Title:

Influence of Spool Bore Position on the Structural and Hydraulic Performance of an Additively Manufactured NG10 Valve

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Introduction:

In industry today, when motion is required, hydraulics is usually the main solution. This is due to the simplicity and accessibility of hydraulic components. In hydraulic systems, multiple components are used, and all of them create pressure losses as a side effect because the flow is internally restricted. To reduce these internal losses some form of optimization is required. The largest contributors to pressure drop in hydraulic systems are valves, which direct the flow of fluid.

Hydraulic valves are typically manufactured with simple internal geometries due to traditional machining constraints. Suboptimal internal geometries are usually the main cause of pressure losses, resulting in increased fluid temperature. Additive Manufacturing (AM) enables more complex internal flow paths compared to traditional production technologies, thereby improving hydraulic performance. Optimization of both the internal geometry of fluid channels and the material distribution becomes possible when designing for AM [1, 2, 4]. External geometries are typically optimized to conserve material and reduce the mass of the part using Topology Optimization (TO). Many studies have focused on the optimization of external geometries, achieving significant material savings and consequently reducing the mass of the final part [3, 6]. However, these approaches usually assume a fixed internal structure and therefore neglect potential improvements in flow behavior. While valve inlet and outlet connections are typically standardized, the internal geometry of the flow channels and the spool bore position remain adjustable design parameters.

The influence of spool bore position on the combined structural and hydraulic performance of AM hydraulic valves has not received much attention. Therefore, the authors chose to conduct a systematic evaluation of spool bore position as a design parameter for hydraulic valves. Size 10 (CETOP 5) hydraulic valve was chosen due to its complex internal structure and widespread industrial use. The goal of this research is to identify the best spool bore positions regarding structural and hydraulic performance. Because it is unlikely for structural and hydraulic performance to be optimal simultaneously, trade-off analysis is needed as well to give insights into how to position spool bore for wanted performance.

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Methodology:

Reference geometry is based on proportional directional hydraulic valve size 10 according to ISO 4401 [5]. This standard provides exact positions of connecting holes for the valve to ensure interchangeability with any other valve of the same size. Internal geometry was generated parametrically to adapt to spool bore position. Two variables were used to define different configurations of the geometry. These were vertical (Z) and lateral (x) offset as shown in the figure 1. The design space is defined by vertical spool bore offset ranging from 40 to 60 mm and lateral offset (x) ranging between -10 mm to +10 mm compared to the baseline position. Three positions for vertical offset were considered. Since the lateral offset was expected to have a stronger influence on the internal flow paths and consequently on both the optimized geometry and flow characteristics, five different positions were evaluated.

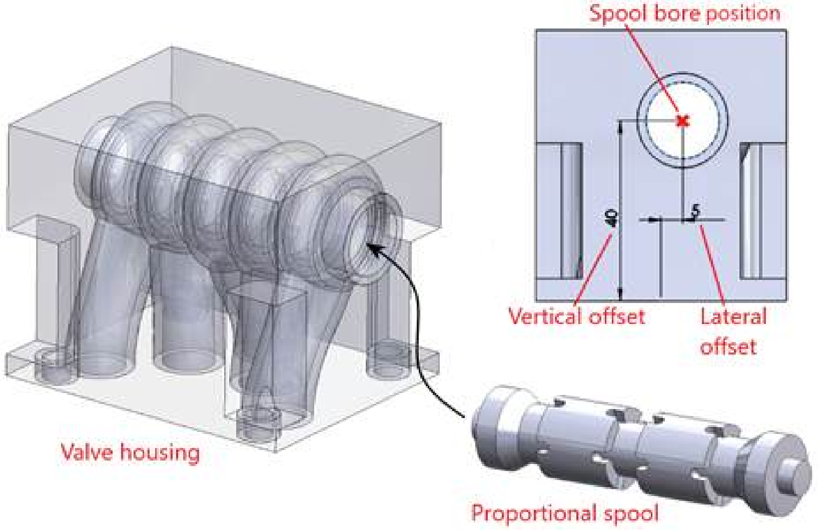

Fig. 1: CAD model for the configuration Z = 40 mm and x = 5 mm.

After creating geometry with SolidWorks, TO and CFD analysis was performed for each configuration of spool bore position. All simulations were performed in Ansys 2025 software package. At the end trade-off analysis was conducted for pressure drop, Turbulent Kinetic Energy (TKE) dissipation and final mass of the optimized geometry depending on the spool bore position.

CFD Evaluation

Analysis of the fluid flow was carried out in the ANSYS Fluent software. Solver setup was steady-state, incompressible, single phase flow. Water was used as hydraulic fluid because of the lower viscosity compared to the hydraulic oil to promote turbulence effects and also because it is relevant for eco-friendly modern hydraulic systems. Different volumetric flow rates were used ranging from 60 to 120 L/min. Spool configuration was set and fixed at 3 mm opening comparable to 75 % opening. Turbulence was modeled using k-omega SST model because it is robust and computationally efficient while maintaining acceptable accuracy for parametric comparisons.

Meshing strategy used was unstructured mesh with local refinements near the critical spool regions and channel transitions with boundary layers applied to walls. Evaluation metrics relied on calculation of total pressure drop as primary performance indicator. Authors have also quantified the results of TKE dissipation and velocity fields in a view of uniformity and potentials for recirculation. Higher values indicate regions where TKE is rapidly converted into heat, corresponding to more chaotic, mixing-intensive and energy loss dominated flow. Lower values reflect smoother flow structures with reduced turbulence intensity and lower hydraulic losses.

Proportional spool was used to promote higher pressure drops and stronger sensitivity of the geometry because of smaller cross-sectional flow area.

Topology optimization:

TO was performed in Ansys Mechanical for each selected spool bore position. The structural model included internal pressure, axial loading at each end of the spool bore, fastening loads and supports at the mounting holes. A density-based SIMP (Solid Isotropic Material with Penalization) TO approach was used. The objective combined compliance minimization and mass minimization, with greater emphasis placed on mass reduction with weight ratio of $5:1$. To ensure functional stiffness of the valve, a maximum displacement constraint of 0.01 mm was applied to the inner spool-guiding surfaces. Minimum member size of 2 mm and 45 degree AM overhang constraints were also included to improve manufacturability and avoid excessively thin structural members. Functional surfaces with applied loads or supports were excluded from the optimization.

Results and discussion:

Results of CFD analysis and TO for every configuration are given in table 1.

Configuration number	Vertical offset (Z) [mm]	Lateral offset (x) [mm]	Pressure drop [MPa]	TKE dissipation [m^2/s^2]	Final mass [kg]
1	40	-10	15.50	120.2	0.552
2	40	-5	15.23	137.2	0.576
3	40	0	15.32	115.4	0.580
4	40	5	15.15	95.3	0.589
5	40	10	15.62	180.6	0.598
6	50	-10	15.51	150.3	0.673
7	50	-5	15.54	157.1	0.666
8	50	0	15.37	141.6	0.688
9	50	5	15.23	132.3	0.687
10	50	10	15.71	186.8	0.684
11	60	-10	15.58	148.5	0.749
12	60	-5	15.46	161.3	0.774
13	60	0	14.95	180.0	0.790
14	60	5	15.71	138.2	0.805
15	60	10	15.39	202.0	0.794

Table 1: Pressure drop, TKE dissipation and final mass for every spool bore position configuration.

Pressure drop results of the CFD calculations show non-linear dependence on lateral offset. Local minimums are observed at slight offsets (5 mm) while extreme offsets of 10 mm both directions show increases in pressure losses. This can be seen in figure 3 (left). For visualization of general trends in the design space, the discrete results were interpolated using cubic interpolation. Results show that lowest calculated pressure drop was 14.95 MPa for the vertical offset of 60 mm and a lateral offset of 0 mm. This is approximately 30 % improvement compared to conventionally manufacturable design. Compared to the baseline configuration (Z = 40 mm and x = 0 mm), this means improvement of around 1.8 %. Velocity fields are much more uniform in the case of the designs for AM compared to conventional model where local accelerations and recirculation zones are clearly visible and more pronounced (figure 2). TKE dissipation shows slightly different response to lateral movements of the spool with negative lateral offsets presenting lower turbulence values as shown in figure 3 on the right. The best TKE dissipation was found at configuration Z = 40 mm and x = 5 mm with value of 95.3 m^2/s^2. This is 17.4 % improvement compared to the baseline configuration.

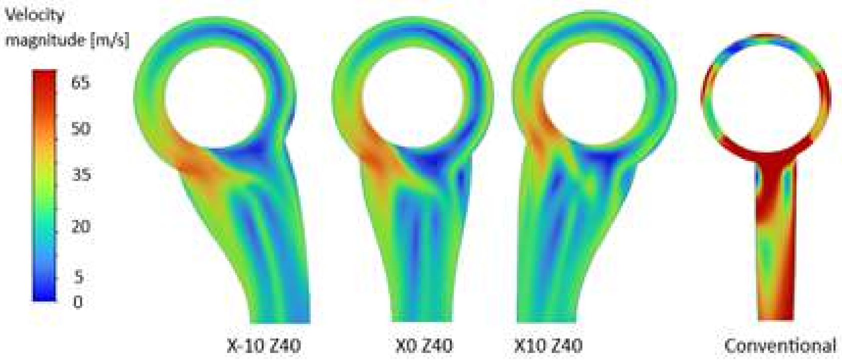

Fig. 2: Velocity contours for cross-sections of hydraulic channels with different lateral spool bore positions and conventional design.

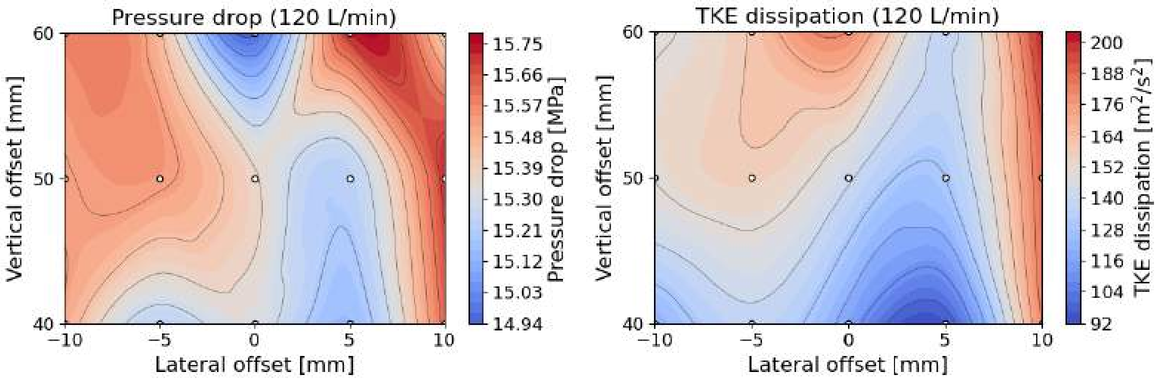

Fig. 3: Pressure drop (left) and TKE dissipation (right) for all spool bore position configurations.

The initial masses of valve geometries prior to TO ranged from 1.47 kg to 2.07 kg. The adopted TO setup achieved approximately 60 % mass reduction compared to the initial geometry in all cases. Bigger vertical offset resulted in longer internal flow paths and since material near functional surfaces was excluded from the optimization, this led to an increase in the final mass. Moving towards negative lateral offset generally reduces final mass as seen in figure 4 on the right. The best result was obtained at the configuration Z = 40 mm and x = -10 mm which had mass of 0.552 kg. It can be seen in figure 4 on the left. This is a 4.8 % improvement compared to the baseline configuration.

To determine the most suitable design, multiple performance criteria must be considered. While certain parameters clearly benefit from spool bore relocation, others may deteriorate simultaneously as seen in figure 5. Ultimately, the optimal configuration depends on the intended application. Some applications prioritize mass reduction, whereas others place greater emphasis on hydraulic performance.

In our case, configuration Z = 40 mm and x = 5 mm represents a suitable compromise for overall performance, since it gives the lowest TKE value and the second-lowest pressure drop while maintaining a relatively low final mass.

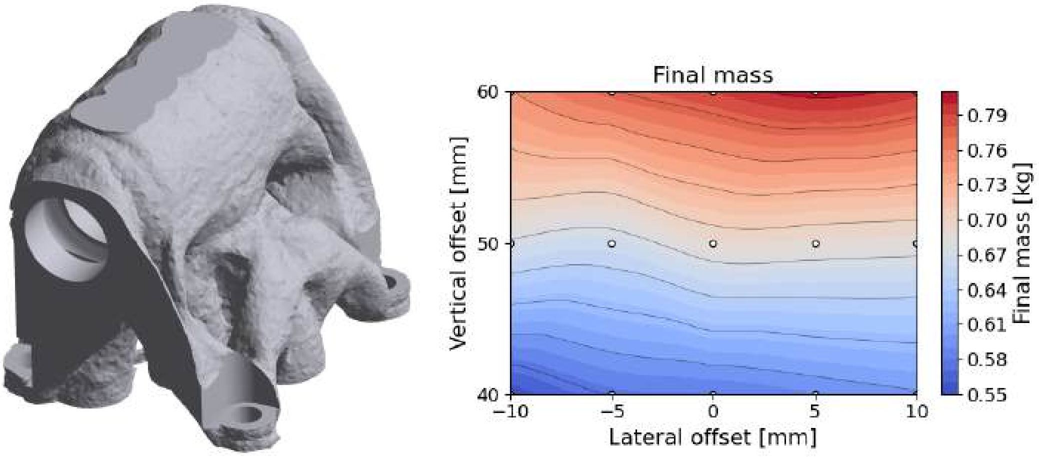

Fig. 4: Final optimized geometry for the configuration Z = 40 mm, x = -10 mm (left) and final mass for all configurations (right).

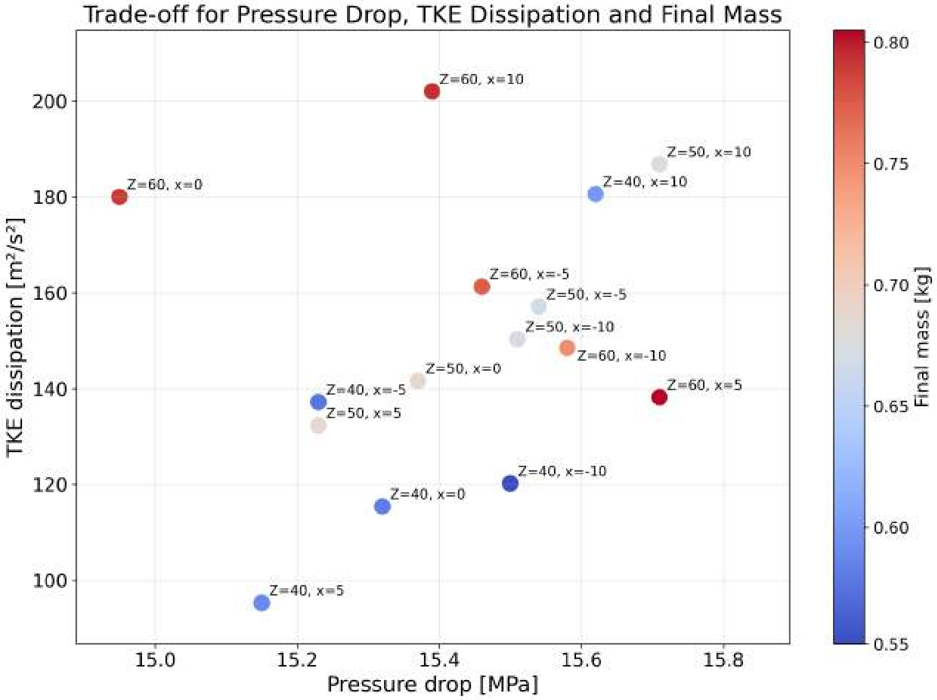

Fig. 5: Visualization for the trade-off analysis.

For future work, additional valve parameters can be investigated, such as rotation of the spool valve around the vertical axis. This may introduce further design flexibility and yield additional improvements in both TO and CFD performance. The most promising geometries are planned to be manufactured using AM and subsequently tested in real hydraulic systems. These experiments will serve to validate the numerical results and confirm the functionality of the newly designed valve under real operating conditions.

Conclusions:

Multiple spool bore position parameters were evaluated to assess their influence on mass reduction through topology optimization and on hydraulic performance. We showed that the spool bore position is a parameter that can be optimized in hydraulic valve design. Relative to the baseline configuration, the best configurations achieved a 1.8 % reduction in pressure drop (Z = 60 mm, x = 0 mm), a 17.4 % reduction in TKE dissipation (Z = 40 mm, x = 5 mm), and a 4.8 % reduction in final mass (Z = 40 mm, x = -10 mm). However, these optima did not occur at the same spool bore position. Structural and hydraulic performance do not strictly correlate and must therefore be considered simultaneously through a trade-off analysis.

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References:

[1] Arena M.; Ambrogiani P.; Raiola V.; Bocchetto F.; Tirelli T., Castaldo M.: Design and Qualification of an Additively Manufactured Manifold for Aircraft Landing Gears Applications, Aerospacem10 (1), 2023. https://doi.org/110.3390/aerospace10010069

[2] Bartolj J.; Schmitz K.; Vukašinović N.; Majdič F.: Numerical Optimization of Internal Geometry for Additively Manufactured Hydraulic Manifolds, International Conference Fluid Power 2025: Conference Proceedings, University of Maribor Press, 2025. https://doi.org/10.18690/um.fs.7.2025.4

[3] Biedermann M.: Automated Design of Additive Manufactured Flow Components, Doctoral thesis, ETH Zurich, Zurich, 2022. https://doi.org/10.3929/ethz-b-000587405

[4] Hofmann, U.; Fankhauser, M.; Willen, S.; Inniger, D.; Klahn, C.; Löffel, K.; Meboldt, M.: Design of an additively manufactured hydraulic directional spool valve: an industrial case study, *Virtual and Physical Prototyping*, *18* (1), 2023. https://doi.org/10.1080/17452759.2022.2129699

[5] International Organization for Standardization, Hydraulic fluid power - Four-port directional control valves - Mounting surfaces, Geneva, Switzerland, 2005.

[6] Zhang C.; Wang S.; Li j.; Zhu Y.; Peng T.; Yang H.: Additive manufacturing of products with functional fluid channels: A review, Additive Manufactoring 36, 2020. https://doi.org/10.1016/j.addma.2020.101490