LiView®: a disruptive sensor technology for intelligent hydraulic components


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LiView® is an innovative stroke transducer for hydraulic cylinders, that is based on the electrical measurement of the cylinder structure in order to gain information on the piston absolute position and speed. In our paper we present the main characteristics of the LiView® product, the achieved results in the last two years of development and we discuss the performance of the system as measured throughout the many test campaigns run both at cylinder and machine level in the first target customer applications. Moreover, the implications deriving by the use of this technology on hydraulic systems are discussed, showing its disruptive potential for future machines.

Keywords: Cylinder stroke measurements, disruptive technology, cylinder state measurement, real-time state, high-speed control, hydraulic cylinder position control, hydraulic cylinder velocity control, transducer robustness by design.

Target audience: Mobile Hydraulics, Stroke Sensors for Machine Automation, Product Development

1 Introduction

The LiView® technology allows the measurement of the physical state of a hydraulic cylinder by performing a real-time electrical measurement of its mechanical structure /1/. The first implementation of this technology is the LiView® stroke transducer that is entering the hydraulics market in 2018. Both, absolute cylinder position and velocity can be measured by this technology by default.

This measuring technique is particular advantageous in heavy-duty applications, since no moving parts have to be installed inside or outside the cylinder that is used as sensing element. Two probes integrated in the piston rod bearing allow the coupling of high-frequency signals in and out of the cylinder structure reducing the overall envelope required for the installation. The electronics unit is connected to the probes through conventional coaxial and does not depend on the cylinder characteristics.

The absolute position measurement is performed within a few hundreds of microseconds, thus ensuring real-time measuring cycles with low latencies compatible with high demanding control applications. In the following paragraphs we will present the basic product idea, introducing the physical working principle, its configuration and implementation on the cylinder and the achieved performance in target applications. Furthermore, we will present how the demanding functional safety requirements (SIL2 and PLd) can be fulfilled for the whole system, which comprise the measuring device, probes as well as the cylinder.

2 The LiView® Idea and Working Principle

The working principle of the LiView® technology has been described in /1/. The basic idea is based on the use of the hydraulic cylinder as sensing element, which is an intrinsically robust structure conceived to transform hydraulic energy into mechanical one. The cylinder mechanical structure is considered as a multi-port electrical system, that can be thoroughly characterized by means of its of scattering parameters, a technique that is extensively used in high-frequency electronics for circuit characterization. In particular, two ports, identified as port 1 and 2 in the following picture, are used for injecting a stimulus at a given frequency and at the same moment receiving the cylinder response. At the third port, that is not directly accessible from outside, the cylinder pipe is connected. The piston position defines the length of the pipe, therefore influencing the cylinder response.

From an electrical point of view, the system is fully described by a 3x3 scattering matrix, which defines the relationship between injected and reflected electromagnetic waves at either two ports:

\[ b_i = [S] \cdot a_i \]  \hspace{1cm} (1)

with \( b_i \) and \( a_i \) representing the reflected and injected waves respectively. The transmission factor \( S_{21} \) between port 1 and port 2 is related to the impedance of the cylinder tube that can be modelled as transmission line.

![Figure 1: Equivalent electrical model of the hydraulic cylinder](image1)

The length of this transmission line is defined by the piston position, thus producing a direct relationship between phase of the electrical signal and position information. The electrical response of the hydraulic cylinder can be precisely described by a mathematical model, through which the absolute piston position can be calculated by transforming the measured scattering parameters. This makes the LiView® principle an absolute stroke transducer, allowing the calculation of the position at each new measurement cycle and without requiring a starting position information.

![Figure 2: Three-port representation of the hydraulic cylinder](image2)
Figure 2 shows the steps of one measuring cycle. The electronics generates a signal at a predefined frequency (step 1) and injects it into the cylinder structure through port 1 (step 2). The injected signal propagates through the cylinder structure up to the piston, where it is reflected back (step 3) and intercepted at port 2 (step 4). In the final step the analog signal is digitized in the electronics and processed allowing the position calculation (step 5).

3 Mechanical Implementation

3.1 Cylinder Implementation

LiView® constituent parts are the electronics unit in charge of generating, acquiring and processing the signals for the measurement of the cylinder structure, two probes for the coupling of the signal into and out of the cylinder mechanics and a high-frequency passive element that operates as a guard ring isolating the cylinder cavity from the external environment. The latter mentioned guard ring ensures a stable boundary condition for the electric measurement. A pictorial view of the cylinder subsystem with integrated LiView® is shown in Figure 3.

The electronics unit can be installed anywhere, either on the cylinder structure – as shown in the picture – or in the surrounding environment depending on the application constraints. The only limitation arises from the cable length, that shall be limited in order not to degrade the signal characteristics by attenuation. The typical maximum suggested length for optimal performance is 2m. In principle longer cables are suitable if the proper attenuation characteristics are selected. Remember that the cable length is not depending on the cylinder stroke at all, it is just a matter of the installation position of the electronics vs. the probes.

3.2 The LiView Electronics Module

The LiView® Electronics Module (LEM) is composed of two different sections. The high-frequency front-end generates the signals used for the cylinder measurement, acquires the cylinder response and digitizes it. In the digital back-end the signal is processed and the position measuring algorithms are applied allowing the position calculation. Each single measurement includes signal generation, injection, acquisition, conversion and processing and is performed within approximately 300us. Within this time frame both the processing algorithms for the position and speed calculation and the safety surveillance functions described in section 5 are run. This condition allows real-time position measurements in high-dynamics applications with very low latencies compared to most other established measuring devices. Each measuring cycle is repeated at different frequencies that are selected based on the specific cylinder characteristics, thus providing redundant position information, that can be used to compensate for instabilities and other effects.

The LEM can be considered as a universal measuring equipment. Different cylinder types require different operating parameters, that are stored in the electronics unit in terms of calibration parameters. They are generated offline and downloaded to the LEM during the initial pairing procedure of LiView® with the specific cylinder. The cylinder length has no impact to the system calibration, the parameterization is mainly dependent on the ratio between piston and rod diameters.

3.3 The LiView® Probes

3.3.1 Design

The LiView® probes provide the electric contact to the cylinder structure, implementing a capacitive coupling between electronics and piston rod. They are integrated in the high-pressure side of the hydraulic cylinder rod bearing, i.e. behind the primary seal. The probes fulfill multiple functions: they realize a sealed high-pressure cable feedthrough, allowing the routing of a coaxial cable inside the cylinder structure. They couple the signal into the cylinder inner cavity. They compensate the relative displacement between piston rod and rod bearing, thus ensuring an optimal signal transmission during cylinder operation even in harsh environments. This is essential for heavy duty applications, where strong lateral forces continuously stress the cylinder subsystem.

The following pictures show the probe configuration for typical heavy-duty hydraulic cylinders with bolted rod bearings. Alternative designs have been conceived for smaller cylinders with screwed piston rod bearing.

Figure 4: LiView® Probe stand-alone (left) and integrated into the piston rod bearing (right).

The contact element is electrically connected to the cable inner wire and hosted on a floating bearing, ensuring a stable capacitive electrical connection in a dynamical system, allowing relative displacements along all three main axes and preventing wear to both the contact element and the piston rod. The capacitive coupling is achieved by pressing the contact element with a small force towards the piston rod.

An intensive qualification campaign has been performed on the LiView® Probes, in order to verify their robustness and suitability for heavy-duty applications. In addition to the normal quality assurance program, special attention was provided to the susceptibility to wear of the contact element and to the stress induced by pressure.

3.3.2 Wear resistance

The wear resistance has been investigated with a lifetime test campaign performed on several probe samples, by measuring the change of the capacitive coupling while the piston rod continuously moves within the cylinder during the whole investigation. Results are shown in the following figure.
temperature cycles, in order to achieve an initial pre-aging of approximately 1,000h. Then they are installed in a pressure chamber (Figure 6), where they are exposed to periodical pressure bursts from zero to 420bar at a constant temperature of 85°C. If the probes pass this test campaign at a given environmental condition without failure, they can be considered to be safe over the whole lifetime.

4 Performance

4.1 LiView® Accuracy Model

Figure 7 shows the accuracy model for the LiView® stroke transducer. The ideal behavior (represented by the dashed blue line) describes a perfect linear system. The piston position is calculated during each measuring cycle by means of a mathematical transformation of the scattering parameters measured from the electronics. The mathematics of the position calculation algorithms—that exploits the cylinder characteristics expressed by cylinder specific parameters—introduces some non-ideal effects caused by the oscillating nature of the phase of the electrical signal. This condition produces some deviations w.r.t. the ideal behavior, which is shown in the curve as superimposed ripple. At the present product maturity stage the typical maximum ripple amplitude observed is of the order of 1 mm. Obviously the goal is to eliminate it completely through proper algorithm design optimization.

Figure 6: Pulse test set-up hosting 14 total probes. Burst pressure cycles between 0 and 420bar have been run with a frequency of 1.3Hz at the nominal working oil temperature of 85°C.

The probe resistance to pressure is still in the qualification phase, having achieved almost 40% of the targeted lifetime. The goal is to achieve the design lifetime of a typical heavy-duty cylinder used in mobile machines. In the frame of this qualification program, probes are first exposed to a hot temperature oil environment and to
framework in order to understand the LiView® measurement accuracy and the effects impacting on it. In real applications all above mentioned effects are superimposed, such it is very challenging to disassemble them into their single contributions.

4.2 LiView® Accuracy

The following figures show the measurement repeatability (precision) and the overall accuracy measured on a hydraulic cylinder with LiView® in a laboratory environment. The piston position has been measured dynamically performing 10 consecutive movement cycles between retracted and fully extended positions. The LiView® signal has been acquired and compared to the absolute reference position provided by a high-accuracy measuring device mounted externally on the cylinder structure. Both, the accuracy error and the non-linearity of the external stroke transducer are included in the measurements, what means a worst case performance scenario. The plot shows the min-max distribution of the positions over 10 cycles both for each piston position (Figure 8) and over the full stroke (Figure 9).

The performance is typically better than 500 μm over the full stroke, with standard deviations as low as 100 to 200 μm. These values confirm the performance prediction already given in /1/ and the suitability of the stroke transducer for mobile machine applications.

4.3 Sensitivity to oil instabilities and compensation techniques

As introduced in paragraph 4.1 and deeply discussed in /1/, the measurement accuracy of the LiView® stroke transducer is susceptible to oil characteristics variations. In particular, any parameter influencing the oil dielectric constant, like pressure, temperature and aging, influences the propagation speed of the electric signal inside the cylinder cavity. Any change of the signal travelling speed generates a phase error of the measured signal, thus producing a systematic error on the calculated position. This error depends on the length of the path traveled inside the dielectric, which is maximum in the condition a completely retracted piston rod and is almost negligible for a fully extended piston rod.

Figure 10 shows data acquired on a plunger cylinder of a mobile machine operating at different temperature and pressure conditions in a real working environment.

The machine was stored overnight in a climate chamber at -20°C and then operated from cold to warm condition. Temperatures were recorded at different locations along the hydraulic circuit, including the cylinder structure. The plot shows the position deviation measured w.r.t. a conventional wire potentiometer for different oil operating temperatures and under different cylinder load conditions. The different error contribution related to the piston position is clearly visible in the plot. The temperature coefficient measured on this specific cylinder is 156 ppm°C. Typical temperature dependences observed for other types of hydraulic cylinders range between 150 to 220 ppm°C.

Changes in the oil characteristics represent the main accuracy limitation for transducers that exploit the mechanical structure of the cylinder to perform the measurement. This behavior has to be compensated, in order to achieve acceptable performance in real applications. Figure 11 shows the performance improvement when temperature compensation algorithms are activated. The temperature susceptibility of the plunger cylinder analyzed in Figure 10 is reduced to a value as low as 30 ppm°C, that can be considered as acceptable for many heavy-duty mobile applications. The temperature compensation is based on the recognition of the dielectric constant change, that is used for the correction of the calculated piston position. The correction algorithm runs in
real time during every measurement cycle allowing for the compensation of temperature, pressure and aging effects of the hydraulic fluid.

4.4 Performance in Mobile Machines

As discussed in paragraph 4.2, the repeatability of the measured position represents one important performance parameter for stroke transducers in real applications. Repeatability, often referred to as precision, is evaluated as the total deviation (minimum vs. maximum) recorded on each single position during dynamic cylinder operation. For conventional stroke transducer the declared performance typically refers to ideal testing conditions in a laboratory environment. For the LiView® system this is not possible, since measurements require the presence of the cylinder structure, which represents the major source of inaccuracies. In fact, the measurement performance at cylinder level is influenced both from dielectric constant changes of the fluid and from displacements and deformations induced by forces and temperature gradients acting on the cylinder structure during operation.

Figure 10: Absolute Position Accuracy measured on a real machine under different working conditions. The hydraulic cylinder has been operated in the unloaded condition and with 0.6t and 3.4t load. The deviation does include the inaccuracy of the reference wire potentiometer.

Figure 11: Laboratory measurements of the same plunger cylinder used for the machine tests above implementing a prototype temperature compensation function. The cylinder has been operated unloaded. Positions are referenced to an external high-accuracy magnetostrictive stroke transducer.

Figure 12: Position distribution measured during dynamic cylinder operation in a real mobile machine under different load and temperature conditions. The distribution reflects the total observed position deviation at each piston position over multiple stroke cycles.

Figure 13: LiView® Electronics operating on a 77mm plunger cylinder in a mobile machine.
We have performed several measurement campaigns on different types of mobile machines in different environments, in order to evaluate the overall system performance. We present in Figure 12 the precision recorded on a plunger cylinder of a mobile machine operating under different working conditions that include both temperature and load effects. Figure 13 shows the LEM mounted on the cylinder structure during the testing campaign. All data refer to dynamic cylinder cycles performed during machine operation and have been obtained comparing the LiView® signal to the machine wire potentiometer, thus including the inaccuracy of the latter. The results show the precision resulting from all performed stroke cycles, confirming that signal precisions well below 2\% peak-to-peak can be achieved over the major part of the cylinder stroke.

5 Functional Safety

5.1 The Safety Problem

LiView® has been developed in order to fulfill Performance Level d (DIN EN ISO 13849) and SIL 2 (DIN EN ISO 61508) requirements. The main difficulty within our approach is related to the intrinsic different nature of the LiView® sensor concept compared to conventional transducers. While the latter are based on the measurement of a well-defined measuring path (e.g. in magnetostrictive transducers the measuring path is encapsulated within a predefined metal bar, that can be precisely manufactured and controlled by the sensor provider), LiView® performs the electric measurement of an external cylinder structure, which is typically not under full control of the LiView® manufacturer (Liebherr). This unique set-up, that on the one hand features the main advantage in terms of system robustness and serviceability in-field compared to other solutions, introduces additional complexity for the safety case.

5.2 Safety Approach

The Safety approach is schematically explained with the block diagram shown in Figure 14. The main objective of the safety function is to ensure the correctness of the measured cylinder position and is solved by introducing surveillance functions operating at two different levels, the component and the system one.

At component level the electronics unit is surveilled. The primary objective is to ensure that a reliable electrical measurement is performed, in order to consider the LEM as a certified measuring equipment. For this task the cylinder is considered perfectly ideal, thus not contributing to measuring errors at all. The probes are also neglected. Surveillance functions have been included in the electronics unit in order to verify the signal characteristics that are produced and measured. They are implemented either as hardware or software monitoring functions, as shown in Figure 14. Hardware monitors include temperature and housekeeping acquisition on the circuit board and monitor all power supplies and core hardware elements through a complex surveillance circuit that includes a watchdog. Software monitors allow the analysis of both, the generated as well as the acquired signal characteristics. Both the firmware and all data processing algorithms are running on a lockstep processor with two independent computational cores (identified as core A and B in the figure above) that are continuously compared through the hardware surveillance function. The whole development has been performed according to safety standards. This way the major part of the possible errors can be identified and either compensated or, if not feasible, the defined counter-measures have to be started. The resulting diagnostic coverage is as high as 97.6%, meaning that only 2.4% of the possible total errors remain undiscovered. The resulting FTT rate for undetected dangerous errors is 47.

At this level the LiView® electronics can be considered as a Safety compliant vector network analyzer, able to measure reliable scattering parameters of a hydraulic cylinder. Passive components like HF guard ring and probes are thoroughly qualified fulfilling the standards required by the Safety Standards for Machinery.

The system level Safety functionality is implemented as surveillance algorithm running in the LEM. It checks the cylinder response to a known stimulus and compares the measured scattering parameters to the expected ones. The cylinder behavior can be predicted with a high degree of accuracy – of the order of 1% – through a mathematical model, that allows both the prediction of the expected electrical quantities measured at the cylinder ports, as well as the transformation of the measured scattering parameters into position values. For this purpose, the cylinder is measured at different frequencies thus producing intrinsic redundant information. The relevant cylinder model parameters are generated off-line in the frame of a cylinder type release procedure and include the probe length information. The parameters are stored into the LiView® Electronics Module.

The scattering parameter measuring technique allows a continuous monitoring of the state of the probe cables compensating for drifts occurring due to mechanical, temperature and aging effects. This is performed at each measuring cycle. In case of anomalies the position information is flagged as potentially dangerous but still broadcasted on the bus.

6 LiView® as a Disruptive Technology

In paragraph 4.3 we have introduced the main error sources caused by changing oil dielectric properties and proposed a strategy in order to compensate them. A detailed analysis of the accuracy degradation due to oil state variations has been presented in /1/. One important effect that is frequently encountered in real applications is cavitation. In bucket cylinder for instance, it is observed when an abrupt variation of the mechanical load produces a fast displacement of the piston rod, that cannot be followed by the hydraulic system with the proper amount of oil flow. As a consequence, the pressure in the fluid drops suddenly allowing the evaporation of air or water contained in the fluid. This situation leads to a condition, where the fluid electrical properties are changed and impacts on the measuring accuracy.

LiView® is able to detect this state, being the measuring principle extremely sensitive to any change of the fluid dielectric constant. The comparison of the measured position and the one predicted by the cylinder model, allows the generation of a signal that is correlated to the presence of air inside the cylinder chamber, thus providing important information to the machine control unit for the control of the actuating valves and thus supporting a more stable operation of the hydraulics control.

Figure 14: Schematic representation of the LiView® Safety concept. Red path show real-time diagnostic functionality aimed to error detection, blue arrows show design-in data that are used by the cylinder mathematical model in order to perform consistency checks.
This is visible in Figure 15, where the position measured without any compensation technique is shown (green dots) and compared with the information that can be extracted from the surveillance algorithms (blue square signal). The presence of air in the fluid impacts on the dielectric constant of the oil, that would result in an undetected position error. The surveillance algorithms allow the identification of this state in real-time. This information can be used in the LEM in order to generate a warning signal.

![Graph showing Detection of Cavitation State through LiView Real-Time Data](image)

Figure 15: Real-time cavitation recognition based on the evaluation of the LiView signal.

In general, this ability can be further exploited, in order to generate state information both on the component and on the hydraulic system that includes the cylinder, that would not be possible by using conventional technologies, in which the sensor is a well confined subsystem. In this view, LiView® can be understood as a technology platform allowing the real-time monitoring of the cylinder system state. The technology is based on a complex measuring hardware, on which software functions can be added at a later stage, implementing new functions and providing further insight on the cylinder health state.

7 Summary and Conclusions

In this paper we have presented the progresses in the development of the LiView® stroke transducer. The basic idea of using the cylinder as sensor, without introducing parts into its mechanical structure with the exception of two LiView® probes, is a very promising approach for many heavy-duty applications, where both sensor performance and robustness have to be achieved and for which conventional sensors do not represent an option. The very limited envelope required for the integration of the probes in the piston rod bearing makes LiView® suitable for cylinders with small diameters, where other solutions cannot be integrated. All components developed so far have C-sample maturity allowing the implementation of LiView® in selected targeted applications.

The innovative approach based on the prediction of the cylinder physical state through a mathematical model allows the realization of a surveillance function that extends beyond the boundaries of the component. This allows the fulfillment of functional safety requirements, that would not be possible without having full control on the measuring path. Moreover, this innovation can be further exploited in order to provide e.g. cylinder state information to the system control unit, that would normally require dedicated additional sensors and complex algorithms at system level. A new approach to system level state monitoring is therefore opened.

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Nomenclature

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<th>Variable</th>
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<tr>
<td>C</td>
<td>Capacitance</td>
<td>[F]</td>
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<td>FS</td>
<td>Full Scale</td>
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<td>LEM</td>
<td>LiView® Electronic Module</td>
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<td>s</td>
<td>Scattering Parameter</td>
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<tr>
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<tr>
<td>ε</td>
<td>Oil Dielectric Constant</td>
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