

New generation of intelligent electromechanical valve actuation

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Modern hydraulic systems of mobile machines are requiring components with new control structures, in order to be compatible with the modern networks of the future. The new generation of electro-mechanic valve actuation technology of Sonceboz is presented in this paper. Compared to the previous actuator, the performance has increased significantly. Moreover, the new control concept enables a wide range of connectivity and on-board diagnostic features. The result is a high innovative valve actuation system with online diagnostic functions that can operate in a network with decentralized intelligence. Therefore, supporting hydraulic valve manufacturers to meet the challenges for the highly connected systems of tomorrow.

Keywords: Mobile hydraulics, valve actuation, connectivity, OBD, decentralized intelligence

Target audience: Mobile Hydraulics, Valve Suppliers

1 Introduction

Proportional hydraulic valves are key components in mobile equipment, such as agricultural and construction machines. The role of these valves is to control motion for a wide variety of functions through cylinder actuators and hydraulic motors. Electrohydraulic actuation is a state of the art design used to control the valve main spool. These actuators need low pressure pilot oil to act on either side of the spool in order to move it, using solenoids to control the pressure of the pilot stage. The drawbacks of such solutions are well known. The valve control is dependent of the pilot oil parameters (pressure variation, particles, temperature, etc.) and not precise unless closed loop control with a position sensor is integrated. The system requires low pressure pipes which are not always present, especially when mechanical solutions are electrified. For lower flows the spool can be directly actuated by two solenoids without a pilot circuit. Such arrangements present very high hysteresis and need additional stand-alone sensors when precision is requested. Alternatively, spool valves can be controlled with electromechanical direct actuation (*Figure 1*). In this case, no pilot oil is needed which allows better controllability (i.e. temperature dependencies), reliability and even reduces complexity. The integrated electronics allow a smart control of the actuator and integrate sensor signal processing.

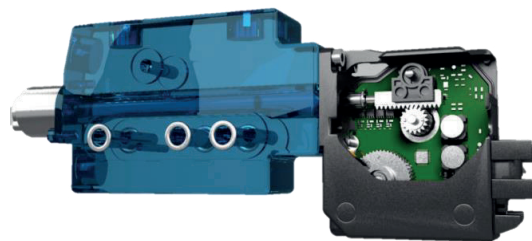


Figure 1: Electromechanical valve actuator

This paper discloses the new generation of the Sonceboz valve actuator S40 and discusses its benefits and new features, such as increased power density and enhanced control architecture. Furthermore, this paper shows how the new actuator can be used to perform predictive maintenance in mobile applications and discusses the challenge of the future.

2 Sonceboz valve actuation technology and new generation

2.1 Benefits of electromechanical valve actuation

Sonceboz current electromechanical valve actuation generation is based on an electric stepper motor with integrated electronics, and is controlled by the CAN bus (*Figure 2*). The intelligent actuator provides enough power to directly actuate the main spool of the hydraulic valve. The electrical control system ensures reliability and precision, completely independently of the oil circuit. Hydraulic pressure does not have to be applied if the working hydraulic system is not in operation. This increases the efficiency of the system. In addition, no through-holes are required for the pilot pressure lines as a result of the electrically controlled valve with smart actuator.

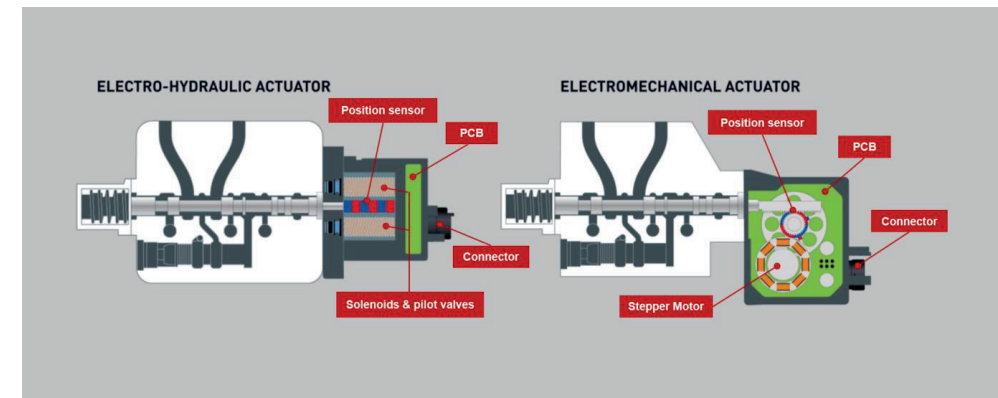


Figure 2: Electrohydraulic and Electromechanical valve actuation

Sonceboz uses a robust electric motor here, which is resistant to strong vibrations. Its two-speed gearbox transforms the rotary movement of the motor to a linear movement of the valve spool. The motor and integrated electronics are enclosed in a stable and leak proof aluminium die cast housing with IP6K9K protection rating and therefore can withstand the toughest ambient conditions.

A high-performance microcontroller is used to control the stepper motor and signal processing. A vector control system clocked at 20 kHz extends the controllability and positioning of the hybrid stepper motor, which is used beyond that of a classic stepper or partial stepper mode. The typical properties of a stepper motor are retained, such as: precise positioning, high torque and holding torque, and moderate residual force. The system approaches opening points precisely with a linear resolution of 7 µm and without overshoot. With the 12 V version, adjustment speeds of up to 80 mm/s can be reached on the valve spool, while up to 100 mm/s is possible with the 24 V version. For example, together with the acceleration ramps, step response times of from 0 to 7 mm in 110 ms or in 100 ms are possible.

Software concepts with a configurable parameter structure offer maximum flexibility with minimum effort. These concepts can be used to illustrate any valve curves in the actuator. Together with dead zone detection and storage of the valve-specific spool overlap in the actuator's EEPROM, this leads to the required valve characteristics without mechanically adapting the shape of the spool. This results in a high-precision hydraulic valve, which can compensate for mechanical tolerances, mechanical play and wear-related inaccuracies throughout the entire service life of the valve and the machine.

The actuator is extremely compact and requires the same space for installation as electrohydraulic actuators, when the valve connection plate including control lines is taken into consideration. The integrated electronics make this possible. The PCB for the electronics is specially designed for strong vibrations and is securely fixed in position.

within the actuator housing, including the adapted electrical protective components. A CAN bus J1939 protocol is used as the standard interface. Other protocols and analogue interfaces can be additionally supplied.

An intelligent evaluation of the different motor data without the use of sensors ensures reliable and precise valve control. Any disruption to this caused by external influences, such as a mechanically blocked valve spool, is reported to the ECU by the actuator. Additional temperature sensors enable online diagnostics. Actuator characteristics adapted to specific temperatures can also be saved, so that the actuator can respond to valve changes caused by the poor viscosity of the hydraulic fluid at low temperatures. This makes it possible to control the valve reliably and precisely at ambient temperatures as low as -40 C.

A summary of the benefits of the electromechanical valve actuation is shown in **Table 1**:

Category	Benefits of Electromechanical Actuators
Installation space	No additional drilled holes on the valve block
	Pressure source for pilot circuit is omitted
	Modular structure regardless of the valve block
	Compactness
Controllability	No influence of oil properties
	Flexible valve characteristics
	Dead zone compensation
	Hysteresis compensation
	Stall detection
	Simple safety implementation
Effectiveness	Efficient operation (power on demand)
	Same system costs as EHAs

Table 1: Benefits of electromechanical valve actuation /1/

To meet the challenges of tomorrow, Sonceboz developed a new generation of electro-mechanical valve actuation. The new design, the new control concept and the new connectivity features are presented in the following chapters.

2.2 S40 – New generation of electromechanical valve actuation

Sonceboz brand new generation of electromechanical actuation, the S40 (patent pending), is the result of more than 2 years of extensive R&D work. New motor and sensor technology improve performance and control flexibility of the actuator.

2.2.1 Higher Power Density

The heart of the new actuator is a patented innovative three phase brushless direct current (BLDC) motor technology designed for lean, high volume automotive manufacturing. Its special design allows Sonceboz to improve power density by more than 50% compared to its current generation and thus to reduce the gap to hydraulic power density, while keeping the advantages of electromechanical actuation.

Furthermore, the thickness of the actuator has been reduced by 2 mm in order to get a width of less than 40 mm. This dimension is key to addressing a large number of different valve slices by providing a very flat actuator. This result has been achieved, thanks to a special motor bobbin arrangement where all three motor phases are located within a 120 degree surface. This specific design allows to integrate the gear extremely close to the motor.

A completely re-engineered electronic architecture leads to a more compact printed circuit board assembly (PCBA) design and a higher control performance. Beside its intelligence, the single PCBA assembly is directly plugged on the stator and has the function of integrating the electrical connections, thus avoiding wires and connectors within the device. The new motor control uses position sensors to detect the rotor position for the closed-loop control of the BLDC motor. This important improvement allows reliable precise positioning. A motor closed-loop control is realized, in short, by continuously monitoring the rotor position and adjusting the phase current according to the offset between the target position and measured position through the controller. This results in less thermal stress for the actuator and the possibility to boost the power for a limited period of time, this is important to overcome load peaks, which may happen in a valve. Furthermore, an absolute position sensor to measure the valve spool position is installed on the output gear.

In order to reduce costs, material and assembly processes have been selected carefully. For example the housing integrates many functions in one single component: the stator of the motor and the connecting lead frame are over-molded with a thermoplastic material in the plastic injection machine. Although aluminum die cast has been replaced by plastics for the housing, the actuator is able to work in environments with 20% higher temperatures.

Figure 3 shows the core components of the new S40 actuator:

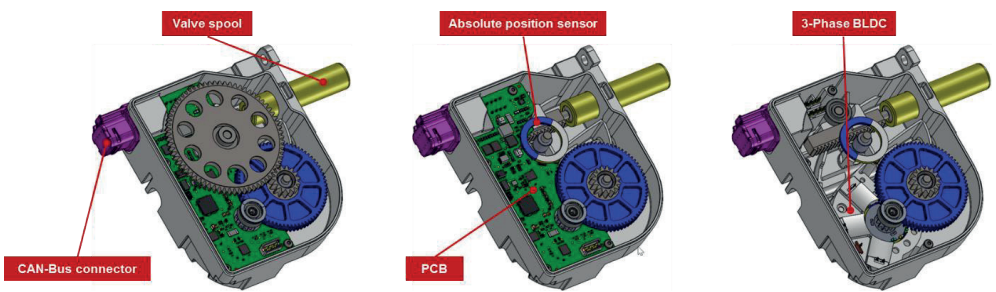


Figure 3: Core components of the S40 actuator (patent pending)

2.2.2 New control concept

The new control architecture uses Hall Effect position sensors that are completely integrated in the actuator and continuously monitor rotor and valve spool position. This very cost efficient sensor technology is the key component in the new control concept. The architecture of the new control concept is shown in *Figure 4*.

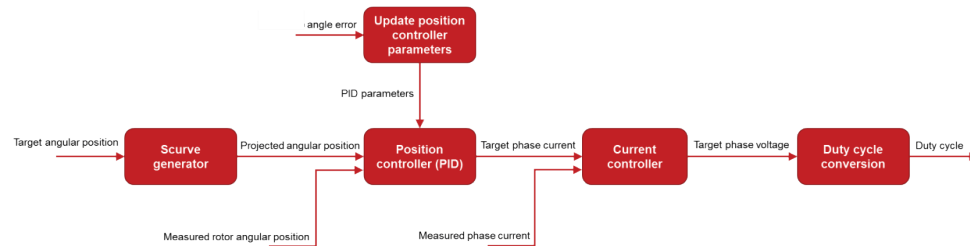


Figure 4: New control methodology

Here, the angle error is detected, having a direct impact on the control parameters of the PID position controller. Measuring the offset of current and target position allows a dynamic parameter setting of the PID controllers. This improves the control characteristics and dynamic behavior of the actuator. The desired angular target position proportional to the joystick position is treated first by the S-curve generator. The acceleration ramp can be parametrized dedicated to the application and boundary conditions of the system. Rotor angular position of the motor is mandatory for the BLDC motor control. *Figure 5* depicts the hall sensors on the rotor of the 3-phase BLDC. The output of the position controller is the target phase current for each phase. Actual phase current is measured by the electronics and gives a feedback to the current controller. This controller transforms the current off-set to a target phase voltage. This target voltage that is transformed into a duty cycle voltage.

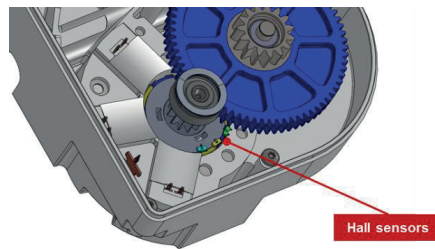


Figure 5: Hall sensors for motor control

The new control structure simplifies on-board diagnostics. The current actuator generation works with an algorithm based on stepper motor phase current and voltage information. With this methodology, stall of the spool valve is detected /5/. But further diagnostic is not possible because of the unknown spool position. Therefore, the absolute position sensor enables additional diagnostic functions, like predictive maintenance, and implementation of functional safety. Chapter 3 discusses the possible options for on-board diagnostics (OBD) based on this control methodology in detail.

2.2.3 Performance S40

Figure 6 shows the step response of S40 (12V) at 300 N load. 84 ms are needed to move the valve spool 7 mm. Compared to the previous generation, the step response time is reduced by 11%, the maximum force is increased by 66% and the width of the actuator is reduced by 5%.

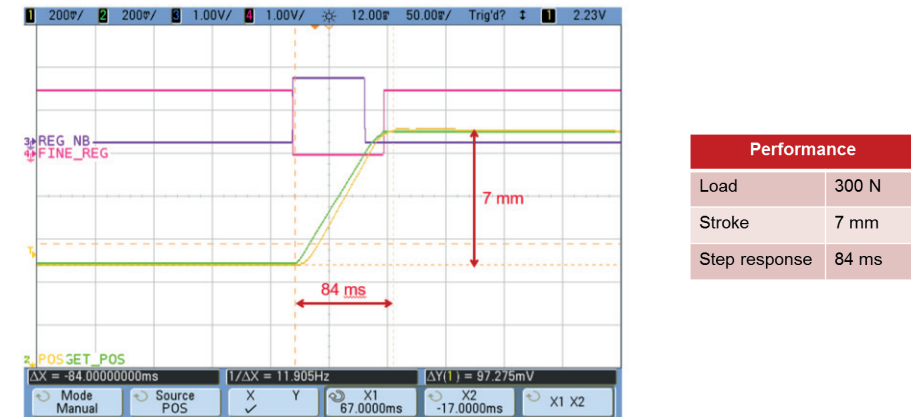


Figure 6: Step response of S40 at 300 N load

On *Figure 7*, the maximum force characteristics of mobile valves are shown for different flow rates and pressure levels. This maximum force is needed, to achieve the required dynamic behavior of the spool valve. This diagram is a simplified rough estimate based on experience. There are discrepancies due to specific valve designs in reality. However, with 400 N maximum force the S40 actuator is able to pilot valves up to (approximately) 250 l/min at 200 bar working pressure. At a 400 bar pressure level, flow rates of 125 l/min can be handled. It is necessary to have a good understanding of the spool forces for suitable actuator-valve optimisation.

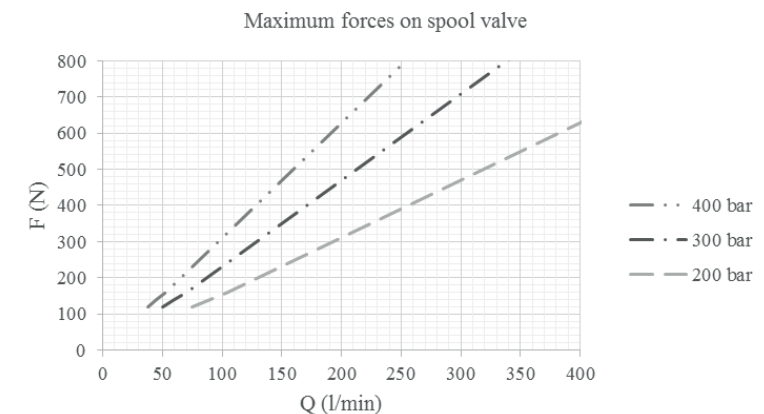


Figure 7: Maximum spool forces approximation for mobile valves

3 On-board diagnostics (OBD) and connectivity

The new electronics design is ready for integration in modern communication networks of mobile machines, such as agriculture and construction 4.0.

3.1 Direct failure detection on valve spool with on board diagnostics (OBD)

Four kinds of failures can occur during a mobile spool valve operation, **Figure 8**. Stammen analysed all possible failures in detail /2/. Further research was performed by /3/ and /4/.

First, particles in the fluid can clamp the valve spool. This failure occurs suddenly and has to be detected online. Previous versions used an indirect current / voltage monitoring to detect a stall situation. Details were published in /5/. With the absolute position sensor, a direct stall detection is possible with S40. This reduces the complexity and capacity of data processing.

Second, abrasion occurs at the control edges during the lifetime. It increases the leakage and affects the valve control behavior. To detect this change, a measurement or estimation of the flow rate is necessary. This is only feasible with additional sensors in the hydraulic system (pressure sensors, position sensor on the cylinder etc.). Further, precise knowledge of the machine operation status (e.g. under-saturation) and the environmental conditions (e.g. temperature) are necessary in order to detect the abrasion of the control edges. S40 can share its sensor data to a central diagnostic unit.

Third, friction behavior will change during the life cycle. This change is a slow process by time and it is not necessary to perform an online monitoring. The current is proportional to the spool force. Without using any filters, the force can be estimated with a tolerance smaller than 5% for the complete operation range at nominal ambient temperature. The accuracy can be improved by integration of filters and algorithms using further sensor signals like temperature sensor.

Fourth, the spring characteristics are changing during the lifetime due to fatigue. Similar to the friction force, this process runs slowly and can be detected by the force estimation.

To detect friction or spring force fatigue, a test cycle is recommended before shutdown of the machine. Running the test cycle at this time ensures that the oil temperature is at operation temperature. The spool will be moved against the spring with no-pressure and flow on the valve stage. A histogram of the performed tests can be logged with the integrated actuator data-logging system. A comparison of the current test results and the previously performed tests will show the trend of force behavior. A practical tolerance definition allows the detection of a critical force behavior achievable. In this case, the actuator sends a warning signal to the ECU of the machine.

It is also possible to perform a dynamic test like Stammen /2/ proposed. Step responses can be registered and frequency analysis executed. For this purpose, further investigations have to be done. Tests on the machine and realistic operation conditions must be performed to achieve a robust failure detection. In collaboration with OEMs and valve suppliers, Sonceboz will provide customized solutions dedicated to their application.

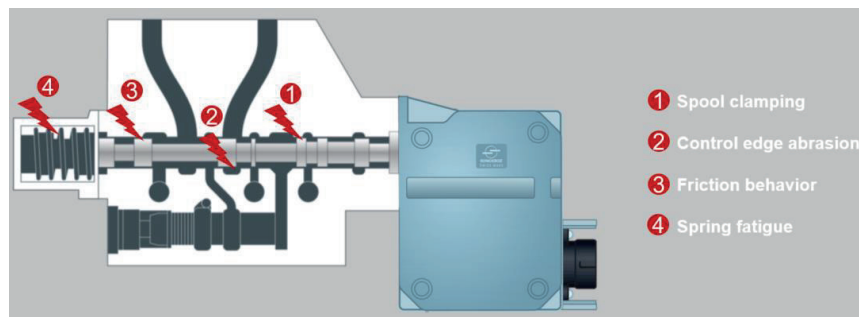


Figure 8: Failures on spool valve

3.2 Connectivity and decentralized intelligence

The on-board electronics of the S40 allows a decentralized system architecture. That means, only data that affects an upper level is transmitted to the ECU. Internal data like the control of the motor is processed locally. Even condition monitoring and predictive maintenance functions can be treated on the PCB as mentioned before. A special diagnostic algorithm monitors the valve-actuator status during operation and/or regular tests are performed before or after operation. The actuator sends a signal to the ECU when there is combination of non-plausible parameters. A good example is clamping of the valve spool: The position signal does not fit to the current and voltage signals. Furthermore, the derivation of the position signal is double checked by the derivation of the motor-control position sensor.

Based on a J1939 diagnostic layer, it is possible to connect the Sonceboz diagnostic technology to the main diagnostic tools already in use on mobile machines. The CAN autobaudrate detection automatically anticipates the communication speed of the used CAN bus like 250 Kbits/s, 500 Kbits/s or 1Mbits/s. The command resolution can be selected and adapted to the application (8bits or 16bits). To simplify maintenance operations, the actuator automatically selects its CAN address. These features make the integration of S40 in existing or newly designed structures of mobile machines easy.

The data logging function helps in providing a better understanding of the user profiles. In the histogram stored data can be extracted by the valve supplier. It provides valuable information about lifetime behavior and operation modes. Valve manufactures can adapt lifetime tests as a result of this data and plan development processes of new valve generation more efficient. Internally, it helps to improve production quality by a fast investigation of “in field” returns.

Additional functions can have a direct impact on the valve actuation. To avoid stick-slip effects, an Anti-Stick Slip function (Dithering) can be implemented in the actuator. Combined with additional sensors in the hydraulic circuit, it is possible to generate a spool position - flow curve. That means, the actuator sends a flow rate signal directly to the ECU. The valve behavior can be adapted and dedicated to an individual user profile or operation mode. There will be many manually operated valves electrified in the future. According to this, the actuator can detect and switch between manual lever actuation and electric control. Environmental impacts on the valve and system behavior, like a changing oil viscosity, can be compensated by the control. Beside the temperature sensor on the PCB, it is possible to connect external temperature sensors to the actuator.

For autonomous machines it is important for the connected devices to have the right communication. The Sonceboz actuator technology allows implementation of pre-set autonomous cycles on actuator electronics. This reduces the data transfer and simplifies the system design. It is much easier, for the ECU to select the duty cycle and the cycle is in turn performed by the actuator itself. Otherwise, all feedback data must be transferred to the ECU by the CAN bus. This can quickly lead to an overloaded CAN bus communication.

4 Summary and Conclusion

This paper highlights the benefits of electromechanical direct actuation for mobile valves. The mechanical connection of the actuator with the valve spool enables a direct force and position feedback. Integrated electronics on the actuator process this signals locally and a decentralized on-board diagnostic is performed. Furthermore, performance and power density are significantly increased by the new hardware and software concept. The new design achieves an increase of cost-effectiveness for serial production. Therefore, the S40 actuator is the ideal valve actuator for agriculture and construction machines 4.0.

The connectivity features lead to a better integration of hydraulic components to modern networks of future mobile machines. Moreover, its decentralized intelligence reduces system complexity of new mobile machine networks and helps valve suppliers to provide innovative electro-hydraulic products to OEMs.

All of these features improve the efficiency and productivity of mobile machines. Furthermore, it makes autonomous duty cycles possible. The objective of Sonceboz development is to support hydraulic component suppliers in integrating their products successfully into the modern OEM networks of tomorrow.

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