PRACTICAL REVIEW OF RELIABILITY METHODS COMBINED WITH VIRTUAL VALIDATION TECHNIQUES TO SHIFT LIMITS OF TODAY'S HYDROSTATS

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ABSTRACT

Ensuring sufficient technical reliability is a key factor in the market success of industrial products. However, for the off-highway industry, especially for battery-powered vehicles, the constant trend towards higher power densities of fluid-mechatronic components means an increase in component loads and a reduction in the necessary reliability reserves. To improve key performance indicators such as speed range and pressure limits, while considering the required performance level, deep technical understanding must be systematically transferred into new designs and software.

Innovative hydraulic pumps with modern electronic controls increase mobile machine productivity and reduce energy consumption simultaneously. By utilizing high-end multiphysics simulation within a design for reliability (dfr) approach, it is possible to achieve a robust design for stability at high dynamics using only electronic feedback from a swivel angle sensor signal, without mechanical feedback. Additionally, it is possible to achieve much smoother operation, especially at the beginning of the actuator movement.

Ensuring the benefits of variable pumps and meeting new system requirements, such as high speed and low speed levels with high torque, is becoming increasingly relevant, especially for electrically driven machines. By employing leading-edge simulation of flow fields, cavitation, and thermo-elastohydrodynamics, it is possible to meet these challenging demands.

The overall goal is to make the best possible use of the machine-specific operating limits by ensuring reliability and considering the load/stress on the hydraulic components. This holistic approach has been proven through the first serial system validations.

Keywords: hydraulic, pumps, hydrostats, reliability, virtual validation, electronic control

1. INTRODUCTION

Modern mobile machines are undergoing a continuous technological transformation [1,2,3]. The Off-Highway sector is experiencing increasing demands, growing electronic control, and the introduction of new primary drive systems. The integration of electric motors in mobile hydraulic applications, in particular, presents significant changes and opportunities [4]. This raises questions for the hydraulic components industry regarding the requirements for their products and the future role of hydrostatics. It is expected that a portion of drive systems will be purely electric, while a substantial portion will remain hydrostatic. In the case of work functions, hydraulic systems will continue to be essential due to the need for compact linear movements and decentralized users.

Discussions on alternative displacement principles have gained momentum in recent years. New displacement principles are being proposed as alternatives to current axial piston units for specific applications [5,6]. However, due to higher costs and technical challenges, none of these designs are suitable for the broad Off-Highway machine market.

So, what requirements are changing or need to be met for successful placement in a competitive displacement market? According to the authors of this paper, these requirements include:

1. Providing optimal solutions that meet classical key performance indicators for current and future requirements.
2. Addressing increasing demands, particularly in terms of speed variability and acoustics.
3. Offering customers maximum flexibility and individuality in their load cycles.
4. Ensuring reliability and robustness.

2. ANSWERING TODAY'S DEMANDS

Expectations regarding power, power density, efficiency, and especially reliability of hydraulic components are continuously increasing [7]. However, the remaining technological potentials of current hydraulic pumps and motors require more advanced tools. Improvements through newer materials, enhanced manufacturing processes, and design changes are gradually diminishing.

In some cases, market expectations even contradict each other. For example, there are desires for higher pressure limits alongside desires for higher rotational speed limits. Without a design change, an increase in one value would require limiting the other.

The answer to these demands is "design smarter"

Our understanding of smarter design includes:

1. Increased granularity in design and development: "From product view to detail view"
2. From overlayed total load-collective to application specific demands

2.1. Solving contradictions by increasing granularity

Defining operating limits for higher complex machines like axial piston pumps and motors on machine level necessarily leads to a safe but minimal operating space. The logical reason behind lies in the multitude of damage mechanisms and failure modes, which limit the possible operating space in partially contradicting manners (Figure1).

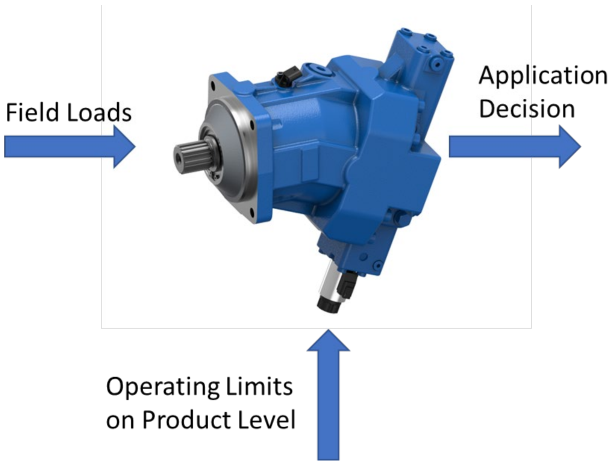

Figure 1: Classical Design Approach on Machine Level

By increasing the granularity during design and application, the operating space can be increased but still kept safe. The approach is shown in Figure 2.

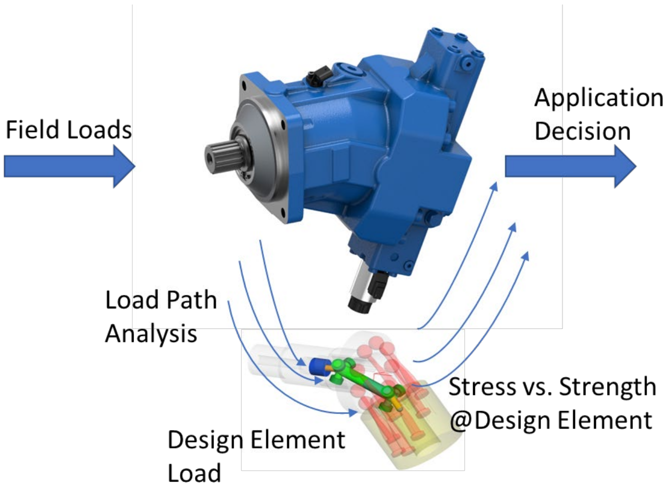

Figure 2: Improved Approach on Design Element Level

To give a simplified example: Many tribological design elements fail roughly proportional to a friction-power called property:

$$P_{friction} = p_{contact} * v_{contact}$$

Friction-power is defined as product of local contact pressure (usually driven by operating pressure) and contact speed (usually driven by rotational speed). It can be understood as the amount of energy per time that triggers many failure modes.

By defining operating limits in the local domain “critical friction-power at design element”, operating limits extend without increasing the risk of product failures. This is caused simply by allowing higher maximal values in operating points, where only one of the two influencing stresses reaches high values.

Exemplary from real live: Pressure operating limits for some high pressure units in closed loop were extended by 5,7% for specific breaking operations without increasing the risk of failures.

This increased granularity during the design process creates benefits on many levels:

- Increased cross-product knowledge management: Knowledge on design elements can be used for multiple products.

- Deeper know-how per element can be achieved without increasing design and research efforts by increasing knowledge reuse due to element view.
- “Elephant cut into slices”: Design element view leads to easier understanding and research capabilities, e.g., speeding up problem solving cases or specific product improvements.

2.2. From overlayed sum-collectives to fitting solutions

As stated in the previous example: Simply by shifting the focus from machine level to design element level, operating limits can be increased under the condition of deeper knowledge of field loads.

Therefor the second pillar of “design smarter” is the improved use of field load information. By creating load path models, design element loads can be derived from field loads. This enables a closed loop from application demand (stress) and product capability (strength) during product application. In combination with a modular design approach, application specific solutions create smartly designed products. Practically, the approach leads to a shift of the application process: From comparing simplified field loads with product catalogue data to a data driven application decisions.

- Reliability can be approached as design domain and therefore be optimized.
- Operating limits can be increased without increasing field failures.
- Enabling system optimizations by comparing element loads.
- The design process opens to enable the use of increasingly available knowledge on field loads.

3. USE OPPOSING OPTIMIZATION APPROACHES BY ELECTRONIC CONTROL

In addition to approaches within the product development process, electronically controlled units for mobile applications offer opportunities to optimize performance and meet customer requirements. Electronic control systems open up two crucial development paths:

- Expansion of the solution space by introducing additional degrees of freedom in components and systems. Shown in Figure 3.
- The ability to selectively influence a larger number of these parameters.

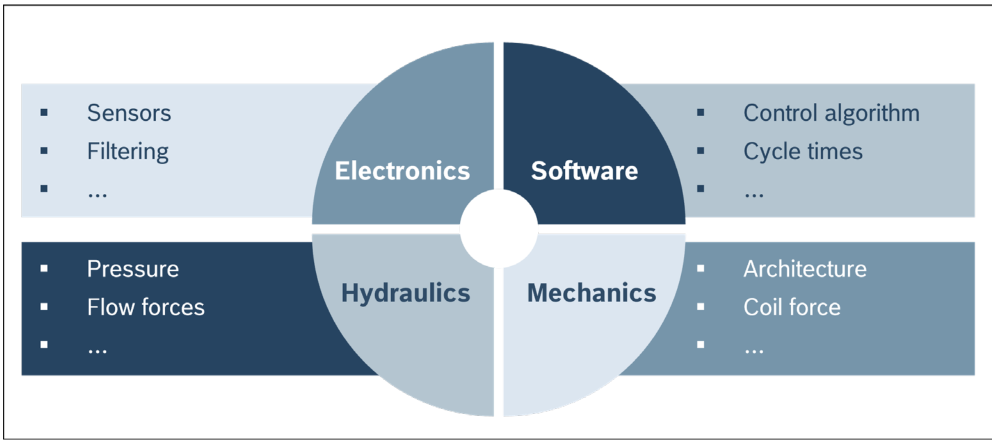

Figure 3: Involved domains for the electronic open circle pump control [10]

By implementing this approach, it becomes feasible to integrate an additional opportunity: by reducing the swivel angle, it is possible to increase the speed limit of a pump (in this case for mobile applications) by 35 %. This adjustment enables an increase in speed within the overall system and allows for an increase in power in other areas.

Traditional hydraulic-mechanical solutions either prove to be highly complex or influence the system in a way that corresponds to continuous parameter shifts across all operating ranges. These hydro-mechanical design elements are either optimized for a specific operating point or represent a compromise for the entire machine.

The implementation of electronic open circuit pump control (eOC) offers a partial solution to these compromises. One common conflict, for instance, is finding a suitable compromise between dynamics and stability. Additionally, dynamics and cavitation erosion phenomena present two distinct problems that require optimization approaches in opposite directions.[7]

The implementation of electronic pump control in open circuit greatly simplifies the management of these compromises, as optimal parameters only need to be determined or selected for each individual operating point. Customers benefit in particular from the possibility of tailoring parameters to their needs, especially by operating point-dependent parameter fields, which allow optimization for finally many operating points. This optimization can be applied to both control strategies and dynamics (Figure 4).

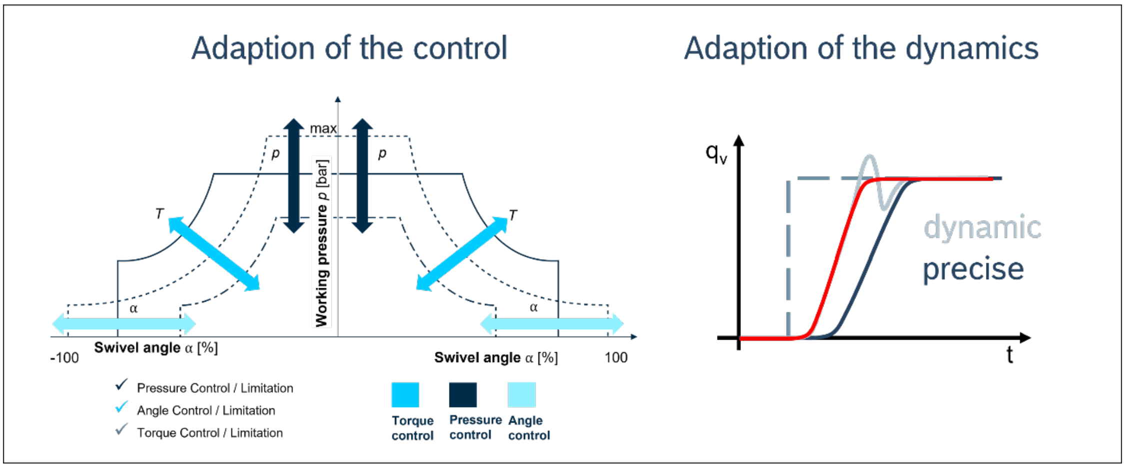

Figure 4: Adaptive application specific control

Moreover, it is possible to achieve specific parameterizations in dynamics, allowing for discrete parameterization in milliseconds or adaptive dynamics. This results in a system that is better suited to meet customer requirements [8]. In contrast, conventional nozzles in a system tend to reduce dynamics across the entire operating range [9]. In comparison, an eOC-controlled pump can achieve a 30 % lower swivel out time depending on the operating point, leading to a reduced swivel time of up to 40 ms in certain applications.

Furthermore, the installed capacity can be utilized more effectively. With better knowledge of the operating conditions, the required reserves can be determined more accurately. This enables a reduction in the overall amount of reserves, resulting in a more efficient use of resources. Additionally, the installed capacity can be accessed as needed, providing flexibility in meeting demand.

4. USE VIRTUAL VALIDATION TO SHIFT TODAY’S LIMITS

To ensure the reliability and robustness of hydraulic pumps, a profound technical understanding of the hydraulic system and its components is crucial. In this regard, advanced simulation techniques serve as a foundation for the virtual validation of products during the development process and for exploring the possibilities of shifting operating limits. These techniques enable thorough investigations and analysis of the system's behavior.

4.1. Set up of the virtual validation process

In order to reach possible potentials in main described requirements, three major points should be noted.

1. It is essential to have reliable tools and methodologies that can be used to verify the design against the specified requirements.
2. These tools must be cleverly combined and connected in a way that generates an added value.
3. The process must be created in a "modular and self-improving" way.

Rexroth recognized the importance of this early on and has implemented a multi-stage, systematic validation process that combines testing and simulation tools of varying quality in an appropriate manner. In the field of simulation, there are different approaches to address specific questions, as depicted in Figure 5. In many cases, the simulation domains interact with each other, requiring a multidomain approach to solve them. Depending on the problem at hand, the user can perform quick and simple computational fluid dynamics (CFD) calculations to estimate the suction limit, or conduct highly detailed cavitation erosion calculations that accurately map the timing reversal process when necessary.

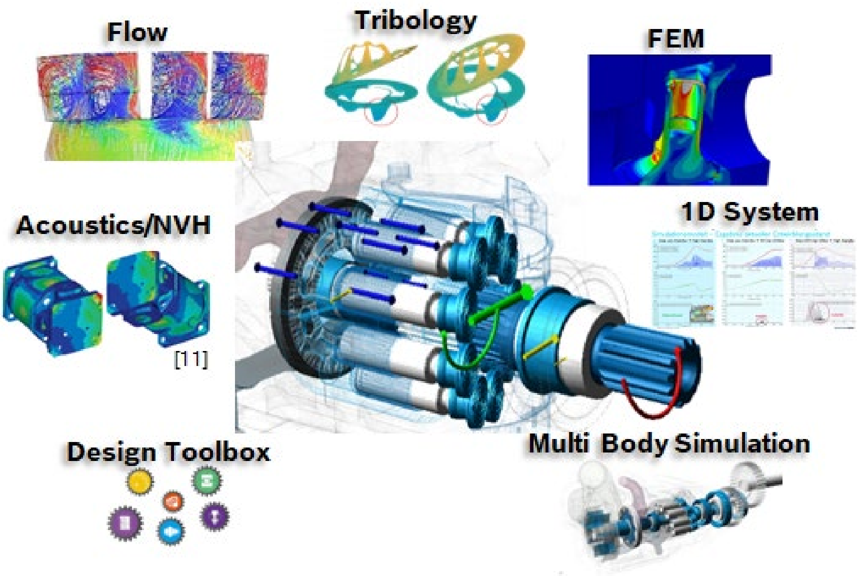

Figure 5: Simulation overview

With the assistance of a tool, users can generate automated validation plans instantly and easily submit and track test and simulation tasks, as illustrated in Figure 6.

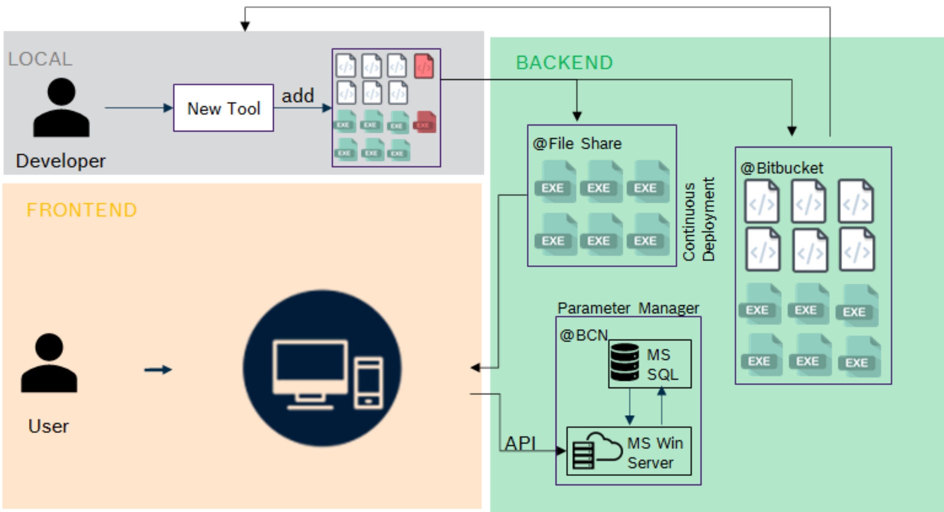

Figure 6: Simulation approach

This streamlined approach allows for increased work efficiency and minimizes unnecessary steps.

Importantly, this tool enables the entire validation process to be measured, allowing for the identification of potential areas for improvement and facilitating continuous enhancements to the overall process.

4.2. Usage in series products and results

This validation process has already been successfully applied to products such as the new axial piston unit for the speed-variable industrial market and the new axial piston unit for the mobile market. With the aid of this new validation process, the limits of these products could be explored in much greater detail within a significantly shorter timeframe. Additionally, this approach has allowed for the identification of areas where defining simulation standards would be beneficial in improving cycle time and quality.

To put these improvements in figures:

The overall efficiency of the new industrial unit could be improved by 3 % by using our simulation standards. Another significant result is the improvement of power density by 88 % as well as nearly doubling the maximum speed. At the same time the NVH level regarding pressure pulsation could be reduced by 66 %.

Similar improvements were especially made in the new mobile unit. Here, the overall efficiency was increased by remarkable 7 %. Additionally, the power density improved by 49% and the maximum speed increased by 15%.

5. CONCLUSION

Acknowledging the enduring significance of hydraulics and the emergence of new technologies like electrified solutions, some of which may even replace hydraulic systems, it is imperative to propel their evolution based on the outlined aspects. The primary requirements are growing more intricate and demand comprehensive solutions. Reliability, customization for individual customers, and the enhancement of key performance indicators form the bedrock of economic success. There continue to be opportunities for performance improvements in established hydrostatic designs (Figure 7). However, the path to achieving these improvements is becoming more complex. The initial products within this holistic framework have been implemented and will validate this approach in the forthcoming years.

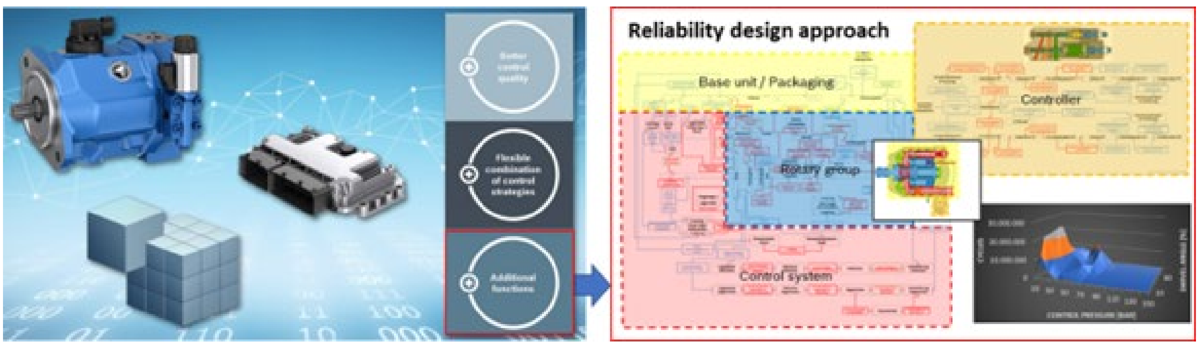

Figure 7: Shifting Limits of today's hydrostats by reliability methods and virtual validation

NOMENCLATUR

$P_{friction}$	Frictional power	W
$p_{contact}$	Contact pressure	N/mm^2
$v_{contact}$	contact speed	m/s
dfr	design for reliability	

eOC	electronic open circuit pump control
CFD	computational fluid dynamics
NVH	Noise vibration harshness

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