Smart hydraulic cylinder with force measurement system

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The trend of intelligent components can be observed in various fields. Intelligent component means components with highly integrated sensors and control technology. This enables the system manufacturer to design more complex equipment, and nevertheless decrease in the required integration effort. As a customer-oriented supplier and development partner WEBER-HYDRAULIK concern itself with the development of highly integrated, reliable and reasonably priced sensors for hydraulic cylinders. While an optical position transducer is developed for mass production, this article focuses on the development activities of an in-cylinder integrated force measurement. Parallel to the further development of the application-specific force measurement system for supporting cylinders, a universally applicable concept for contactless force measurement was investigated.

Keywords: smart components, contactless force measurement, integrated sensors, hydraulic cylinders
Target audience: Mobile Hydraulics, Stationary Hydraulics, Hydraulic System Designers

1 Smart hydraulic cylinders from WEBER-HYDRAULIK

WEBER-HYDRAULIK is following the path of evolving from component supplier to system solution provider over the past years. We have observed that application areas of the customer are becoming more complex where the performance, energy efficiency or ease of use of drive systems must be maximized mainly through the application of electronic control systems. The control systems require acquisition of information from various process parameters. Integration of measurement systems is often challenging. On the one side, the application effort must be kept to the minimum. On the other side, the sensor components must be protected in the best way against harsh environmental condition e.g. on the construction sites or in the agricultural environment. Against this background, WEBER-HYDRAULIK develops smart hydraulic components with fully integrated sensor technology. An optical position measurement sensor which can be integrated into a cylinder and a customer-specific solution for force measurement in supporting cylinder are already in mass production. /1/

1.1 Integrated optical position transducer

There are various technical solutions for measuring the current position of hydraulic cylinders. The developed integrated measuring sensor detects the cylinder position by optical recognition of a binary barcode applied on the piston rod, which has a unique code structure in every position. The sensor is available as a redundant version to meet more strict safety requirements. Its compact design makes the sensor particularly suitable for mobile applications in agricultural and construction machinery.

Figure 1: WEBER-HYDRAULIK optical position transducer

The sensor is made up of an exposure unit, a sensor unit to capture the image and an electronic module for image processing and communication. A section of the code is illuminated by the exposure unit for a short period of time which is detected by the sensor unit then. This takes place at specific intervals which adapted to suit the maximum traversing speed of the rod. The images are analysed individually, and the position is determined respectively.

The code is unambiguous over its entire length. This means that every change of position results in a unique piece of code over the entire measured length.

The sensor is mounted on the cylinder guiding piece outside of the pressure chamber and directly behind the wiper. It is thus an external sensor, which is, however, highly integrated into the cylinder design. Nevertheless, its installation can be optimally adapted to suit the customer's system. In many cases this allows the sensor to be implemented without increasing the retracted length of the cylinder. At the same time, the sensor is protected against manipulation, as it cannot be influenced from the outside, for example by being mechanically separated from the system.

Due to its design, component reliability and the safety measures implemented, the sensor is suitable for requirements corresponding to PLe (EN ISO 13849 [1]). The maximum feasible measuring length for the planned system is approx. 6,000 mm.

1.2 Integrated force measurement

WEBER-HDRAULIK was previously involved in the development of an application-specific solution for integrated cylinder force measurement and currently pursues the further development of integrated supporting force measurement.

To monitor the stability of supported mobile vehicle e.g. cranes, aerial ladders or concrete mixer pumps it would be advantageous to have information about supporting condition. In daily practice, the loading capacity of the supporting base is often unknown since the surrounding condition doesn't allow for a complete outrigging of supporting plates or the load carrying capacity of the ground is limited. The safety can be increased using electronic monitoring system for loading condition. This means the acquisition of outrigger positions as well as the supporting load of each supporting cylinder.

Figure 2: Supporting cylinder with integrated force measurement

The force of supporting cylinder is commonly measured indirectly through the pressure of piston chamber. Although this method is not precise especially that measurement deviation over 20% can occur under transversal loading condition, due to the friction of the sealing system. To assure a safe operation at any given moment, safety factors are required which consequently reduces the available loading capacity of the system.

Using a supporting cylinder with integrated force measurement system, the force will be measured directly on the ball head. Hence, a force gauge was developed that is fully integrated into the piston rod. The measurement signal is transmitted directly through the cylinder and end cap to the crane control system using a standard interface. Consequently, a sensitive and disturbing cable connection outside of piston rod of the supporting cylinder is not required anymore.

The goal of further development of this system is mainly reduction of sensitivity of the system to transversal load as well as enhancement of robustness of the system in the field. An exemplary goal is increasing the allowable transversal load from 10% to 20% of the axial supporting load.

2 Contactless force measurement

Hydraulic cylinder with integrated force measurement is not solely interesting for the supporting application. There are several applications such as force controlled manufacturing processes where the force measurement is required or the performance and finish quality can be enhanced with.

As a reason, WEBER-HYDRAULIK is not only following the development of a new generation of supporting force measurement system but also the development of a universal integrated solution of force measurement for cylinder applications

2.1 Measurement concept

The loading condition of a component can be mainly categorized to tensile, compressional, bending, shear and torsional loading, which are illustrated schematically in the following *Figure 3*.

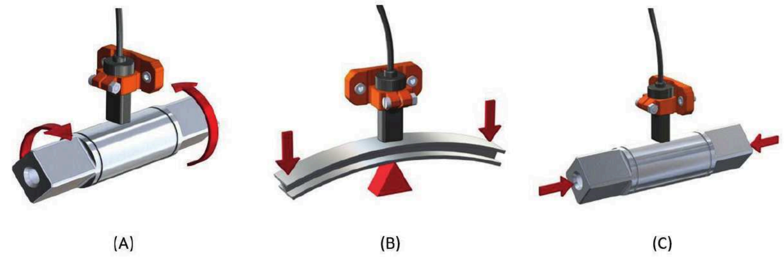

Figure 3: Torsional (A), bending (B), Tensile/Compressional loading conditions

Various methods are developed to measure the loading ranging from strain gauges to piezoelectric crystal. Among them, strain gauges with various executions are widely used in industrial and mobile applications. The requirement of contacting point in this technique is a major disadvantage which makes it liable especially as the component is overloaded. The contactless measurement system developed by TRAFAG GmbH based on the magnetic induction principle is beneficial as the measuring cell is not touching the component. Since the sensor is not directly subjected to forces, the possibility of occurrence of mechanical damage due to the loading (especially by shock and vibration) decreases drastically. Consequently, the degradation of performance due to fatigue can be prevented. The components of the inductive sensor are illustrated schematically in *Figure 4*.

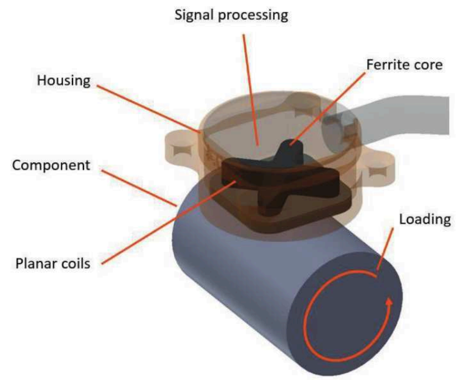

Figure 4: Components of the measurement system

The planar coils generate a magnetic field which penetrates in the component and receives the resulting magnetic field as measurement signal. A ferrite core acts as a magnetic flow conductor to guide direction dependent measurement signals during the loading of the component. The measurement signals are processed directly in the signal processing.

The exciter planar coil generates an alternating magnetic field with a frequency within kHz range. The alternating field is emitted through the ferrite core in the component. The resulting magnetic field of the component induces a current in four signal coils S1 to S4 which are referred as measurement signals which are depicted in the *Figure 5*. Ferromagnetic materials are principally suitable for contactless inductive measurement. The magnetic properties of the material change under a loading as it deforms. This changes the magnetic flux in the signal coils consequently which affects the induced current. These changes show a linear dependency on the applied loads /2/. The sensor calculates the force by measuring these changes. The component shall be dimensioned properly to achieve the desired safety by overloading and to enhance the precision of measurement.

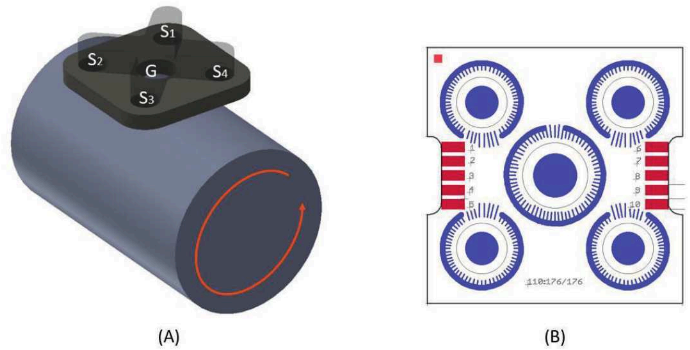

Figure 5: Arrangement of the planar coils to the component (A), top view of the arrangement of coils (B)

2.2 Hydraulic cylinder integration

Through the application of multiple sensor and proper arrangement, one can measure a multiaxial loading condition (e.g. compression and bending). In a preliminary investigation, the sensor was adapted to measure the forces of a hydraulic cylinder with a piston diameter of 110 mm and rod diameter of 90 mm. The rod of the cylinder is made of case hardened 30CrNiMo8 which makes it suitable for inductive contactless measurement. Two different executions are considered in this investigation to find an appropriate assembly for further development. In the first execution form which is depicted in *Figure 6* (B), the sensor housing is attached to the piston rod next to the rod head. Up to four sensor modules are placed circumferentially orthogonal in the housing to consider the effects of the lateral forces. There's a gap of up to 1 mm between the rod surface and the sensor modules. In the second execution form, the sensor housing is mounted at the cylinder gland while the piston rod can slide freely in the housing (Figure 1*Figure 6* (A)). This assembly is beneficial in many applications as the signal/power transmission line doesn't have to compensate the length changes during cylinder's extraction and retraction.

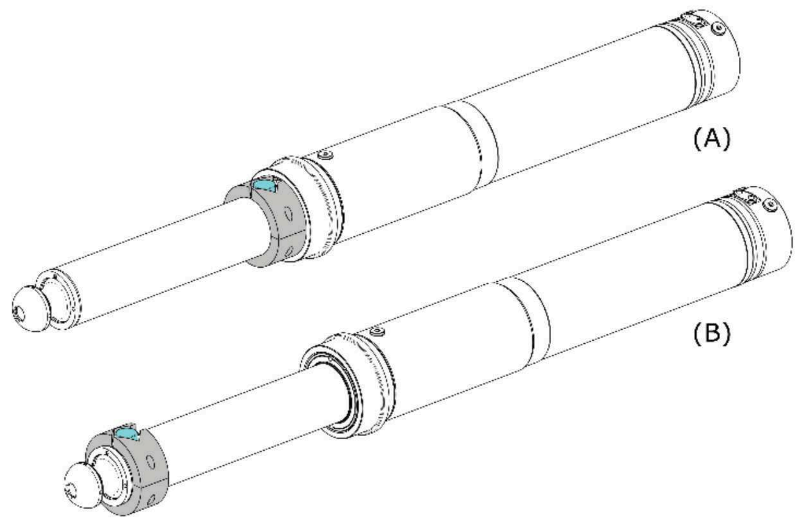

Figure 6: The sensor housing attached to cylinder's gland (A) and to the cylinder's rod (B)

2.3 Concept verification

A series of tests are performed to study the linearity of measurement signal as well as reproducibility of the results. Meanwhile the precision of the measurement results using a contactless sensor can be estimated against the calibrated reference force measurement system. A detailed description of the reference system can be found in section 3.

2.3.1 Rod mount design

First step was to investigate the rod mount design. Performing basic functionality tests, the unfiltered signals of sensors are evaluated using a USB oscilloscope with a downstream amplifier since the prototype modules are not equipped with integrated processing units. A multi-cycle loading program with load steps of 50 kN was applied to the cylinder. The step wise increase of the load in each cycle facilitates the comparison of sensor values and the measurement of a reference system.

1. Loading from 0 to 300 kN and unloading back to 0 kN
   (Reference loading to prevent measurement deviations due to setting effects)
2. Loading from 0 to 300 kN and unloading back to 0 kN
3. Loading from 0 to 300 kN and unloading back to 0 kN
4. Preload of 50 kN with five load cycles between 200 kN and 50 kN

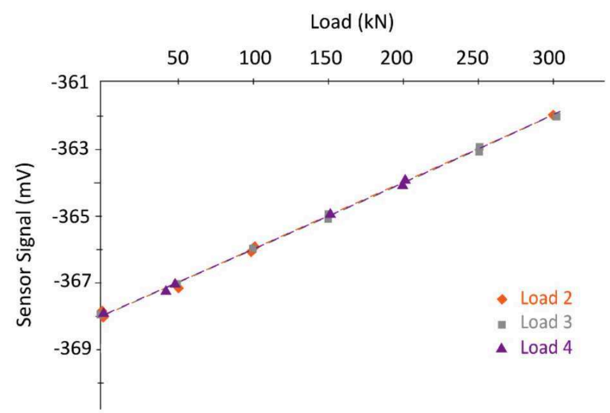

Figure 7: Characteristic curve of the sensor under a multi-cycle loading

The measured characteristic curve of the sensors shows a good linearity as depicted in *Figure 7*. The linear balance lines are used to evaluate each measurement to determine the sensitivity and zero point. The standard deviation of sensitivity is 0.4 %. Not considering the zero offset between the first and second load step, the deviation of offset is ±0.85 kN which correspond to ±0.28 % of the nominal force of 300 kN.

The test results of this study promise applicability of this technique. Combined with design modification such as flat surfaces on the rod the performance of this method may be further improved which makes it a convenient and robust method for direct force measurement.

2.3.2 Gland mounted design

In the preliminary test investigating the gland mount design, the piston rod extracts and retracts without load while the sensor measures continuously. As the piston rod moves, a zero-point offset of up to 800 kN appears which is more than 200 % of maximum loading (*Figure 8*).

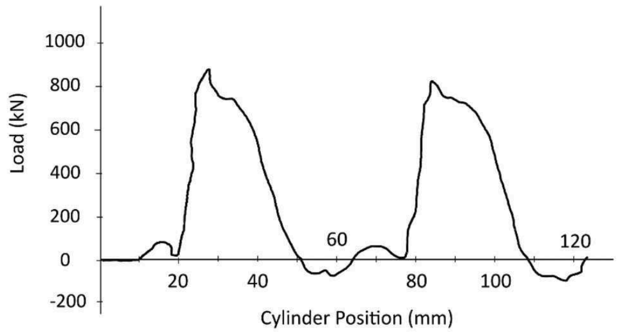

Figure 8: Zero-point offset of the gland mount design

This phenomenon can be caused due to residual magnetism or inhomogeneities of the piston rod. The result suggests an impossible short-term implementation of the gland mount design. But different mid-term approaches are considered. For example, an active rod position based compensation of the zero-point or a compensation facilitated by the application of more sensor elements.

3 New cylinder force test bench

A modern test bench for development and validation was developed as the foundation for an effective implementation of the long-term strategy of WEBER-HYDRAULIK through to intelligent components. The hydraulically driven test bench with reference force measurement has been developed study the repeatability, precision, reproducibly and hysteresis of the new integrated force measurement systems (Figure 9). Equipped with a calibrated reference force measurement system in axial and transversal directions which are capable of measuring axial forces up to 3.000 kN and realizes overall deviations under 0,5 % of the maximum load.

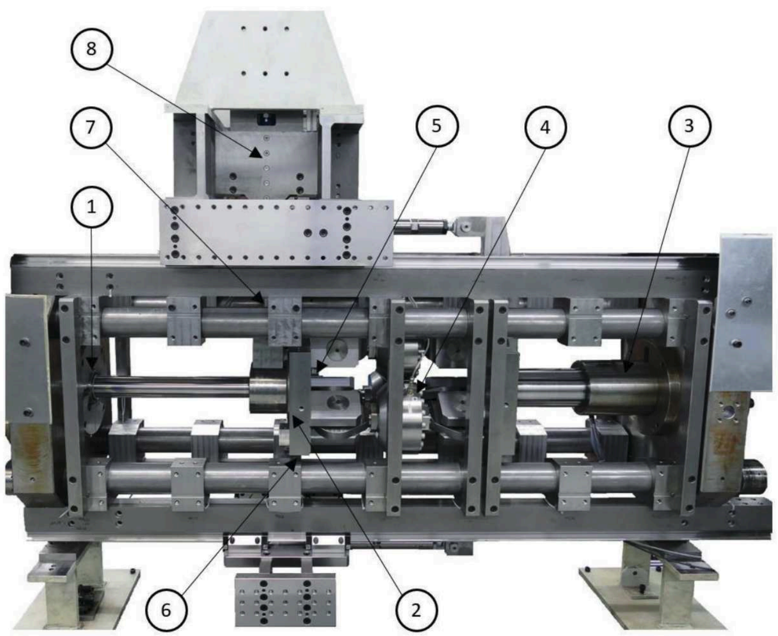

Figure 9: Picture of the new test bench, capable up to 3.000 kN axial force.

The test bench consists of a specimen holder (1) and a force measuring platform (2). The test cylinder is installed in-between where the platform is pivoted to be able to move horizontally. The axial load is exerted using the axial load cylinder (3) which is transmitted over three flexibly connected reference force cells (4) to the force measurement platform. The platform is held in its position by the push rod (5) and loss force cell (6). If the specimen should be loaded transversally a non-positive connection between specimen and force measurement platform is required. When this requirement is met, the transversal force can be transmitted over a transverse force unit (7) and an intermediary force cell (8) where the force cell (6) the loss of transverse force due to friction can be measured.

4 Summary and Conclusion

With the aim of development of intelligent hydraulic components, WEBER-HYDRAULIK has developed an optical position measurement system for mass production. Moreover, the current integrated force measurement for supporting cylinder is developed further to enhance the robustness of the system in field applications. Another development project, which is the focus of this article, is a universal system for integrated force measurement in a hydraulic cylinder. A contactless magnetic induction-based force measurement technique is investigated and different integration concepts are elaborated. Preliminary functional test with sensors attached to the piston rod has shown promising results in term of linear deviation and repeatability. Rest magnetism and irregularities in the piston rod hampers the short-term implementation of the cylinder gland execution which is beneficial from various aspects. Despite the disturbing factors the concept will be follow up and the chances of different compensation method will be investigated.

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