15th IFK
Proc. of the 15th International Fluid Power Conference <Symposium/Conference>
<DOI>

Development of a flow-optimised slip-in servo cartridge valve for high-performance applications

Kristof Schlemmer[1], Jörg Wagner[1], Felix Lang[2]

[1]*AXXERON Hydrolux S.à r.l., k.schlemmer@axxeron-hydrolux.com*
[2]*SMS group GmbH, felix.lang@sms-group.com*

Abstract.

Hydraulic drive technology remains essential in applications demanding high force, power density, and precise dynamic control. Systems such as die-casting machines require extremely high flow rates to manage large cylinder volumes, rapid motion sequences, and fast pressure build-up and release. This paper presents the development methodology of a new, flow-optimized generation of hydraulic slip-in servo cartridge valves tailored to such high-performance requirements. The process includes the derivation of performance criteria from demanding use cases, the identification of key influencing parameters, and the formulation of a suitable design approach. State-of-the-art simulation methods and extensive experimental investigations are employed to evaluate design variants and optimize flow efficiency, dynamic behaviour, hysteresis, repeatability, and positioning accuracy, while enabling digital control and sensor integration. The result is benchmarked against relevant performance indicators. The study demonstrates how combining high dynamics with high flow capability provides a technical advantage in modern hydraulic systems and supports industrial efforts to reduce carbon footprints. A case study illustrates system integration and quantifies the resulting performance benefits.

Keywords. Hydraulic servo cartridge valve; slip-in valve; CFD; FEA; high-flow hydraulics; dynamic response; open-die forging press.

1. INTRODUCTION

Hydraulic drive technology remains essential in industrial applications that require high force density, compact installation space and reliable control behaviour. Many systems operate with large cylinder volumes and high operating pressures while demanding fast motion profiles and accurate pressure regulation. As a result, substantial hydraulic flow must be controlled with precision, particularly during rapid pressurisation and equally fast release or decompression phases. Applications such as die casting machines, open die forging presses and large injection moulding units exemplify these combined requirements and place correspondingly high demands on the components used.

Slip-in servo cartridge valves provide a suitable basis for such environments because they combine high flow capacity with the controllability of servo-actuated designs. Their architecture supports efficient flow guidance, low pressure losses and stable closed loop behaviour across a wide range of dynamic operating conditions. By virtue of their fundamental characteristics, valves of this class thus provide specific advantages in high performance hydraulic systems.

The present work discusses the development of a new flow optimised generation of such valves, named X700 [1]. The approach follows a structured methodology that integrates application driven requirement analysis, numerical design and simulation, and iterative experimental refinement. By combining mechanical, hydraulic and electronic design aspects within a coordinated development process, a new valve series has been created that offers significantly improved flow efficiency and dynamic control behaviour.

The resulting design is evaluated using representative performance metrics and is examined in a system context through a case study of an open die forging press. This example illustrates how the characteristics of the new valve generation influence manifold architecture, system dynamics and energy efficiency, and how the systematic development approach supports tangible improvements in demanding hydraulic applications.

2. Development Methodology

The development of high-performance hydraulic servo cartridge valves at Axxeron Hydrolux follows a structured and repeatable methodology that combines virtual analysis and physical testing within iterative loops. This approach ensures that functional, structural and dynamic requirements are met with a high degree of reliability before a new valve design is released for field use.

2.1. Requirements Analysis and Definition of Performance Targets

The process begins with a systematic requirement analysis for the relevant classes of applications. Flow demands are derived from cylinder dimensions, volumetric stroke requirements and acceptable speed profiles, whereas upper pressure limits are determined from structural load cases of the hydraulic system. Requirements concerning dynamic response, hysteresis and control precision arise from the motion control tasks of the target machine. Energy related aspects, such as permissible pilot stage leakage and acceptable pressure losses, further influence the performance targets. The result of this phase is a consolidated and quantified specification that governs all subsequent development stages.

2.2. Virtual Development Cycle

The first development loop takes place in the virtual domain. Three-dimensional CAD models of sleeve, poppet, cover and pilot interface form the foundation for numerical analyses. Strength evaluation is performed using finite element methods to assess static and cyclic loading up to the intended nominal operating pressure. This ensures that critical elements such as flow windows, seat transitions and connecting threads provide sufficient safety margins. The methodology includes both static load analyses and pressure cycling evaluations, with results systematically reviewed against design rules.

Flow behaviour is evaluated using computational fluid dynamics. Throughout the entire stroke range, simulations provide detailed information on pressure distributions, velocity fields, potential cavitation and flow induced hydraulic forces. The numerical development workflow, illustrated in Figure 2.1, supports the comparison of alternative geometries under identical boundary conditions and assists in identifying variants that combine low pressure losses with favourable dynamic characteristics. By iterating CAD design, FEA and CFD within the virtual loop, only the most promising concepts are transferred into physical prototypes.

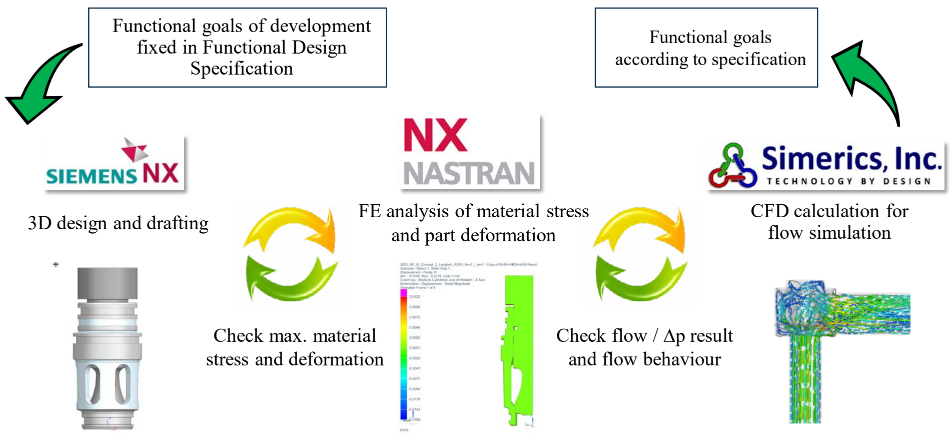

Figure 2.1. Iterative numerical development in continuous refinement loop.

2.3. *Experimental Development Cycle*

After virtual optimisation, selected variants are manufactured as prototypes and subjected to a standardised functional testing programme. This includes the measurement of flow characteristics in both flow directions at controlled pressure drops, typically ranging from a few bars to double digit values, depending on the intended application scenario. Dynamic evaluation involves step response measurements at pilot pressures up to 210 bar and frequency response tests across a representative bandwidth. Threshold, hysteresis, and drift behaviours are measured at different temperatures to assess control accuracy under varying environmental conditions. The complete experimental workflow is depicted in Figure 2.2.

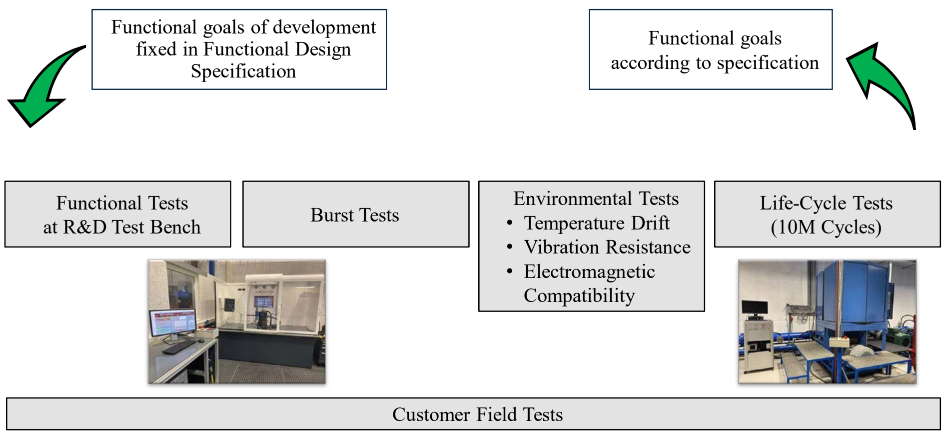

Figure 2.2. Iterative experimental development involving various types of testing.

These experiments validate the simulation results and provide insight into frictional behaviour, guiding tolerances and poppet position stability. Any deviation between measured and predicted behaviour triggers an additional virtual development loop, ensuring alignment between numerical predictions and hardware performance.

2.4. Static and Dynamic Validation Testing

Once a prototype demonstrates stable operation under functional conditions, it enters the structural verification phase. This includes pressure cycling tests with amplitudes up to the intended nominal operating pressure and endurance tests amounting to several million switching cycles. These tests assess the long-term stability of the main stage, potential wear mechanisms of guiding surfaces and drift behaviour of measurement and pilot components. Static burst pressure tests to several times the nominal operating pressure serve as an additional safety measure. Together, these assessments demonstrate that the valve design withstands the mechanical loads expected throughout its life cycle.

2.5. Environmental Qualification Testing

Environmental qualification ensures that the valve performs reliably under demanding industrial conditions. Vibration tests with multi axis excitation up to 30 g and shock tests up to 50 g evaluate mechanical robustness. Thermal cycling and temperature dependent measurements assess the stability of materials, electronics and hydraulic components across the intended ambient conditions. Electromagnetic compatibility testing confirms the robustness of the integrated electronics with respect to both emitted interference and immunity to external disturbances.

2.6. Consolidation and Release for Field Testing

Only when virtual, functional, structural and environmental evaluations all converge does a design enter field testing. Pre series valves are installed in selected customer machines, enabling long term observation under real operating conditions. These tests confirm dynamic behaviour, leakage stability and robustness against contamination and installation tolerances. The feedback from this stage closes the development loop and supports the final release for series production.

3. Application of the Development Methodology to the New Valve Series

The methodology described in Section 2 was applied to the development of the X700 series, a new generation of two-way slip-in servo cartridge valves intended for applications with exceptionally high flow demand and stringent dynamic requirements. While the individual development steps follow the generic process, several aspects of the X700 project required particular attention due to the unusually high flow-to-size ratio and the intended operating pressure of 420 bar across the entire flow range from NG32 to NG100.

3.1. Derivation of Application Specific Requirements

The requirement analysis was carried out with a focus on die casting machines and metal forming presses, as these applications represent some of the most demanding use cases for servo cartridge valves. A comparative assessment of design drivers, shown schematically in Figure 3.1, highlighted flow capacity, operating pressure and dynamic response as primary influencing parameters for both application classes. Press systems additionally emphasised failsafe behaviour and the need for compact manifolds, while die casting machines placed stronger emphasis on control precision during fast injection and decompression phases. Based on these boundary conditions, the X700 development targets included significantly higher flow performance compared to earlier cartridge generations, reduced pressure losses through the main stage, and improved dynamic behaviour through the use of direct drive pilot valves and integrated digital electronics.

Criteria	Die Casting	Presses
Flow capacity	++	++
Operating pressure	++	++
Dynamics	++	+
Control	++	+
Size and space	+	++
Failsafe functionality	○	++
Digital and IoT features	+	+
Robustness	++	+

Figure 3.1. Application-driven requirement matrix for die-casting and press applications.

3.2. Virtual Development and Design Evolution

The virtual development stage started from a baseline design as used in conventional servo cartridge valves. Early variants followed established geometries with drilled radial bores and cylindrical poppets, which provided a useful reference but proved insufficient to achieve the targeted flow levels. Subsequent design iterations explored alternative sleeve window shapes and modified poppet contours. The systematic comparison of these variants through FEM and CFD simulations led to the identification of a geometry that allowed a substantial increase in effective flow cross section while maintaining acceptable stress levels. This evolution is illustrated in Figure 3.2, which shows how the transition from drilled bores to shaped flow windows enabled larger port diameters and lower local pressure losses.

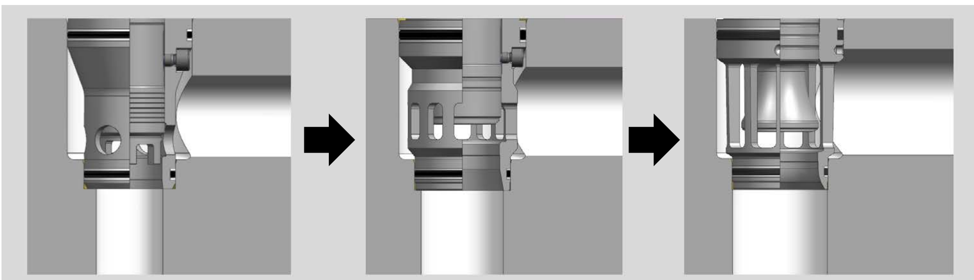

Figure 3.2. Evolution of main stage sleeve and poppet geometry.

Structural analysis confirmed that the resulting geometry provided sufficient safety margins under both static loading at 420 bar and dynamic pressure cycling. CFD simulations demonstrated improved flow characteristics and a favourable force balance over the stroke range, which was essential for ensuring stable poppet motion under high flow rates. Figure

3.3 and Figure 3.4 summarise typical FEA and CFD results processed during the design evaluation.

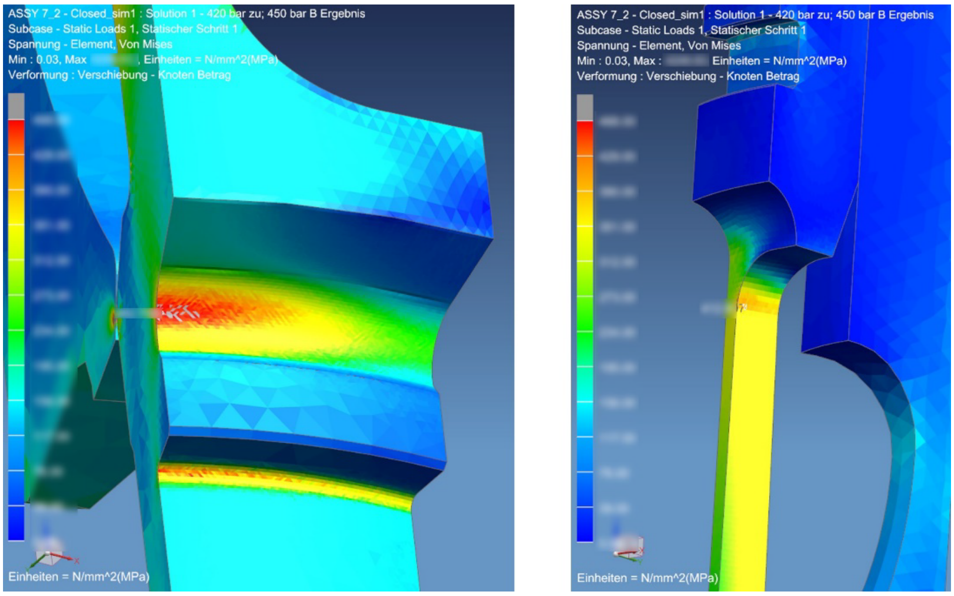

Figure 3.3. FEA-based stress distribution used to verify structural integrity.

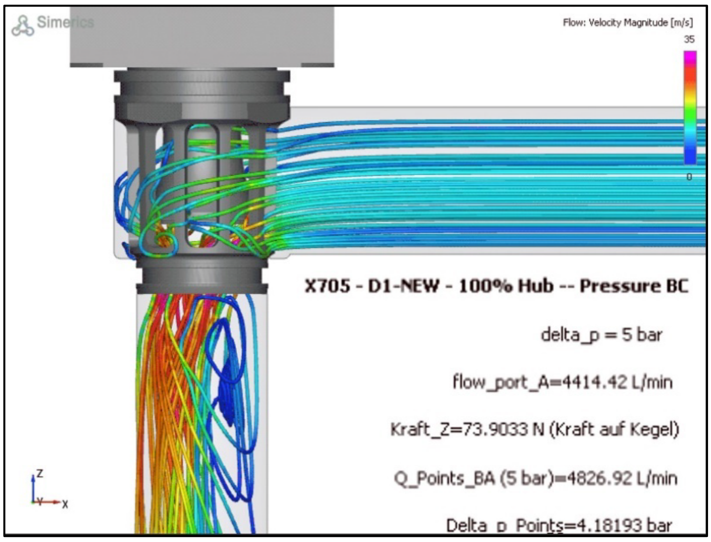

Figure 3.4. CFD-based evaluation of velocity field and flow induced forces.

3.3. Experimental Verification and Iterative Refinement

The experimental development phase follows the methodology outlined in Section 2 and typically reveals aspects of the valve behaviour that cannot be predicted with full precision using numerical tools alone. This is an inherent characteristic of hydraulic systems operating at very high flow rates, where small geometric deviations or local pressure effects may influence the dynamic response. In the case of the X700 development, such an iterative refinement step occurred during functional testing of early prototypes. While the overall flow behaviour and pressure loss characteristics closely matched the CFD predictions, one prototype variant showed a lightly oscillatory poppet motion in a narrow operating range at high flow demand. This observation was not treated as an anomaly but as a natural part of the iterative process, in which simulation and physical testing complement each other.

A combined analysis of measurement data and targeted CFD studies revealed that, in this particular geometry, the hydraulic force balance at certain intermediate stroke positions was sensitive to small variations in the surrounding pressure field. As shown by result in Figure 3.5, the pressure acting on the poppet surfaces could shift slightly under these conditions, producing alternating net forces that caused a lightly damped dynamic response. Since such behaviours are difficult to capture fully in simplified simulation models, this finding demonstrated the value of the iterative test and refine loop that is integral to the applied development methodology. Several modified poppet geometries were subsequently analysed and manufactured. Among these, one variant achieved a consistently stable force balance across the full stroke range while maintaining the targeted flow performance. The refinement confirmed that virtual models and physical testing converge most effectively when such iterative corrections are incorporated into the development process as planned and expected steps.

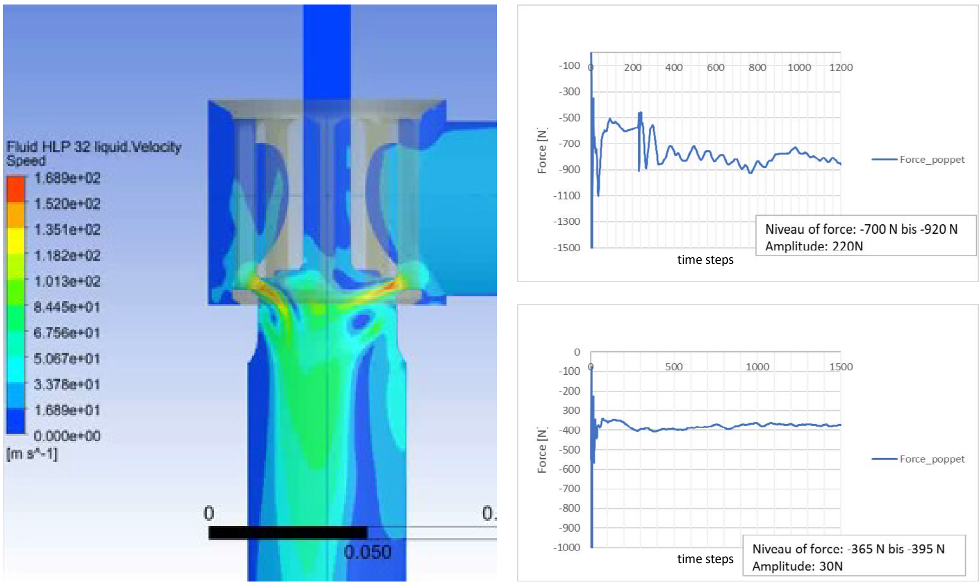

Figure 3.5. Flow-induced force imbalance as identified during prototype testing.

3.4. Qualification and Validation for Series Release

After resolving all functional and dynamic issues, the X700 prototypes were subjected to the standard qualification programme described in Section 2. This included extended endurance testing with up to ten million switching cycles at elevated pressure levels, verifying fatigue behaviour, wear and long-term stability of the main stage mechanics, the pilot valve and the displacement transducer. Structural safety was confirmed through burst pressure tests conducted up to a multiple of the rated pressure. Environmental testing demonstrated robustness against vibration, shock loads and thermal cycling, while EMC qualification ensured the immunity of the integrated electronics against electromagnetic disturbances. These results validated the valve for field installation. Pre series units of the X700 were subsequently tested in selected industrial machines to verify performance in operational conditions. The field tests confirmed the high flow capacity, excellent dynamic behaviour and low leakage levels predicted in simulation and demonstrated in laboratory tests.

4. Development Results

The X700 series represents the consolidated outcome of the virtual and experimental development loops described in Sections 2 and 3. The resulting valve family covers ISO sizes 32 to 100 and is designed for an operating pressure of 420 bar across all variants. Its performance characteristics reflect the accumulated effects of the flow optimised main stage geometry, the direct drive pilot concept and the iterative refinement of dynamic behaviour and stability margins. Figure 4.1 provides an overview of the final valve design and its structural elements.

Figure 4.1. Final design of the X700 servo cartridge valve series.

Across the entire size range, the valves exhibit a consistently high flow efficiency. The shaped sleeve windows and coordinated poppet contour minimise pressure losses in both flow directions, so that the valves reach required flow levels at comparatively low command signals. This behaviour enhances the achievable dynamic response, because the cylinder velocity rises more quickly after a change in the command value. The measured dynamic flow characteristics and excitation responses shown in Figure 4.2 illustrate this relationship for representative size and cavity configurations. The curves confirm that the valves translate command signals into valve opening and subsequently into stable and repeatable flow behaviour across the full operating range.

The dynamic response of the valves is supported by the direct drive pilot stage, which provides rapid actuation without the pilot oil consumption associated with traditional two-stage concepts. The integrated electronics ensure a stable closed-loop relation between command value and poppet position, even under varying pilot pressures and temperatures. This contributes to the low hysteresis and high repeatability observed in testing, which remain within the targets established during the requirement analysis. The low internal leakage of the pilot stage enhances energy efficiency, particularly in cyclic operation where leakage-related losses accumulate significantly over time.

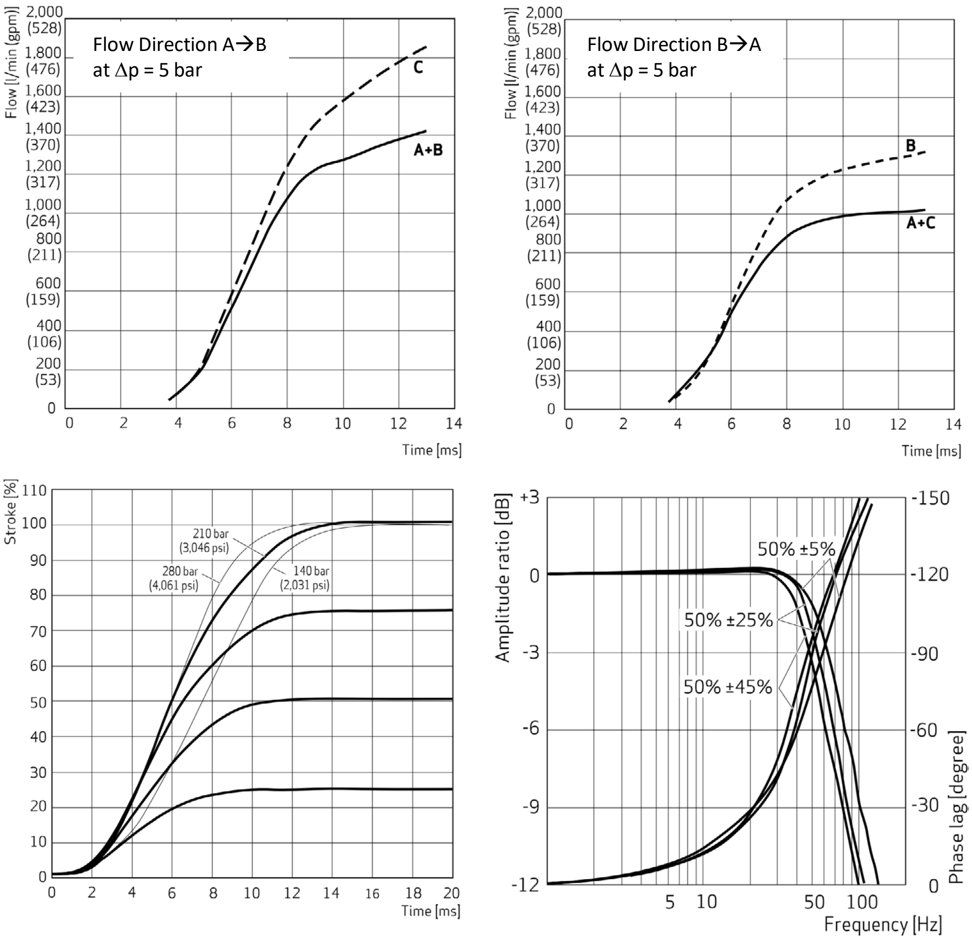

Figure 4.2. Characteristic dynamic flow response, step response, and frequency response for size 32. [2]

When assessing the achieved performance relative to predecessor products and competing valve families, the X700 series demonstrates a clear step forward. For a given valve size, the flow-optimised geometry provides noticeably higher flow capacity than previous slip-in servo cartridge designs, and the direct-drive pilot concept delivers a more favourable combination of dynamic response and control precision. In this regard, the essential improvement lies in the enhanced capability to quickly, but in a stable and controlled fashion ramp up volumetric flow, i.e. to provide a superior flow rate increase. This is shown exemplarily for one size in the comparison in Figure 4.3. Notwithstanding, the available flow performance exceeds that of comparable servo cartridges in many size classes by a substantial margin, enabling downsizing of one or more valve sizes in typical installations. As an example, Figure 4.4 exhibits the increased dynamic response of cylinder velocity in an existing die-casting machine, where the previously installed size-50 valve was outperformed by the newly developed size-40 valve. This improvement is not only a result of geometric changes but a direct consequence of the systematic application of the development methodology, in which simulation, testing and iterative refinement were closely aligned.

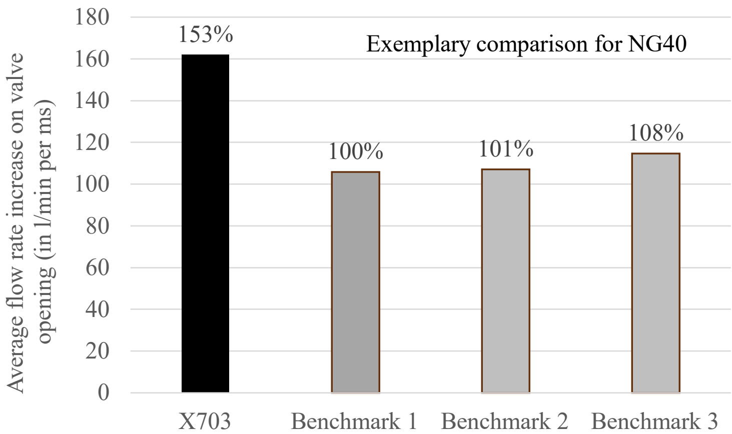

Figure 4.3. Flow performance indicator for exemplary Size 40.

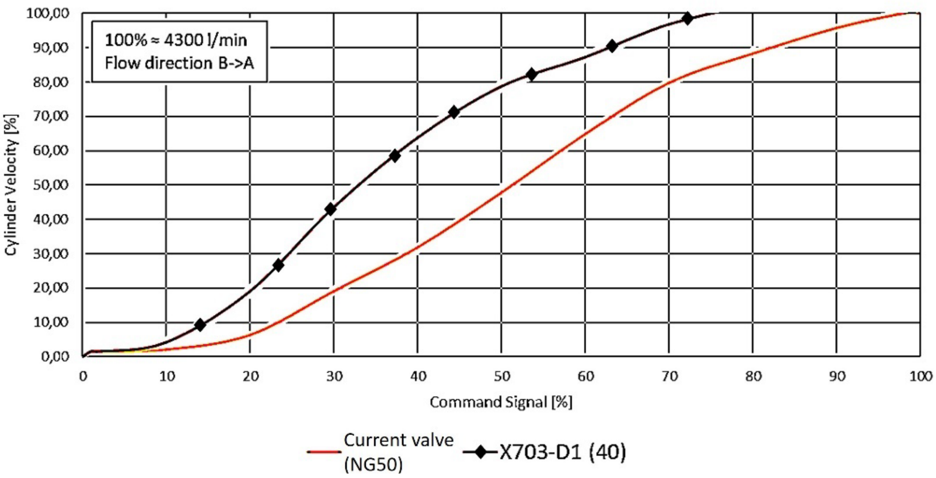

Figure 4.4. Increased dynamic performance at downsizing in a die-casting machine.

The X700 series therefore establishes a new level of performance within its class. The valves combine high flow capacity with stable dynamic behaviour and robust closed loop control. Their characteristics support the implementation of compact manifold layouts with reduced pressure losses and allow machine builders to achieve faster cycle times and higher productivity. The series is well suited for applications in which both high volumetric flow and precise motion control are required, as demonstrated in the case study of Section 5.

5. Case Study: Integration in an Open-Die Forging Press

The improvements achieved in the development of the X700 series become particularly evident when the valves are integrated into a demanding hydraulic system. A representative example is an open die forging press in the 50–55 MN class, which combines large cylinder volumes, high operating pressures and stringent requirements for cycle time and repeatability [3]. Figure 5.1 depicts an exemplary press implementation. The hydraulic system must provide fast approach motions, accurately controlled forging strokes and rapid decompression, while executing a high number of cycles over the machine's lifetime. Figure 5.2 illustrates the typical functional layout and working cycle of such a press and the role of servo cartridge valves in the inlet and outlet flow paths (all pictures courtesy of SMS group GmbH, Mönchengladbach).

Figure 5.1. Exemplary open-die forging press.

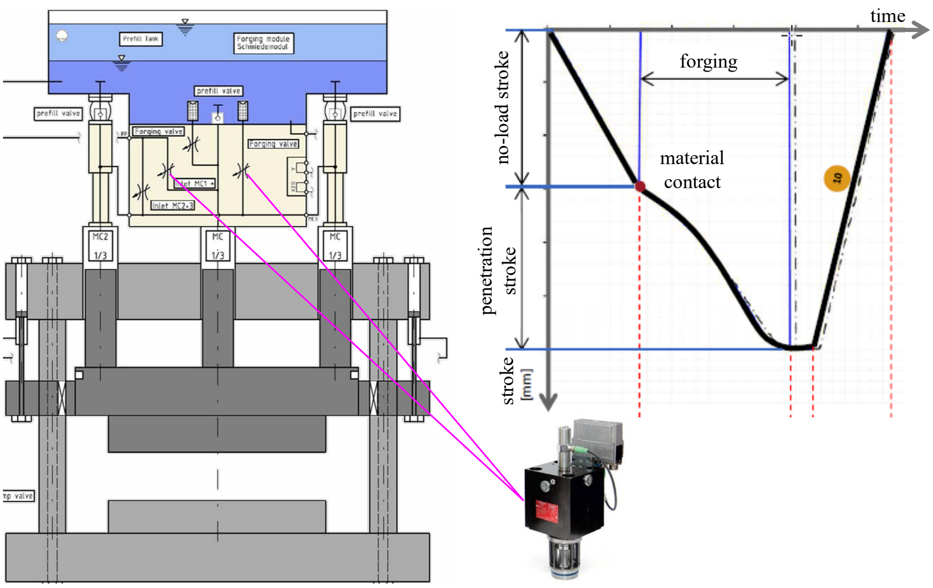

Figure 5.2. Simplified layout and working cycle of the open-die forging press.

5.1. Integration of the Valves into the Forging Manifold

In the hydraulic manifold originally used for this press class, several large servo cartridges are installed in parallel to achieve the required pressurisation and decompression flows. The configuration includes multiple valves of nominal size 125, complemented by size 80 units, and results in a structurally robust but comparatively heavy and voluminous manifold. With the introduction of the X700 series, the same functional capacity can be achieved using smaller nominal sizes, because each valve provides higher flow capability relative to its ISO size. This enables a simplified configuration based exclusively on size 100 and size 80 valves and leads to a reduction in manifold mass of about 35 %. A direct comparison of the two configurations is given in Table 5.1. Figure 5.3 visualises the achieved result in the revised, compact manifold.

Table 5.1: Valve configurations before and after introducing the new valve series.

Configuration	Inlet Valves	Outlet Valves	Manifold Mass
Before	1 × size 125 + 1 × size 80	3 × size 125	~16 200 kg
After (X700)	2 × size 100	2 × size 100 + 2 × size 80	~12 000 kg

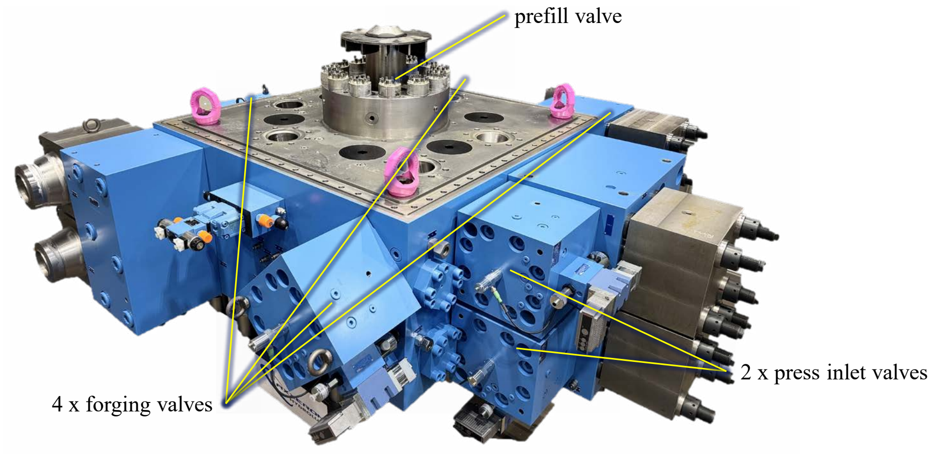

Figure 5.3. Improved manifold configuration and layout using X700 valves.

5.2. Effect on System Dynamics and Cycle Performance

The influence of the new valve configuration becomes clear when examining typical forging cycles. The flow optimised main stage of the X700 series enables the valves to reach high volumetric flows at comparatively low command signals. For example, size 100 valves of the series provide rated flows clearly above 10 000 l/min at a pressure drop of 5 bar, with recommended maximum flows significantly higher when using optimised cavity designs. This behaviour shortens the time required for pressure build up and exhaust. During the decompression phase, the updated manifold can release the hydraulic fluid from the main cylinder more rapidly than the previous design, despite using smaller nominated valve sizes. The corresponding reduction in non-productive time within each cycle contributes to a higher throughput of the press. At the same time, the stable closed loop characteristics of the X700 series support precise control of the forging stroke, so that the higher dynamics do not come at the expense of positioning accuracy or repeatability.

5.3. Energy Related Effects and System Efficiency

Beyond the dynamic aspects, the introduction of the new valve series also influences the energy demand of the forging system. The reduced pressure losses across the main stage, achieved through the flow optimised geometry, lower the hydraulic power needed for a given motion profile. In addition, the direct drive pilot valves used in the series exhibit significantly reduced internal leakage compared to traditional pilot operated concepts. For size ranges up to size 100, the pilot leakage remains below approximately 1.4 l/min at 100 bar, which is substantially lower than the values associated with earlier two-stage solutions.

Figure 5.4. Integration of the forging manifold into the machine structure.

In a forging environment with thousands of cycles per shift, such differences accumulate measurably. Lower leakage reduces the continuous energy losses in the system, while improved flow efficiency decreases the peak power required from the hydraulic power unit. The downsized manifold, with its 35 % lower mass and reduced volume, and thus improved integration into the overall machine structure as shown in Figure 5.4, further supports efficient operation by reducing the total amount of oil in circulation and associated thermal loads. Together, these effects help operators reduce operating costs and support current efforts to lower the carbon footprint of industrial processes.

5.4. Summary of Case Study Findings

The open die forging press illustrates how the X700 series translates component level improvements into system level benefits. Increased flow capability per valve enables a more compact manifold with fewer very large cartridges and a significantly lower structural mass. Dynamic response and control precision are improved, leading to shorter non-productive phases and higher throughput. The reduced pressure losses and low pilot leakage contribute to lower energy demand. Together, these findings show how the systematic development methodology supports the design of more efficient and competitive hydraulic systems.

6. Conclusions and Outlook

The development of the X700 series shows that a systematic combination of numerical simulation, experimental refinement and structured qualification enables tangible advances in hydraulic servo cartridge technology. Building on this foundation, several extensions of the concept have already emerged that broaden its applicability.

One development path concerns variants with moderately reduced performance levels. These valves follow the same design principles as the X700 series but are adapted for applications with lower dynamic requirements or reduced operating pressures. By simplifying selected elements of the main stage and electronics, these variants offer a cost-efficient option for less demanding industrial environments while retaining the characteristic stability and controllability of the base design.

At the upper end of the performance range, versions designed for higher operating pressures have also been realised. These valves extend the pressure capability from the standard 420 bar to 450 bar and are intended for applications that require increased load capacity or additional structural safety margins. Their design and qualification follow the same methodological steps as the standard series, ensuring consistent behaviour across the extended operating range.

In parallel, work continues on new control concepts derived from the same architecture. A digitally pressure compensated flow control valve is currently being developed, combining the mechanical robustness of the slip in cartridge format with electronically controlled flow characteristics. This concept enables more flexible integration into digital machine control systems and supports advanced functions such as remote parameterisation, integrated diagnostic information and coordinated motion control.

Together, these developments demonstrate that the underlying methodology not only supports high performance solutions such as the X700 series but also provides a scalable basis for future hydraulic product families.

7. REFERENCES

[1] Wagner, J., Wiegandt, M. and Jost, F.: (2023): Weniger ist mehr – Servocartridges auf einem neuen Leistungsniveau, in: O+P Fluidtechnik 2023/04, pp. 30-33.

[2] Axxeron Hydrolux S.à r.l.: X700 Series 2-Way Servo Cartridge Valves – Product Catalogue, Rev. E, March 2025.

[3] K. Schlemmer, F. Lang: Leistung trifft Präzision – Servo-Einbauventiltechnik für High-Performance-Anwendungen, IFAS Industrie-Kolloquium, 16 May 2025.

Biographies

Kristof Schlemmer received his Dipl.-Ing. degree in Mechanical Engineering from RWTH Aachen University in 2004, and his Dr.-Ing. degree in the field of fluid power from the same institution in 2012. He currently works as Engineering Manager at AXXERON Hydrolux S.à r.l. in Bettembourg, Luxembourg, and acts as a guest lecturer at IFAS of RWTH Aachen. His areas of activity are focussed on advanced products, systems and applications in industrial hydraulics.

Jörg Wagner received the degree in Mechanical Engineering from Balthasar Neumann Technikum Trier in 2008. He currently works as Team Leader Engineering Products at AXXERON Hydrolux S.à r.l. in Bettembourg, Luxembourg. He is responsible for Product Development focused on cartridge valves and cartridge valve applications.

Felix Lang received his Dipl.-Ing. degree in Mechanical Engineering from RWTH Aachen University in 2010 and subsequently joined SMS group GmbH in Mönchengladbach as Project Engineer in the field of forging technology. Since 2018, he has been leading a team of specialised engineers as Head of Hydraulics Extrusion & Forging Presses.