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Next Generation Valve Actuation Platform

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Abstract.

Danfoss is going to develop a new generation of valve actuation platform for our PVG system. Featured with integrated sensors, enhanced connectivity, memory scalability, etc., it allows the creation of actuator variants customized to the different needs of the application systems. This paper will focus on the modular concept, and key features of this next generation actuation platform. One element of it is the voice coil driven pilot valve actuator. This is an important technology for highly advanced work function control tasks to create application performance driven by software design elements in favor of performance driven by mechanical design elements. This paper presents a design study with the goal to demonstrate the ability to design a cost-effective voice coil actuation for a PVG valve. The preliminary performance and key characteristics of the actuator will be discussed in this paper.

Keywords. pilot valve, voice coil, electro-hydraulic control valve, mobile machines.

1. INTRODUCTION

The quest to achieve seamless control of pressure and flow rate in fluid power systems has undergone major development in the past decades. Back in the 80's the industry shifted from mechanical/hydraulic controls to electro-hydraulic controlled proportional valves. These systems emerged as a cost-effective alternative to servo valves, enabling stepless control of pressure and flow rate via electrical signals.

To improve the performance of proportional valves, relative to the performance of servo valves, the manufacturers added linear variable displacement transducers (LVDTs) to proportional valves in order to sense the spool position. The output signal from the LVDT was used to calculate the difference between where the main spool was supposed to be and where it actually was, and that difference was passed on to modulate the pilot valve in an effort to position the main spool to achieve the desired output based on the input [1]. This simple, yet efficient closed loop control principle enabled machine builders and system integrators to make easy integration, i.e. plug 'n play of high performing control valves.

In 1988 Danfoss launched the PVG32 (Proportional Valve Group) series, a modular control valve system designed for mobile machinery. The system's concept was novel at the time and offered a flexible, load-sensing directional control valve, designed for advanced electrohydraulic control. Over time, Danfoss and others have evolved electro-hydraulic valve actuation with microcontrollers, fault monitoring, integrated sensors, software-controlled options, and CAN bus communication to meet versatile requirements in a broadening application range for electro-hydraulic controlled proportional valves. Concurrently the PVG system has grown with adding new frame sizes, each demanding new variants or series of electro-hydraulic actuation.

Contrary to common assumption, the requirements for different work functions in many applications are far from uniform. The ability to configure a proportional control valve stack, serving versatile work functions, with valves and actuation technology tailored to the actual demand, provides scalable yet cost-efficient solutions to the machine builders to meet the individual value proposition of each work function. As a result, modular valve systems with flexible valve actuation technologies play an important role in helping machine builders to design a control system that is optimally customized to their applications, both in terms of cost and technology.

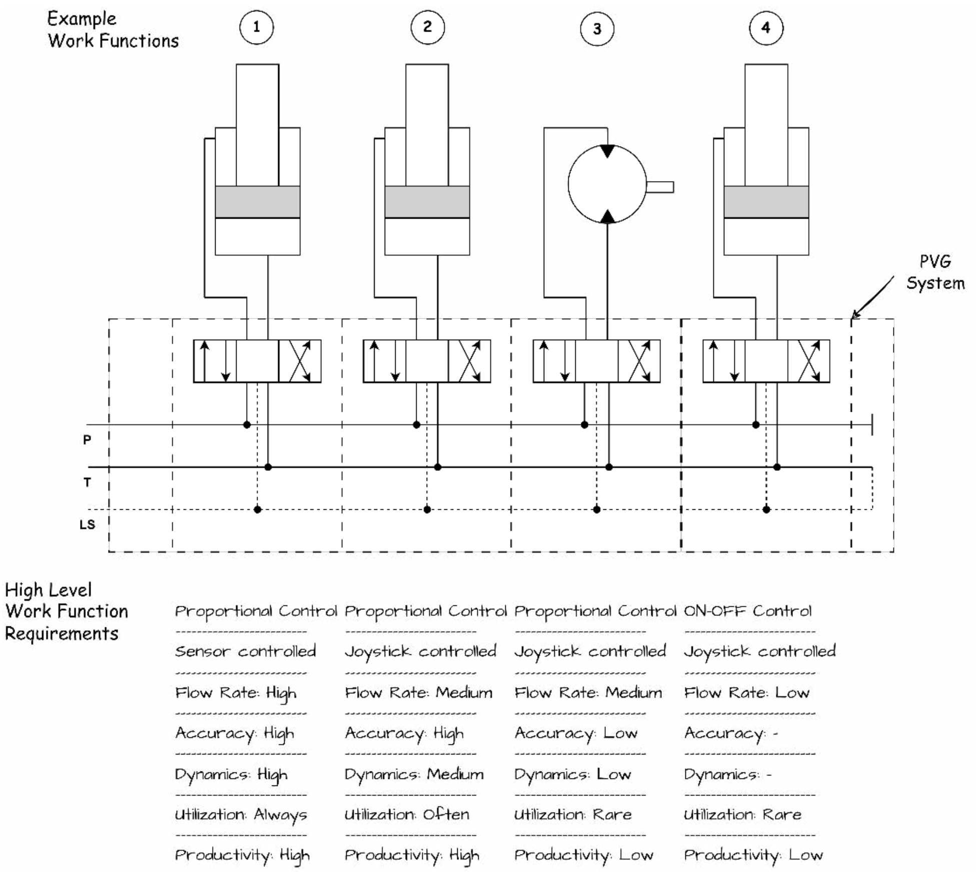

Figure 1. Work functions with basic requirements to illustrate the versatile value proposition of each work function

2. MODULAR VALVE ACTUATION PLATFORM

As customer needs and technology evolve, so must the solution. Therefore, Danfoss is going to develop a new generation of valve actuation platform for our PVG system. It is a new hardware & software platform, fully modularized on electronic hardware and software domain, to support the prospective expansion of our proportional control valve portfolio. The new hardware & software platform addresses the most important needs of an increasingly growing variety of control valves.

Scalability: Product architects need to be able to easily add or remove components (e.g., drivers, sensors, actuators) without redesigning the entire system. Scalability in the design will support future upgrades and expansion.

Reusability: Modules (software blocks, hardware units) should be able to be reused across different product development projects, to reduce development time and cost.

Flexibility: The platform should support the customization of product variants. Flexibility in the design ensures the platform can support a wide range of applications from simple to highly complex applications.

Standardization promotes consistent design practices and interfaces and provides a common, well-known appearance to the system integrator / application engineer. Standardization enables easier integration with application systems. In short: If one knows a single product variant, one knows them all.

The core of the new platform will be a new microcontroller family with scalable memory to accommodate growing software, lockstep core technology and built-in self-tests (BIST) to increase fault coverage capabilities. Lockstep core technology is a mechanism where two processor cores run in perfect synchronization, executing the same instructions at the same time. Their outputs are continuously compared, and if a mismatch occurs, it signals a hardware fault. The external watchdog monitors, among other test points, the MCU’s program sequencing ability with a question-response approach and disables power supply to the driver circuit via the safety switch. Secure Boot is a security feature designed to ensure that a device boots using only software that is trusted by the manufacturer. It helps protect against malware and unauthorized software running during the boot process. It supports compliance with security regulations (e.g. CRA).

A completely new software architecture will be developed, that exploits the microcontroller’s capabilities but is still abstracted well enough to support the modular approach. The architecture will be designed with different peripheral and application specific layers. The layers will be vertically permeated by modular software components with well prescribed interfaces.

The microcontroller supports various analogue & digital input devices for application sensors, CAN Classic & CAN FD interfaces, plus Ethernet interface for future, data-hungry applications. On the actuation side the hardware & software platform primarily supports both solenoid and voice coil technology to control the associated pilot valves. But the electro-mechanical valve actuation technology can also be applied to this new platform to support the transition from mechanically actuated control valves to electrically actuated control valves.

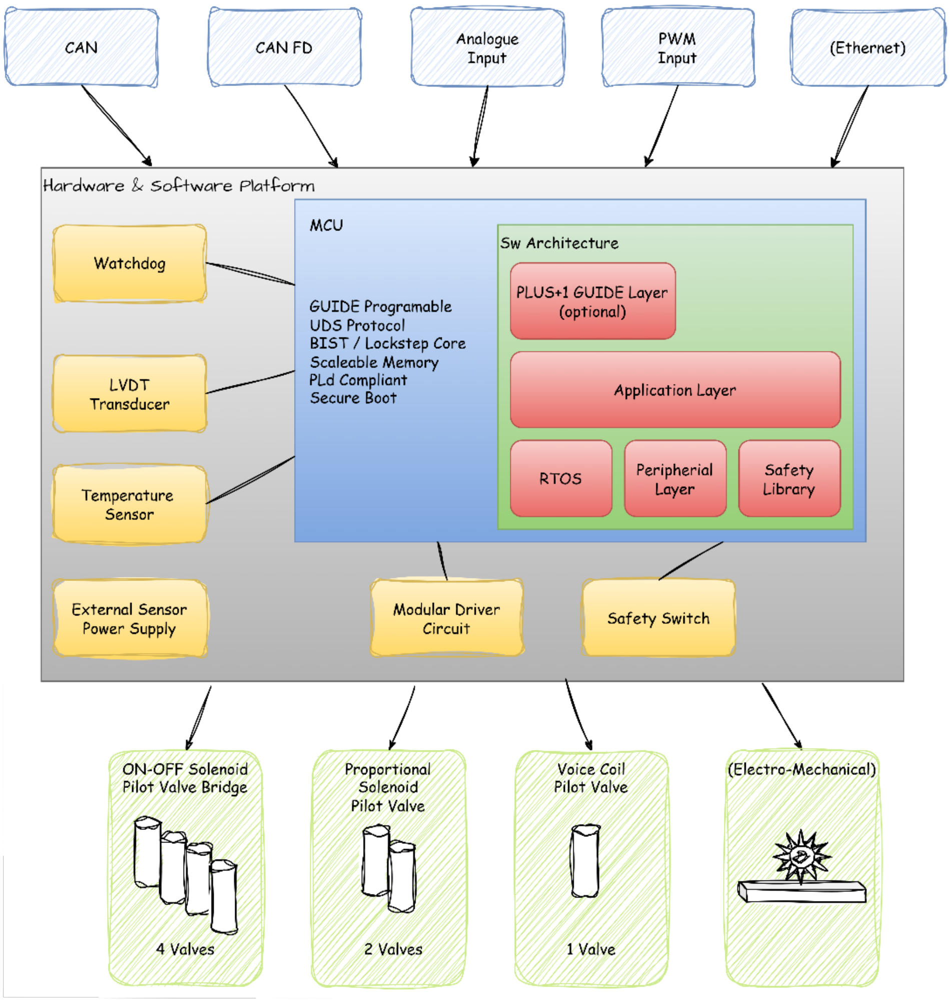

Figure 2. New PVG Valve Actuation Platform.

The platform will be designed to reach PL=d compliance (acc. ISO 13849) for application-level safety function **Safe Stop**. This means that whenever a safety-critical event occurs, i.e. overload situation, the boom movement must be safely stopped and an unexpected start-up from the rest position must be prevented. This platform supports these requirements by selecting highly reliable components and extensive diagnostics. The operation of the on-board electronics and the control valve is continuously monitored. If a failure is detected, the on-board electronics sends an error message on the CAN bus to the machine control unit and concurrently de-activates the solenoids via the integrated safety switch.

The interfaces and basic capabilities will be backwards compatible with current Danfoss PVE actuation series; however, we expect control performance enhancements due to increased microcontroller capabilities that would allow the implementation of sophisticated valve control algorithms. This new platform supports free combinations of input and actuation technology according to the upcoming demand and associated value proposition.

For example, aside from conventional solenoid bridge technology with a classical CAN interface, Danfoss could also offer voice coil driven actuation with pressure or other application sensors. Or it could combine it with free programming space for customers.

All these technologies could be available in the same PVG valve system; individually tailored to the specific value and needs of the respective work function.

3. NEW FEATURES

The new platform provides a couple of new capabilities and features with the aspiration to be prepared for increasing integration, data exchange and control performance objectives.

Enhanced Control Valve Capability refers to offering new PVG features in addition to existing ones.

- Improvement on valve control through the implementation of advanced robust control techniques. In particular, the compensation of the inherent cold oil behaviour is a long-cherished desire.
- Integrated sensors for pressure, temperature and spool position can be utilized for detecting the work function's integrity, i.e. predictive maintenance, or they can be used to optimize the work function's control system.
- Realization of machine learning techniques to capture knowledge of highly skilled machine operators and transfer that knowledge into control logic to make it available to all machine users.

PLUS+1® GUIDE is a graphical software development environment from Danfoss, designed to simplify and accelerate the creation of control systems for mobile machinery. The tool is based on graphical software programming enabling users to develop their own individual work function application. When this development environment becomes part of the valve controller, customers will benefit from its close proximity to sensors and work functions in the development of their own intelligent solutions. This programable space is optional to the embedded application firmware.

CAN-FD (Controller Area Network – Flexible Data-rate) is an enhanced version of the original CAN protocol, designed to meet the increasing demands of modern automotive and industrial systems. It can handle larger and faster data exchanges, which are essential for modern, data-intensive applications. For instance, the controller software can be downloaded up to 5x faster than using classical CAN interface. CAN-FD nodes can coexist with classical CAN nodes, but classical CAN nodes cannot interpret CAN-FD frames.

Automotive **Ethernet** is a specialized version of Ethernet adapted for use in vehicles. It supports data rates from 10 Mbps to 10 Gbps, ideal for streaming large data frames, needed for advanced applications like autonomous driving.

Today it is not yet clear what kind of value Ethernet can offer to work functions. Eventually the move of centralized machine control functions to de-centralized machine control architectures might foster the use of Ethernet. A potential use case is the facilitation of many advanced, data dependent functions into a single valve system controller, servicing a whole valve stack. For example, this controller might process camera data as feedback signal for a given work function control task. When data bandwidth is no longer a constraint, many more options will become apparent.

4. WHY VOICE COIL?

One element of the prospective valve actuation platform is the pilot valve with so called voice coil technology. Danfoss has already developed such a technology in conjunction with the development of CMA / PVX valves. These proportional control valves are known for their independent metering edge technology, their electronic load pressure compensation and superior controllability. They are well recognized by customers, but since they were developed independently, they do not benefit from the scaling and modularity of the PVG platform. On the other hand, the PVG platform does not benefit from the opportunities that the voice coil technology can offer.

The voice coil driven control valve achieves much higher dynamics, similar to servo valves, which enables them to react much more precisely and much faster to sensor signal induced valve commands. Features that were previously provided hydro-mechanically can now be provided by a software-enabled control function that uses sensor feedback and can be configured, tuned, and automatically adapted.

It is exactly the flexible control valve configuration by means of software that is appreciated by the customers. In the end it is the voice coil technology that enables significant gains in controllability/productivity beyond conventional pilot valves. For example, load pressure oscillations or the limitation of load pressure can be effectively controlled by voice coil driven control valves. **Figure 3** shows likewise the load pressure with / without active damping while lifting of a particular load. Actively dampening the load pressure oscillations contributes to stabilizing the work function acceleration, leads to decreased flow ramp-up time, to increased flow rate and operator comfort. Electronic load pressure limitation utilizes the full maximum load potential by precisely adjusting the port pressure by the control valve. All in all, these gains contribute to increasing the productivity of machines.

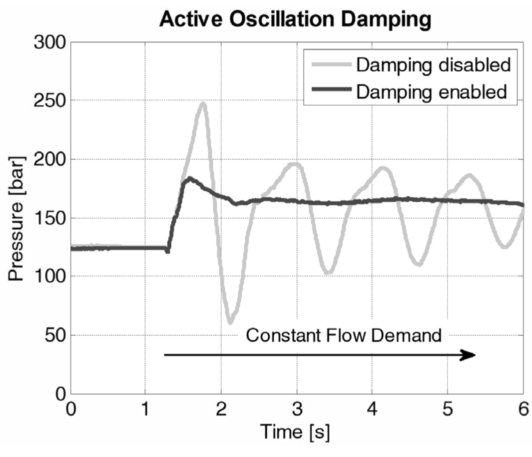

Figure 3. Effect of Active Oscillation Dampening. [2]

Voice coil driven valves also contribute to creating more energy efficient hydraulic systems. They provide the ability to switch the valve state very rapidly during energy regeneration or recuperation scenarios. These often require a fast redirection of the energy flow from one port to another, without interfering with the work function control.

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Although the physics between armature and body is understood and minimized by surface coating means, this influence still generates significant friction and produces significant hysteresis in the solenoid valve behaviour. This inherent hysteresis decreases control valve resolution and reduces control valve dynamics. Both effects put proportional solenoid valves to a technologically inferior position against voice coil driven valves.

6. Design Study

Despite the known performance advantage that voice-coil technology provides to hydraulic valves, one limitation has historically been a relatively higher cost. In this paper we reveal a design study, where we have built an experimental prototype with the goal to demonstrate the ability to design cost-effective PVG actuation utilizing the voice coil principle. See **Figure 5** and **Figure 6**.

Figure 5. Design study for voice coil driven PVG valve actuator.

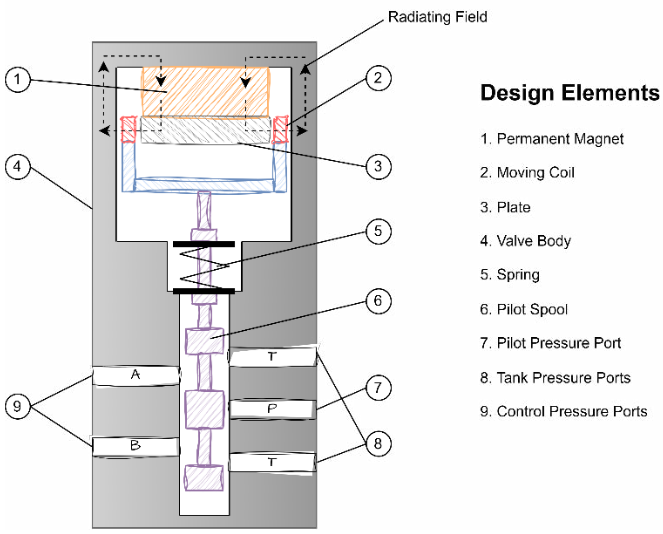

Figure 6. Sketch of the voice coil driven pilot valve. The moving coil is placed in the air gap where the magnetic flux density is highest.

This proof-of concept consists of a permanent magnet (1), a moving coil (2), a valve body (4) and the pilot valve (5, 6, 7, 8, 9). The permanent magnet is assembled with a plate (3) to guide the magnetic field. The magnetic field radiates out of the plate, runs through the coil and enters the valve body. From there it travels through the valve body back to the permanent magnet.

The moving coil is connected to the pilot valve's spool. It is obvious that backlash is not allowed. The coil runs "wet", exploiting the oil bath to function as a heat sink. The coil wires are guided through a valve body opening (not displayed) to the ambience. There they are connected to the on-board electronics.

Further, the friction level of the moving parts must be low and predictable. The low clearance between spool and valve housing enables unambiguous defined bearing for the spool/moving coil assembly. The axial position of the spool/moving coil assembly is defined by a pre-loaded spring. To yield a high dynamic it is important to design the moving elements as light weighted as possible. The valve body offers hydraulic connection to pilot pressure, tank and two control pressure ports. Both control pressure ports are connected to either control chamber of the PVG main spool.

By applying a current to the coil, the spool moves out of the center position to connect pilot pressure with one of the control pressure ports. While the one control pressure port is connected to pilot pressure, the other one is connected to tank. And vice versa for reverted coil current.

As the pilot pressure travels into one of the PVG's main spool chamber, the main spool will move away from its neutral position. Once the main spool approaches its target position the logic reduces the coil current in order to reduce the pilot valve opening from pilot pressure to control port. Reducing the valve opening leads to adjusting the control chamber pressure so it will match the main spool spring force at particular main spool position. The pilot valve spool takes a position where all acting forces, such as coil force, spring force, friction, etc., are in equilibrium. Thus, holding a permanent PVG main spool position to meter a steady fluid flow to the work function requires the application of a permanent coil current.

When the coil is de-energized the pilot spool moves under the influence of the spring force to the center position at which the control pressure ports are connected to tank, and the PVG's main spool will return to its neutral position.

The law of the Lorentz force provides guidance in sizing the design elements to optimize the coil force to given space constraints. To identify the individual design element's sensitivity to the coil force, we have conducted numerous finite element simulations to calculate the coil force for a given design iteration. These simulations confirmed the underlying basic principles which have been discussed before.

The typical coil force characteristic is depicted in **Figure 7**. The force curve is fairly constant, where the force itself depends primarily on the coil current and much less on the coil position. In contrast, the armature force of proportional solenoids depends both on current and armature position. This is very important for the control understanding of any electro-hydraulic valve. Because the electric current induced force, whether voice coil or solenoid, is the control signal used to induce a dedicated reaction based on the control logic input. To achieve the desired closed loop control performance of the PVG valve the actuator force must be capable of precisely controlling the piloting power. Controlling the piloting power means the actuator force must find equilibrium with other force components in the pilot valve, like spring force, flow force and friction forces. For perfect controllability it is necessary that small current changes lead to small and immediate force changes, and that alternating current adjustments are not obscured by hysteresis effects.

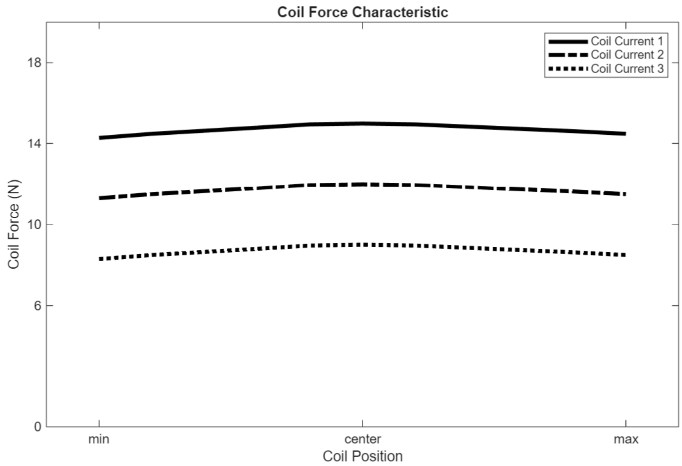

Figure 7. Simplified typical coil force characteristics for various coil currents.

Voice coils have a distinct advantage over solenoids because their force characteristics—being bi-directional, low-hysteresis, and proportional to the coil current—allow for quick and precise adjustments to find the next pilot valve position.

7. Test Results

The presented voice coil feasibility study was mocked together with a LVDT transducer to control a PVG32 valve. Functional tests carried out in the lab showed encouraging results. The voice coil valve was operated at Δ13 bar pilot pressure. The oil and valve components are heated at 50 °C to represent typical operational oil viscosity conditions. The focus for the lab test has been on tracing the spool position based on given commands.

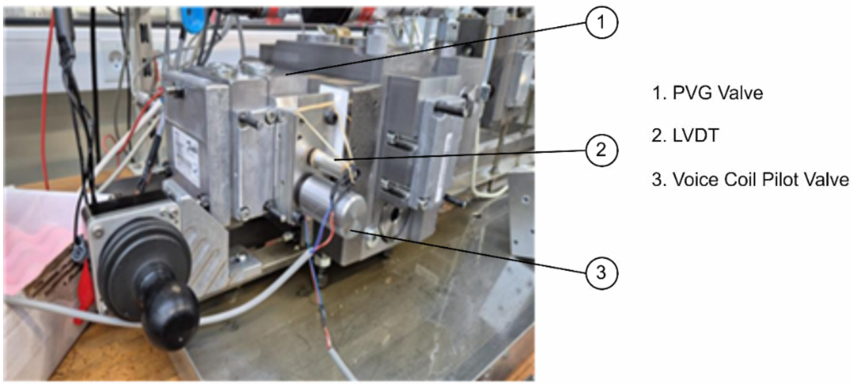

Figure 8. Proof-of-concept demonstration in the lab.

Figure 9 shows the steady state characteristics of spool positioning. It plots the actual spool position over the demanded spool position, showing how much the spool position deviates from the command for almost steady command. The spool command undergoes a sweep from neutral to max stroke and back to neutral within 25 sec.

Figure 10 shows the step response characteristic. It plots the demanded and actual spool position as functions of time, showing how quickly and accurately the spool position gets adjusted to the dynamically changing command value. The response time is evaluated at 95% of the reached steady-state spool position.

Figure 11 shows the frequency response characteristic, describing how robustly the control valve reacts to alternating setpoint commands. The frequency response is characterized by two subplots: The magnitude plot, showing the amplitude attenuation, and the phase delay plot, showing the phase delay of the spool position in regard to its setpoint. A negative magnitude indicates the spool position oscillation is reduced, i.e. dampened, and the phase delay increases by increasing setpoint alternation frequencies. The set point alternation is configured as a sinusoidal signal with a bias of 50% nominal spool stroke and an amplitude of 25% nominal spool stroke.

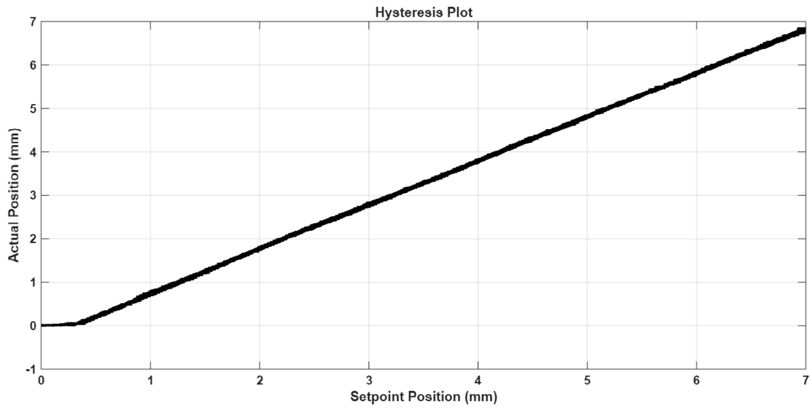

Figure 9. Steady state characteristic for the closed loop main spool position control.

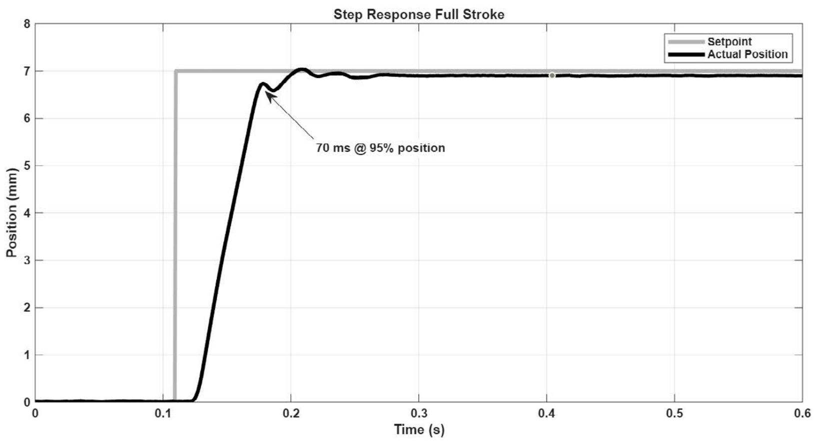

Figure 10. Step response characteristic for the closed loop main spool position control.

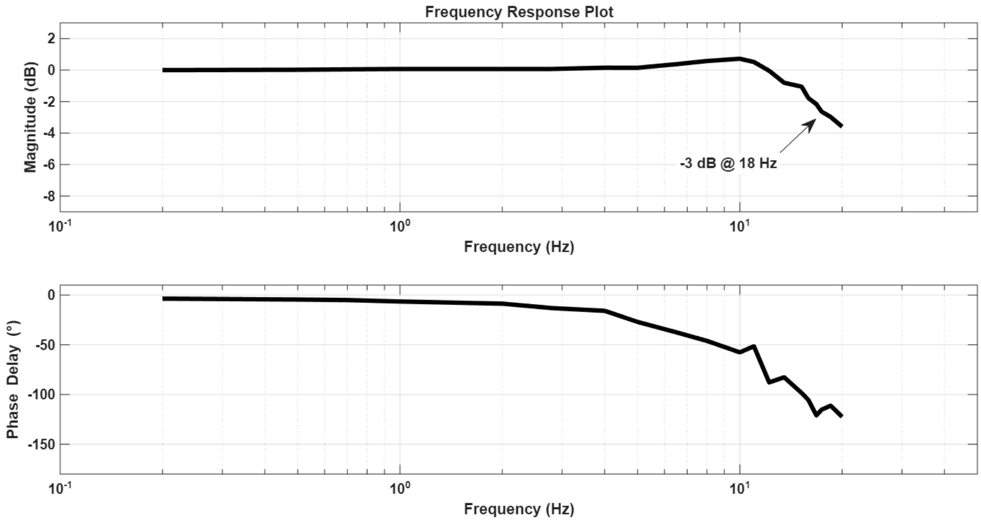

Figure 11. Frequency response characteristic for the closed loop main spool position control.

As can be seen in the figures, the PVG valve displays almost zero hysteresis and almost zero noise for the spool position control. The test results above reveal a deadband around neutral position which is attributed to the imperfect LVDT and control calibration. Besides this, the graph proves that the valve does very well in converting small and slowly changing incremental setpoint changes. The full-stroke step response of 70 ms, with little oscillation or overshoot, is noteworthy. This dynamic capability is underpinned by an impressive frequency response of approximately 18 Hz.

These test results of the feasibility study confirm the anticipated superior spool controllability of the voice coil technology. On a particular note, the frequency response data suggest that such a control valve is well-suited to be integrated into sensor- and software-controlled work functions.

8. SUMMARY

Danfoss is developing a new modular hardware and software platform for its PVG valve system to support future expansion and increasing variety in proportional control valves. The hardware and software platform emphasizes:

- **Scalability**: Easy addition/removal of components without full redesign.
- **Reusability**: Shared modules across projects to reduce cost and time.
- **Flexibility**: Simplified customization for diverse applications.
- **Standardization**: Consistent design and interfaces for easier integration.

Pilot valves are tailored to the work function’s individual value proposition with free combinations of input and actuation technologies, supporting advanced control logic and customer-specific programming.

Low-cost voice coil technology is one element of Danfoss' future valve actuation platform. It significantly improves machine productivity, energy efficiency, and control precision, positioning it as a superior alternative to conventional solenoid-driven valves. It offers:

- **High Dynamics & Precision**: Performance comparable to servo valves, enabling faster and more accurate response to sensor-driven commands.

- **Software-Based Flexibility**: Facilitates the transition from mechanical-hydraulic features to software-enabled controls, improving customization and productivity.

Danfoss conducted a design study with the goal of demonstrating a cost-effective PVG valve actuator using voice coil technology**.** Functional tests carried out in the lab showed encouraging results. These confirm excellent controllability and dynamic performance of voice coil technology.

9. References

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[3] MikeRun, 'lorentz-force-horseshoe-field.svg', License: CC-BY-SA-4.0, Source: commons.wikimedia.org

Biographies

Photograph

Dirk Wroblewski received the master's degree (Dipl.-Ing.) in mechanical engineering from University of Rostock, Germany, in 2002, and the philosophy of doctorate degree in Engineering from University of Rostock in 2010. He currently serves as a Senior Manager overseeing technology development in electro-hydraulic valve control at Danfoss Power Solutions.