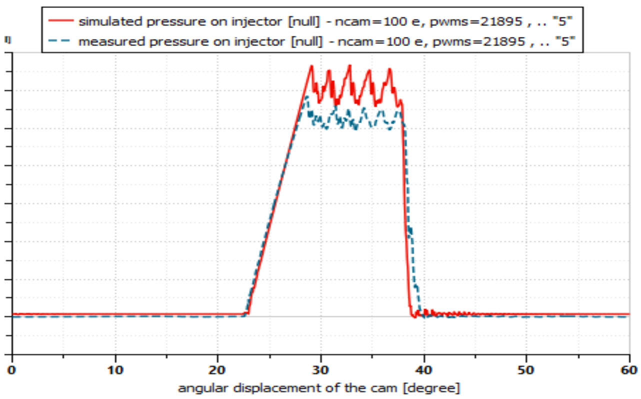
Pic. 13 – Result validation for PT1



Pic. 14 – Result validation for PT2



Pic. 15 – Result validation for PT3



Pic. 16 – Result validation for PT5

CONCLUSIONS

The development of a diesel injection pump is a complex endeavor, and several parameters can affect the result of the product. On top of this, the statistical spread of the parameters of the pumps during production and assembly introduces additional noise. During development, a limited number of samples is available to investigate the possible problems that can appear and can generate a limited amount of useful information.

This paper shows the advantages of working with simulation models based on measured production parameters, as specific-purpose digital twins, or virtual samples, to reproduce failures on the test benches. They allow understanding each event occurring on a complex system where many interactions happen at the same time. Several simulations and results had to be interpreted before the importance of the pressures around the valve area could be identified as culprit for the instabilities. This was much faster and cheaper than traditional methods of building extra samples and installing additional instrumentation on the test bench and could free valuable testing resources for more critical development activities. The chosen method of running full factorial DOEs with the most important parameters of the pump was certainly demanding in terms of computing power, data processing and post-processing, however provided invaluable information for improvement of the design together with the Problem-Solving team.

The simulation of complex systems using Simcenter Amesim at Bosch is a long-term activity, that is present for two decades at the PS-LA development. The results from the investigation and the final validated results presented at the end represent the importance of investing in high-level simulation models, because when the problems arise, the models can be immediately put to use and assist the development team and help achieve a solution within the project timeframes.

The results achieved show that the problem could be successfully addressed and solved, and the product could achieve the technical targets thanks to the teamwork between simulation, design and testing.

REFERENCES

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