The Liebherr Intelligent Hydraulic Cylinder as building block for innovative hydraulic concepts

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Abstract

We present hereafter the development of the Liebherr Intelligent Hydraulic Cylinder, in which the hydraulic component is used as smart sensing element providing useful information for the system in which the cylinder is operated. The piston position and velocity are the most important signals derived from this new measuring approach. The performance under various load and temperature conditions (measured both on dedicated test facilities and in field in a real machine) will be presented. An integrated control electronics, which is performing the cylinder state processing, additionally allows the synchronized acquisition of external sensors. Providing comprehensive state information, such as temperature and system pressure, advanced control techniques or monitoring functions can be realized with a monolithic device. Further developments, trends and benefits for the system architecture will be briefly analyzed and discussed.

KEYWORDS: Absolute piston position and velocity measuring system, stroke transducer, high frequency and low latency signal acquisition.

1. Introduction

Several attempts have been made in the past in order to sense the piston position inside a hydraulic cylinder by exploiting the electric characteristics of the mechanics. Different methods have been proposed ranging from simple DC resistance measurements up to more complex ones including resonance and microwave techniques inside the cylinder cavity [1, 2, 3, 4]. The latter appear as promising solutions thanks to the availability of integrated circuits that combine excellent performance with reduced cost. In all of the above techniques, one main issue for the sensor is the stability of the measured signal, since the sensing element is the mechanics of the cylinder itself. The hydraulic cylinder is in fact a component conceived for transforming hydraulic energy in mechanical work, being subject to extreme mechanical stress and high temperature gradients. In order to achieve the required accuracy, the cylinder structure has to be considered as being part of the measuring system as well. Furthermore, any component integrated in the cylinder has to survive the environment still with an acceptable level of performance.

Liebherr-Elektronik GmbH has developed and patented an integrated sensor approach for the measurement of the piston position of a hydraulic cylinder based on RF measurements. The robustness of the system is achieved by design through the sensing concept, in which the cylinder is electrically sensed through elements that are directly integrated into the piston rod bearing. Hence, extra modifications of the basic cylinder design are not required. Advantageously, there is no need for drilling the piston rod to embed conventional linear position sensors. The electronics performs a measurement of the cylinder characteristics in a period of less than 200µs and processes the data in real-time in order to determine the piston position and velocity with very low latency.

2. Electrical measurement of mechanical structures

2.1. Measuring concept

Liebherr´s innovative stroke transducer exploits the cylinder itself as sensing element, which is considered as three-port system, as shown in **Figure 1**. Two ports are used for injecting a stimulus and reading-out the cylinder response, at the third port – that is not directly accessible – the cylinder pipe and the piston element are connected.

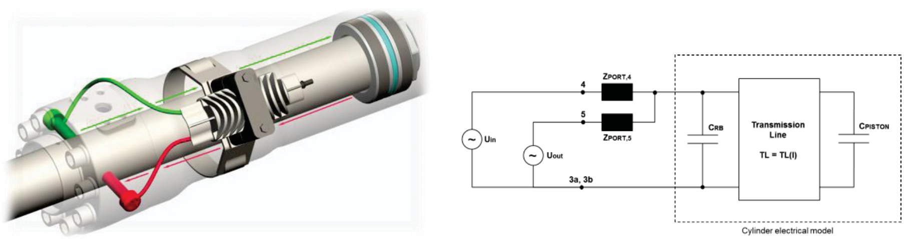

Figure 1: Three-port representation of the hydraulic cylinder

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

$$b_i = [S_i] \cdot a_i \quad (1)$$

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. Since the piston position defines the length of this transmission line, the measurement of the transmission factor allows a direct determination of the piston position. By means of converting the mechanical structure to an electrical multi-port element, the high frequency characteristics turn out to be the electrical counterpart to the mechanical structure. The innovation in this approach *de facto* lies in the interpretation of these high-frequency signals, which simply can be measured by using a conventional vector network analyzer.

2.2. Cylinder implementation

In the herewith-presented approach, two sensing probes representing port 1 and 2 are integrated in the high-pressure part of the cylinder rod bearing. The major advantage arising from this solution consists of the minimal envelope required for the integration of the system. This allows the implementation in small size cylinders, the reduction of the integration costs (among other things due to the absence of a drilled hole inside the rod) and the simple accessibility to any part of the stroke transducer in case of malfunctions, without the need of dismounting the cylinder. The control electronics (CE) stimulates and samples the probes by means of coaxial connections, thus allowing a flexible accommodation of the device straight on the cylinder or on its supporting structure.

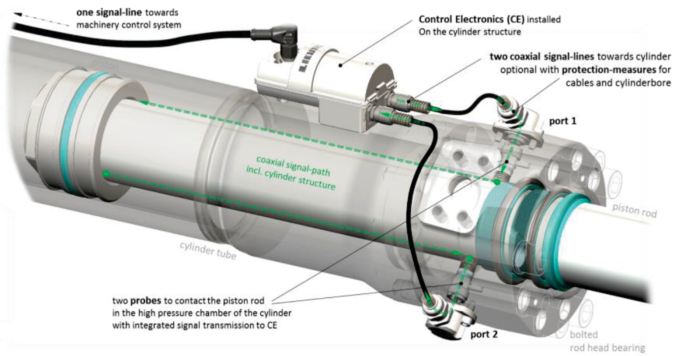

Figure 2: Pictorial view of the stroke transducer

2.3. Theoretical performance

The stroke transducer has been extensively tested under various laboratory conditions. The following figure shows the position accuracy for a 0.5m stroke hydraulic cylinder via the whole stroke measured. The repeatability of the measured position is evaluated as peak-to-peak and standard deviations with respect to the known absolute position, which is given through an externally mounted high-precision position reference system. These measurements were performed under laboratory conditions. The measuring principle approves high accuracy over the whole stroke. The standard deviation depends on the piston position, since all measurements have been performed with a constant frequency.

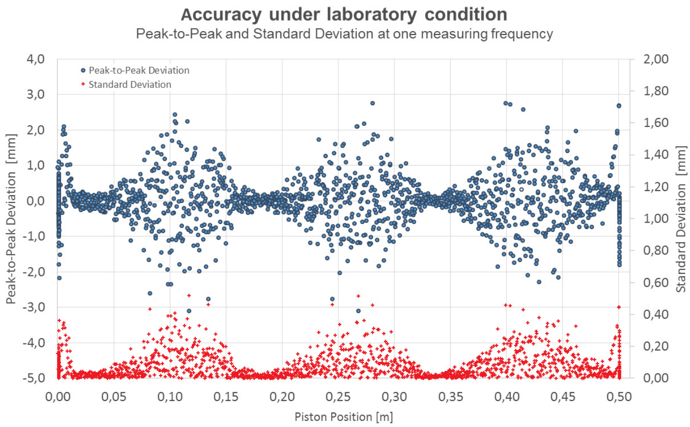

Figure 3: Accuracy measurement over several weeks

In the resonance areas the points are closely distributed around the values representing the average position. The standard deviation is lower than 100µm and provides in these areas a high-precision measurement. In non-resonant position areas, the distribution spreads out over a wider range of values, but the overall measurement performance still remains within a respectable level (the worst-case standard deviation is in the range of 500µm). By means of variation of the measuring frequency, the resonance areas can be shifted along the stroke, thus realizing a high accuracy transducer over the whole cylinder stroke. One measurement cycle is performed within a period of 200µs and has been successfully tested dynamically for piston speeds up to 1m/s. However, this technique gives no limits to higher velocities.

2.4. Influencing factors to the measuring performance

The measuring principle is based on the electrical measurement of the mechanical structure. This results in electromagnetic waves travelling alongside the cylinder cavity while interfusing the fluid medium. The most significant effects influencing the accuracy are related to variations of the fluid dielectric constant and include pressure, temperature and oil aging. We briefly discuss them in the following paragraphs.

2.4.1. Pressure

The following figure shows the test set-up designed to investigate the pressure influence on the piston position accuracy. The tests were performed at the test facility of Liebherr-Aerospace GmbH, conceived for thermo-mechanical qualification of aircraft cylinders. As expected, our measurement approach is almost insensitive to pressure variations on the cylinder bottom side. On the rod side a linear dependency of ±0.2% full scale can be evaluated. This value is lower than being predicted based on oil compressibility, since the two-port measurement concept has an intrinsic compensation of common mode effects affecting both ports.

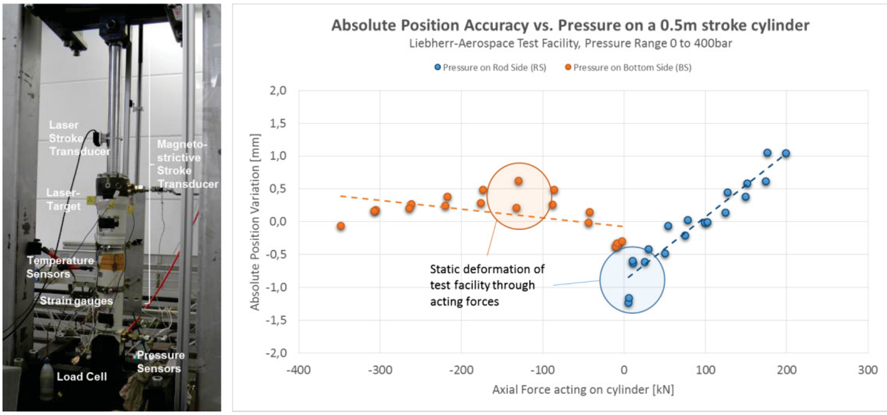

Figure 4: Pressure influence on position accuracy for a 0.5m stroke cylinder

The hysteresis, which has been identified, is due to the static deformation of the test set-up and is related to the forces generated by the high static pressures that are generated. Actually, it is extremely difficult to design a stable reference system with an accuracy better than 1mm at the occurring forces.

2.4.2. Temperature

The temperature coefficient effects have been analyzed in the context of the above pressure investigations. The large temperature gradients during test execution have an impact on the mechanical structure of the test facility in terms of deformation. This produces an uncertainty in the actual position measurement in the order of 2mm.

The following plot shows the recorded position drift as function of the environmental temperature at different measurement frequencies without compensational measures. The temperature coefficient depends on the measuring frequency, as expected. A high degree of immunity to temperature can be achieved in cases where the measurement is operated at an ideal frequency. For typical application values better than 50 ppm/°C over the temperature range 0°C to 100°C can be realistically achieved.

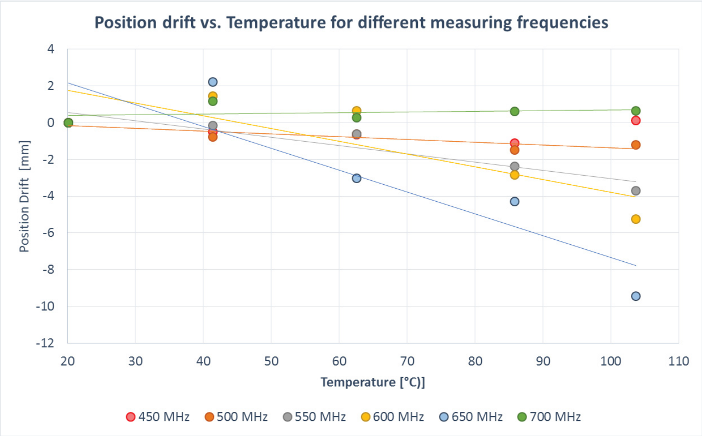

Figure 5: Temperature influence on position accuracy

2.4.3. Other effects

Further contributions are influencing the measuring accuracy. At first, these are geometry variations affecting the cylinder scattering parameters, and secondly, drifts in the oil characteristics (e.g. aging effects, water, air generation, etc.), which directly influence the dielectric constant. Geometry effects have been investigated during the machine tests that will be presented in the next chapter. Fortunatelly, the drift of the oil characteristics is typically a slow process, so it is mainly affecting the absolute calibration. For the short-term operation of a machine (i.e. one-day time period) the drift problem can be solved using self-compensating strategies or even neglected at all, especially in such cases where a relative position information is required only.

2.4.4. Resulting characteristics and specification

Given the thorough investigation campaign presented so far, as well the simulations results, the above target requirements can be derived for a series product.

Characteristics	Value
Max. Length of Cylinder	Not relevant
Max. Read-Out Speed	< 200 µs
Max. Cylinder speed	< 5 m/s
Resolution	100 µm
Non Linearity (incl. pressure effects)	< 0.3% of FS
Temperature coefficient	< 0.5% of FS

Table 1: Summary of the target requirements for the position transducer.

3. Measured performance in-field

3.1. Machine implementation

An early prototype of the Liebherr Intelligent Hydraulic Cylinder has been integrated on both the boom- and the bucket-cylinder of a Liebherr A916 excavator. The measuring electronics has been extended in order to allow the synchronized acquisition of all relevant cylinder state parameters through additional sensors. They include an externally attached magnetostrictive stroke transducer used as reference system for the position, as well as pressure and temperature sensors on both cylinder chambers. For the visual investigations during operation a ruggedized Liebherr camera has been included in the set-up. The following picture gives an impression of the measuring set-up installed on both cylinders.

Figure 6: Test set-up at machine level

3.2. Machine operation in the unloaded condition

The following figure shows the measured absolute position compared to the reference system during excavator operation. No systematic errors have been removed from the position data, resulting in a typical fluctuating behavior of the deviation that depends on the specific piston position. The blue dots represent the unloaded condition while the excavator is moving the cylinder at speeds of up to 300mm/s. The cylinder is continuously operated throughout a longer period. The red dots correspond to a similar dynamics made with the excavator loaded with a 1.6t weight. All measurements are performed at one single measuring frequency. The dynamics induced by the load determine large pressure and geometry variations in the cylinder chambers that slightly affect the measuring performance, as shown in the figure. The overall absolute error remains within a band of ±3mm.

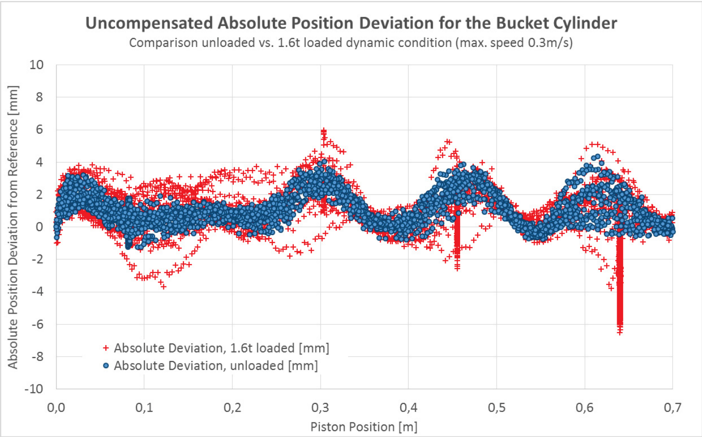

Figure 7: Dynamical accuracy measured on an excavator

3.3. Machine operation in real working conditions

The next figure shows the measuring performance while the machine is excavating, loading and lifting soil material.

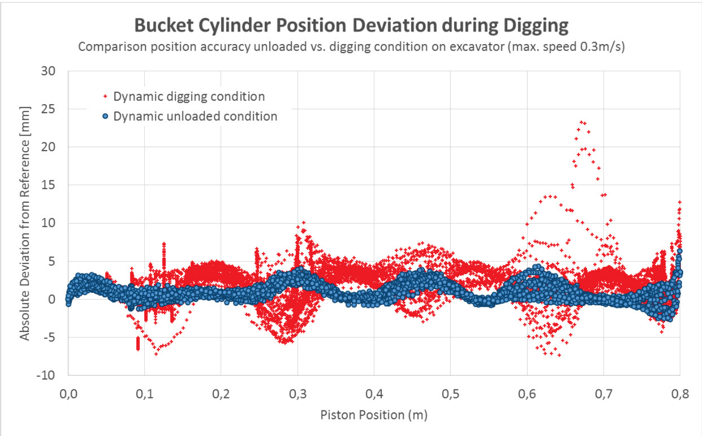

Figure 8: Dynamical accuracy measured while excavating

Pressure variations occur abruptly in the range of up to a few hundreds of bar depending on the speed of the dynamics. The external forces generate local displacements in the cylinder parts that also affect the cylinder electrical characteristics. The fluid temperature increases of some tens of degrees due to friction losses in the hydraulics.

The comparison of the position accuracy (red dots) with the unloaded condition (blue dots) shows still a satisfactory absolute measurement performance of ±5mm. As for the previous figure, systematic effects have not been removed from the plot. All measurements are performed at one single measuring frequency.

The plot shows few larger deviations (up to 25mm) in the position range of 0.6 to 0.7m. During some lifting cycles it was intentionally tried to produce cavitation in the cylinder, by abruptly forcing the whole soil material out of the loader. This operation produces an abrupt variation of the fluid pressure that drops to 0bar thus producing air generation inside the oil. The air generated is detected indirectly through the variation of the dielectric constant. In this case, a degraded position information is generated. This behavior confirms the potential behind this measuring technique for detecting effects that are presently not monitored on conventional machines, but which indicate dynamic limits of the mechanical-hydraulic subsystem.

4. Trends toward the Intelligent Hydraulic Cylinder

Our work is based on the electrical measurement of a mechanical structure, in order to sense its physical status. In principle, this approach can be extended to any mechanical structure comprising some varying cavities.

The focus of this research has been set on the determination of the piston position of a hydraulic cylinder, since this parameter is directly required for machine control. Until now, the accuracy of the position measurement has been discussed, showing its dependency to the specific cylinder working conditions. Systematic errors affecting the position accuracy have been presented so far as dysfunctions. They include variations in oil temperature and characteristics, cylinder pressure and geometry variations.

It is important to notice that the electrical measurement of the mechanical structure already includes all information related to both, position and aforesaid disturbances. With expanding understanding of this overall approach, the measuring technique will allow to sense all relevant state variables of a hydraulic-mechanical subsystem, such as pressures, temperatures or even oil properties, with one single measurement.

The performed machine tests presented in the previous paragraph demonstrates a first step towards this vision. It is a single, highly integrated control electronics which is measuring the cylinder scattering parameters and synchronizes additional external sensors with a time base of 200µs. Piston position, velocity, pressure and temperature status are correlated on a real-time basis, thus generating additional information for the machine control.

Following this approach, the ability to sense and correlate multiple state variables allows the realization of intelligent cylinder subsystems, capable of sensing their status and delivering important information to the main machine controller. A possible architectural sketch is shown in **Figure 9**, in which the intelligent cylinder is represented with its relevant state variables, control valves and processing electronics. It receives hydraulic energy through the main pump and is able to monitor its state while performing defined tasks within the boundaries allowed by the main machine control unit.

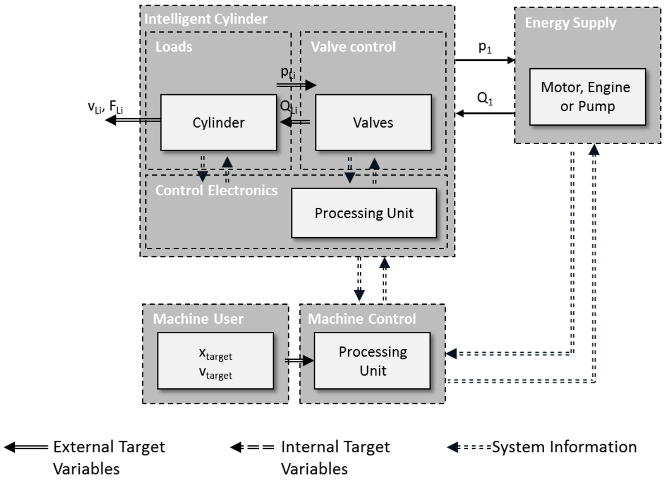

Figure 9: Architecture of the intelligent cylinder with the main system interfaces

The ability to measure and process the position, velocity and pressure signals for each individual cylinder in real-time gives the opportunity for an energy optimized control of the complete machine hydraulics. Based on the specific machine working conditions, the energy supply can be operated in the best energy saving mode. A step forward in machine automation will be achieved through autonomous control loops, managing the information recorded from each individual cylinder. The systematic acquisition of state parameters allows condition monitoring, which require intelligent diagnostic functions supporting the machine user throughout the whole life cycle. Finally, new safety-related functions may be enabled based on the knowledge of the actual state of all subsystems of the machine attachment and the coherency check of their state at system level.

The proposed concept could have some important implications on the overall machine architecture, since at least some measuring functions will be decentralized and performed autonomously by dedicated electronics at subsystem level. The new control electronics, which is in charge of processing the acquired information and broadcasting it through a standard interface, can play different roles inside the overall system, ranging from a simple sensor gateway up to a more intelligent unit directly actuating the hydraulic valves. The hydraulic cylinder mutates this way from a simple hydraulic actuator to an intelligent subsystem, fully characterized by pre-defined system parameters and able to operate in different modes defined by the main machine controller (e.g. heavy duty, eco mode, etc.). In order to converge to an appropriate final architecture, it will be essential to progress towards integrated sensing solutions with on-board processing capabilities and identify the functions at machine level that increase the benefits for the final customer.

5. Conclusions

A novel approach based on the measurement of the scattering parameters of a mechanical structure has been proposed. This method has been successfully applied to a hydraulic cylinder for the measurement of the piston position. The theoretical performance allowed by this sensor concept is comparable with state-of-the-art stroke transducers based on conventional methods (e.g. magnetostrictive or optical sensors) but avoiding those typically required large integration envelopes or immense cylinder modifications. While conventional transducers are characterized by system inherent low speed, high integration costs and a lack of robustness, the new approach promises high dynamics, a high benefit-cost ratio and an ultra-ruggedized design.

Our concept has been extensively verified under real environmental conditions, with temperatures ranging between -40°C and +100°C and under pressure variations of up to 400bar. The verification took place both in a dedicated aerospace test facility and in a real excavator showing a high degree of stability under all working conditions. The new technology is suitable to be integrated in machines operating under harsh environmental conditions, e.g. in mobile machines for mining and maritime applications. Moreover, the compact outline of the sensing probes allows the implementation in applications, where normally no stroke transducers can be accommodated on cylinders.

The high measuring speed in the magnitude of 200µs with extraordinary low latency allows the implementation in ultra-dynamic motion control systems, such as on test facilities, hexapod simulators and injection machines.

Furthermore, the internally processed correlation of stroke information, pressure gradients in both cylinder chambers allow the implementation of innovative hydraulic architectures, providing real-time state variables that can be used at system level for advanced monitoring and control functions. As a future prospect, all these functions will be merged into a highly integrated control unit, in this way contributing to the development of distributed intelligent architectures.

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7. Nomenclature

C	*Capacitance*	*F*
CE	*Control Electronics*	-
FS	*Full Scale*	*M*
S	*Scattering Parameter*	-
TL	*Transmission Line*	-