APPLICATION OF ROBUST DESIGN PRINCIPLES ON THE EXAMPLE OF TOLERANCE ALLOCATION FOR A SPOOL TYPE PRESSURE RELIEF VALVE

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Abstract: *The functional properties of a mechanical product are usually defined by the geometrical specifications of its inherent subcomponents. Therefore, any deviation from the design's nominal assigned values, can potentially lead to loss of functionality and failure to meet quality criteria. In order to ensure product functionality such deviations have to be limited by the assignment and allocation of tolerances. The conventional product development process described in VDI 2221, however does not sufficiently emphasize the importance of tolerance design principles in the early stages of product development. This shortcoming has been met by integrating Taguchi's robust design methodology alongside the VDI guidelines, thus introducing the tasks of tolerance design and process planning to the product development engineer. In this contribution a use case for the application of such wholistic tolerancing approaches is being proposed. A spool type pressure relief valve thereby serves as a function assembly for studying the relationship of the valve's geometrical properties and its resulting functional performance. Functional testing, geometrical inspection and mathematical modelling of the transfer function, are the methodologies used for allocating appropriate tolerance values to the parts.*

Key words: robust design, tolerance design, pressure relief valve, functional tolerancing

1. INTRODUCTION

Products are primarily developed to fulfill specific functional requirements. Consequently, functional requirements become the central criteria for assessing product quality in the development process. (Bohn & Hetsch, 2020). In the case of mechanical products, functionality commonly arises from the geometry of the subcomponents. Hence the product designer assigns nominal values to the geometry to ensure the parts performance. Since all manufacturing and inspection processes are subject to imperfections, deviations from these specified nominal values have to be expected (Wang et al., 2019). In order to limit these deviations tolerance values are allocated in accordance with current standards such as ISO GPS. Tolerance allocation is in every way a highly responsible task that greatly affects the quality of the product as well as the cost of manufacturing. It is thereby suggested that manufacturing and design divisions should take part in the tolerance design process together to better balance the competing aspects of quality and cost (Hallmann et al., 2020). However according to the traditional product development methodology described in VDI 2221, manufacturing aspects are not taken into account before the detail design phase begins in which the final geometries are being specified (Bender & Gericke, 2021). Hence the VDI 2221 guideline for product development does not sufficiently emphasize the necessity for a parallel development of both the product- and the manufacturing process (Bohn & Hetsch, 2020). To address this shortcoming a complementary methodology emphasizing robust product design was formulated by Taguchi. This three-stage approach comprising concept design, parameter design and tolerance design is suggested to be employed alongside the conventional product development process as it aims for design concepts that are inherently insensitive to variations. To be distinguished from Taguchi's tolerance design stage, the tolerance design methodology is not concerned with robustness, but with control of the product's performance. It encompasses the tasks of tolerance specification, tolerance allocation and tolerance analysis (Goetz et al., 2021). The integration of both robust design and tolerance design methodologies into the traditional product development process has been demonstrated by Goetz. His findings suggest that the introduction of tolerancing methodologies in early stages of product design would also require a competency transfer from the tolerance experts towards the product designers, thus enabling them to develop robust products (Goetz et al., 2020).

Based on the literature review, this contribution recognizes the necessity for bringing competencies from the domains of tolerancing and manufacturing closer to the product development engineer. Building upon an earlier work aimed at teaching GD&T-principles, a use case for training in robust design methodologies on the example of a hydraulic pressure relief valve is proposed (Scharf et al. 2023). Hydraulic valves offer an optimal scenario for conducting tolerance analysis, given that their functional attributes are primarily dictated by the geometrical properties of the valve's subcomponents. Moreover, the simple mechanical structure of a pressure relief valve renders the mathematical modelling of its transfer function relatively straightforward. Experimental data is acquired through both geometric measurements and functional testing to validate the accuracy of the produced mathematical model. In a conclusive effort, the model is employed to perform tolerance analysis, aiming to allocate appropriate tolerance values while adhering to the principles of robust design.

2. METHODS

Pressure relief valves (PRV) are predominantly employed as safety valves that activate during emergencies, ensuring hydraulic system pressure remains below a critical threshold. Two basic designs of PRVs have to be distinguished: Seat valves and linear spool valves. Despite the disadvantage of having a permanent leakage due to the annular gap between spool and housing, the latter design is more commonly used for control applications (Murrenhoff, 2014). The proposed PRV is based on a linear spool design consisting of four parts shown in Figure 1 (l). With increase in pressure on the high-pressure (HP) port the force on the spool surface rises, counteracting the preload force of the spring. Once the pressure reaches a level where the preload force is overcome, displacement of the spool occurs resulting in further compression of the spring. As pressure continues to rise, the spool eventually reaches a point where its control windows overlap with the housing's control edge. This action surpasses the set opening pressure, enabling the release of over-pressurized fluid to the low-pressure (LP) port.

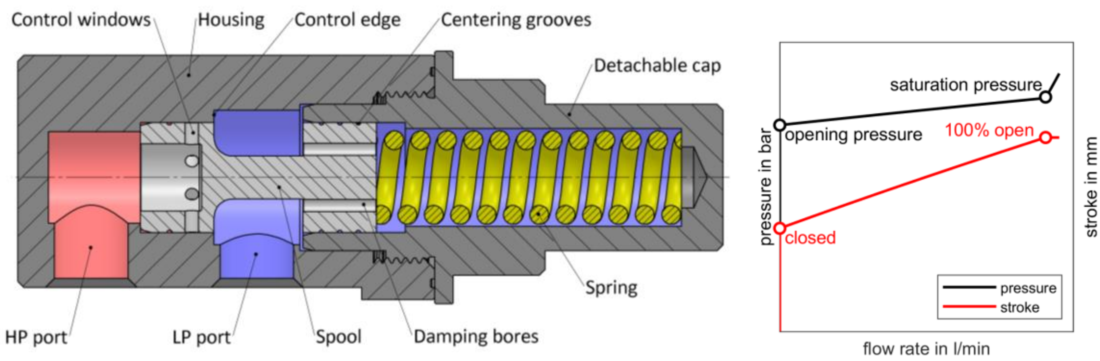

Figure 1: Pressure relief valve in spool design (l), characteristic curve for ideal PRV (r)

The flow passing through the control window is described in equation (1) as the flow through an orifice. Here A_{sp} represents the collective area of the control windows and ρ the density of the pressure fluid. For spool valves the flow coefficient α typically resides between 0.6 and 0.8 (Murrenhoff, 2014). In an ideal PRV, flow only occurs when the control windows of the spool overlap with the control edge, as indicated in the stroke and flow characteristic curves in Figure 1 (r). In reality flow already takes place before the opening pressure is reached due to presence of leakage flow in the annular gap between the housing and the spool. As seen in equation (2) the leakage flow Q_{li} is significantly influenced by variations in radial clearance r_c, owing to its cubic relationship. Unlike the flow through an orifice, the flow through a gap is also dependent on the fluid's kinematic viscosity ν making it sensitive to shifts in temperature.

$$Q_{cw} = \alpha\, A_{sp} \sqrt{\frac{2\,\Delta p}{\rho}} \tag{1}$$

$$Q_{li} = \frac{d_{sp}\, \pi\, {r_c}^3 \Delta p}{12\, \rho\, \upsilon\, l_c} \tag{2}$$

Based on equations (1) and (2) a parametric model was created in MATLAB and tested against a second model produced in the multi-physical simulation software AMESIM. Both models can produce characteristic curves and allow for the variation of design parameters to conduct design and tolerance analysis. Furthermore a set of spools with variations in spool diameter have been tested on the hydraulic test bench and their dimensions obtained on a coordinate measurement machine, thus providing experimental data for the validation of the two models.

3. RESULTS

To confirm the validity of the two generated models, characteristic curves were obtained on the hydraulic test bench and then compared with simulation results from both models using the respective spool geometries. One spool was produced to achieve a minimal radial clearance of 20 µm, while the other was deliberately designed for a significantly larger radial clearance of 97 µm. As depicted by the characteristic curves in Figure 2, both the MATLAB and AMESIM models exhibit strong correlation and align with the curves obtained from the hydraulic test bench. A minor hysteresis can be seen between the upstream and downstream curves of the measured data, indicating frictional forces among the moving components that the mathematical models did not account for.

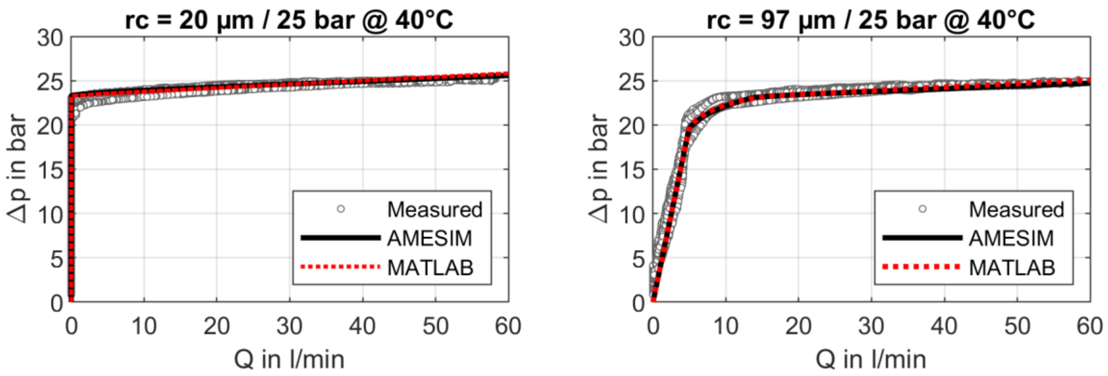

Figure 2: Obtained characteristic curves for radial clearance r_c 20 µm (l) and 97 µm (r)

4. DISCUSSION

Since the proposed PRV design was primarily intended for educational use, the maximum operational pressure during testing was limited to 50 bar. However, in industrial employments PRVs are typically operated at pressure rates exceeding 300 bar, leading to considerably higher leakage flow. Moreover functional tests were conducted at relatively consistent temperatures of 40°C, while maximum operating temperatures of industrial PRVs can reach up to 80°C, again resulting in an increase of leakage flow due to reduced viscosity. Consequently, tolerancing considerations regarding the control of leakage flow must be done under high-temperature and high-pressure conditions.

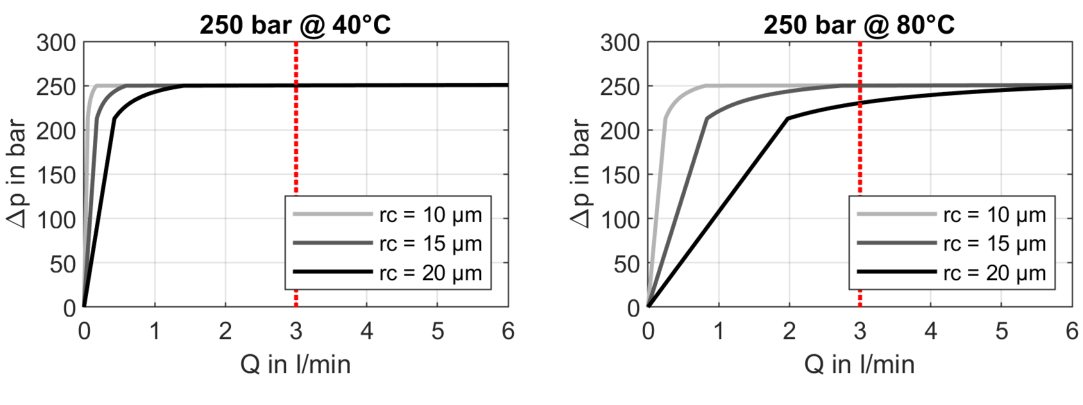

Figure 3: Leakage flow at increased pressure and temperature dependent viscosity @40°C (l) and @ 80°C (r)

Figure 3 shows two sets of characteristic curves at such heightened operating conditions. Here an opening pressure was set to 250 bar which in comparison to the curves in Figure 2 results in notably higher leakage flows. The right set of curves shows the same characteristic curves, but under an operating temperature of 80°C which amounts to a kinematic viscosity of 10 mm²/s compared to 46 mm²/s at 40°C for the pressure fluid HLP46. Given that a PRV functions as a safety valve, engaging only during critical pressure overloads, a permanent leakage flow of substantial amount is undesirable. Such a flow would cause persistent losses, leading to poor energy efficiency of the hydraulic system. Consequently, a tolerable leakage flow can be established by lowering the radial clearance resulting in an appropriate tolerance allocation. Assuming that a leakage flow of 5 % of the nominal flow of 60 l/min would be tolerable, a radial clearance of around 10 – 15 µm could ensure the valves proper functionality under all operation conditions. A more tangible representation of this tolerance specification can be provided using the ISO fit H6/g5, which permits a clearance between the housing and spool ranging from 3 to 12.5 µm. Since fundamental tolerances of IT5 and IT6 are required for this fit, the manufacturing of both the spool and housing bore would typically require the use of grinding or honing machinery.

5. CONCLUSIONS

For the purpose of applying robust design principles within the scope of academic teaching a relatively simple function assembly in the form of a spool type pressure relief valve was proposed. While geometrical measurements and functional tests were conducted on a physical prototype of the PRV, two separate mathematical models were produced in order to study the relationship between geometrical properties and its functional characteristics. Main focus of these studies was on the leakage flow, typical for spool type valves, and how it could be controlled by the assignment of tolerances. By conducting variant analysis and tolerance analysis, appropriate tolerance values for the radial clearance could be allocated and evaluated with considerations from manufacturing aspects. Hence a wholistic approach for teaching robust design principles could be established by integrating elements from product development, tolerance design, inspection and manufacturing.

6. REFERENCES

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