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Novel ultrasonic position sensor for hydraulic clamping cylinders

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Abstract.
Piston position detection for hydraulic actuators is a common task in hydraulic systems. Sensors based on several sensing principles can be found on the market. Nevertheless, a robust and compact solution for short stroke cylinders was missing. To fill this gap, a novel ultrasonic position sensor was designed, built and tested for applications in hydraulic actuators.

Keywords. Clamping position sensing, condition monitoring, clamping cylinder, block cylinder, digitalization in hydraulics, ultrasonic sensing

1. Introduction

Modern industrial production is characterized by a high degree of automation and digitalization. Hydraulic clamping cylinders for automated clamping in machining centers make a significant contribution to efficient and high-quality manufacturing of metal parts such as gearboxes and engine blocks [1].
Until recently, there were no sensors available that could detect and monitor both the clamping status, and the clamping travel of the hydraulic actuators used. In this paper we describe the development of a novel position sensor based on ultrasonic sensing.
The presented sensor enables direct, quick and continuous position measurement in short-stroke hydraulic cylinders up to 80 mm. Additional data for condition monitoring of hydraulic components with quality control for workpieces can be provided. This generates reliable information on the clamping status or piston position and lets the machine operator detect critical deviations or changes in the clamping process or hydraulic system early on. Therefore, the sensor is ideally suited for applications such as swing, lever and vertical clamping cylinders, block cylinders, hydraulic directional control valves, hydraulic chucks and small hydraulic cylinders for precise positioning.

2. Sensing principle: opportunities and Limitations

2.1. Comparison of sensing principles

The goal of this work was the development of a piston position sensor for applications with limited available space. Solutions which need additional space around the hydraulic cylinder were therefore not preferred. Besides, a very compact design is required to avoid damage to the sensor in rugged environments. Since it is not desirable to use add-on parts to transfer the internal piston movement to an add-on sensor outside the cylinder, the measurement should be executed directly inside the cylinder.

Many sensing principles are available for position measurement such as [2]:

- Optoelectronic sensors (triangulation and time-of-flight) using optical lenses are contactless, precise and widely applied in open space but will fail in operation inside the cylinder because of the high-pressure and the opaque hydraulic oil.
- Magnetostrictive contactless sensors [3] provide a robust position detection inside the cylinder up to pressures of several 100 bars but have a poor ratio of the length of the sensor housing to the detection range for strokes < 100 mm.
- Draw wire sensors are prone to wear because of the mechanical movement of the wire.
- Oil flow sensors can provide an indirect indication of the piston position by tracking the oil volume. These sensors are often inserted into the supply line of more than one cylinder and can therefore enable overall monitoring of the status of the hydraulic system only.
- Microwave sensors may be suitable but are not yet available on the market [4].
- Alternately, clamping force sensors may be used for clamping monitoring [5].

As a result, ultrasonic time-of-flight-sensing was chosen as the favourite principle (Figure 1.1).

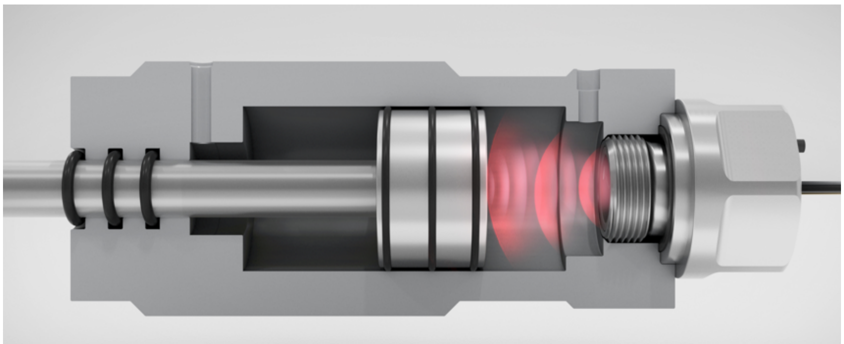

Figure 1.1: Hydraulic cylinder in cross section: rod, cylinder housing with two inlets for hydraulic oil, piston and sensor with cable are shown from left to right. The ultrasonic wave is displayed schematically in red.

2.2. Fundamentals of Ultrasound

Ultrasound is defined as sound in the frequency range of 20 kHz to 1 GHz which is not detectable by human hearing [6]. It can occur in solids, liquids and gases. If particles of a liquid are displaced from their initial position an acoustic wave will propagate through space and time due to the inertia and repulsive forces between the particles. Propagation of sound in matter is one of the fundamental phenomena in physics and may be exploited for technical applications such as sensing. It can be described by the pressure $p(\mathbf{x},t)$ and the sound particle velocity $v(\mathbf{x},t)$ and leads to a set of coupled second-order differential equations. In acoustics as in other physical domains, phenomena such as superposition, interference, attenuation, reflection, refraction and diffraction must be considered.

In liquids, there are only longitudinal waves having a speed of propagation *c* given by (2.1) where *E* is the elasticity and ρ is the density:

$$c = \sqrt{\frac{E}{\rho}} \qquad (2.1)$$

Another important quantity in acoustic systems is the acoustic impedance *Z* given by (2.2).

$$Z = \rho \cdot c \qquad (2.2)$$

If an acoustic wave meets a boundary between two different materials having the impedance Z_1 and Z_2, the wave will be partly reflected and partly transmitted. If p_+ and v_+ are the pressure and the velocity of the incident wave and p_- and v_- of the reflected wave, respectively, the reflection factor *r* is defined by (2.3).

$$r = \frac{p_-}{p_+} = \frac{v_-}{v_+} \qquad (2.3)$$

To fulfil the continuity of pressure and velocity at the boundary, the reflection factor must follow (2.4).

$$r = \frac{Z_1 - Z_2}{Z_1 + Z_2} \qquad (2.4)$$

Table 1 shows the material parameters and impedance of relevant materials. The properties of ceramic are applied for the piezo element.

Property	Hydraulic oil	Steel	Ceramic
Speed of sound *c* [m/s]	1462	5920	10050
Density ρ [g/cm^3]	0.88	7.90	3
Impedance *Z* [Ns/m^3]	$1.29 \cdot 10^6$	$46.77 \cdot 10^6$	$30 \cdot 10^6$

Table 1: Material parameters and impedance of relevant materials

2.3. Ultrasonic Position Sensing

For ultrasonic position sensing, an ultrasonic wave is generated by a wave source such as a piezo element [2]. The emitted wave propagates through the hydraulic fluid inside the cylinder in the axial direction, is reflected by the piston, travels back to the sensor and is finally detected by the piezo element. It results from equation (2.4) and table 1 that approx. 95% of the amplitudes of the incident wave are reflected at the boundary between the oil and piston. The two-way time-of-flight τ_p is acquired by a time-to-digital converter (TDC, chapter 2.5). The piston position s_p is determined from τ_p using equation (2.5).

$$s_p = \frac{c(T,p) \cdot \tau_p}{2} \qquad (2.5)$$

The speed of sound $c(T,p)$ of the hydraulic fluid is dependent on the type, temperature T and the pressure p of the hydraulic fluid.

2.4. Temperature and pressure compensation

To compensate for the temperature and pressure, a second target – the reference target – is designed into the ultrasonic position sensor at a fixed position s_r. The reference target is designed in the shape of a three-armed star and has a fixed distance to the piezo element (Figure 2.1 at the left end of the sensor). The metal structure reflects only a fraction of the ultrasonic wave and allows most of the wave to propagate in the direction of the piston. The speed of sound can be calculated by the central processing unit (CPU, chapter 2.5) by using equation (2.6). The time-of-flight τ_r is obtained from the first echo by the TDC.

$$c(T,p) = \frac{2 \cdot s_r}{\tau_r} \quad (2.6)$$

Therefore, the desired quantity s_p can be continuously determined during the sensor operation by inserting *c(T, p)* into equation (2.5) without any a priori knowledge of the type, temperature and pressure of the hydraulic fluid.

Figure 2.1: Picture of the ultrasonic position sensor

2.5. Sensor design

Figure 2.2 shows the block diagram of the electronic circuitry of the ultrasonic position sensor. The position measurement is controlled by the CPU. An ultrasonic wave is generated by the piezo element which is electrically excited by the transmitter-electronics TX. The TDC starts its timer at the point in time of the wave transmission. After reflection of the wave by the reference target and the piston respectively, the wave is inversely transferred into an electrical signal by the piezo element. The received signal is amplified by the low noise amplifier LNA and the variable gain amplifier VGA. Finally, the signal is compared to a level by the comparator COMP. The VGA compensates for the attenuation of the ultrasonic wave which is dependent on the stroke of the cylinder, the hydraulic oil and the temperature. The output signal of COMP is used as a stop signal for the timer of the TDC. The TDC provides the time-of-flight resulting from the difference between the start and the stop time. After temperature compensation the piston position is calculated by the CPU. Finally, the output stage generates a standardized voltage or current signal proportional to the piston position. Alternatively, the piston position can be digitally transmitted to an IO-Link master [7], [8]. The power block converts the standardized supply voltage of 24 V into 3.3 V to feed the electronic circuitry and ensures electromagnetic compatibility (EMC).

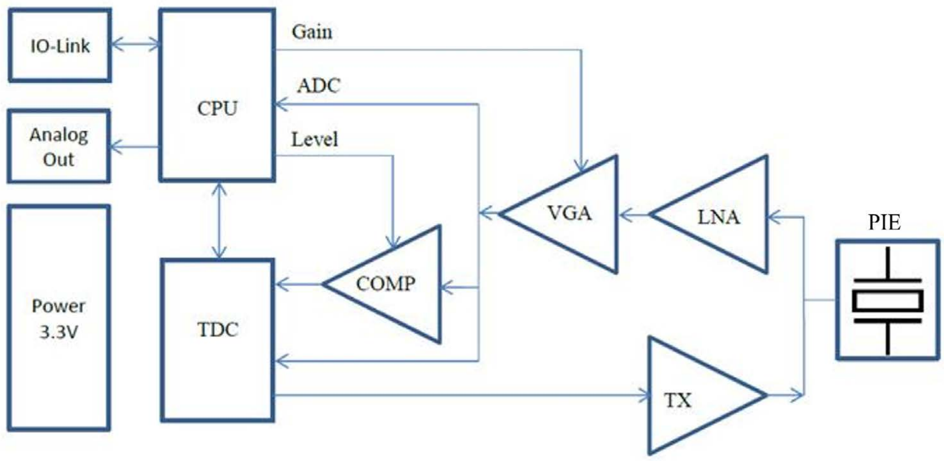

Figure 2.2: Block diagram of the electronic circuitry: CPU central processing unit, TDC Time -to-digital-Converter, COMP Comparator, VGA variable gain amplifier, LNA low noise amplifier, TX transmitter, PIE piezo element

Figure 2.3 illustrates the sensing principle for one measuring cycle. The emitted wave is visible between 0 and 5 µs. A first echo appears at approximately 12 µs resulting from the reference target (Figure 2.1). A second larger echo appears at about 67 µs which corresponds to the piston.

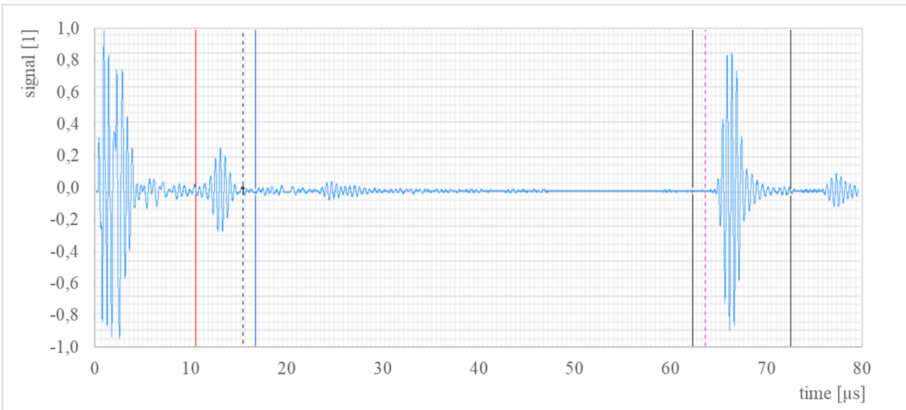

Figure 2.3: Sensor signal of one measuring cycle: x-axis time [s], y-axis normalized signal at the piezo element

Figure 2.4 demonstrates the sensor operation independently of the pressure. The plateaus at 27 mm and 6 mm correspond to the clamped and released state ("open position") of the clamping device, respectively (blue curve). The transient phases of the piston in between these two states can be reliably monitored. The strong increase of the pressure (green curve) in the clamped position to 60 bars does not reduce the accuracy of the sensor output.

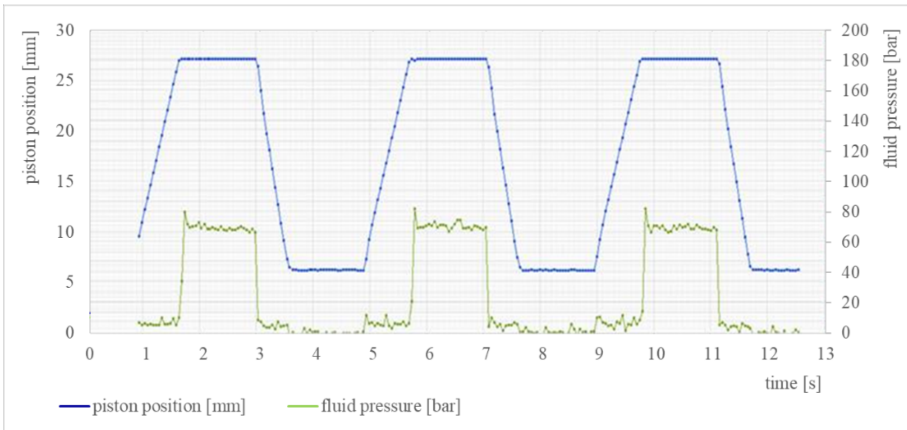

Figure 2.4: Sensor output: Piston position [mm] (blue curve) and fluid pressure [bar] (green curve) plotted during three clamping cycles as a function of time [s]

During the development of the sensor, a non-immersive solution was investigated. The sensor would not be wetted by oil. Instead, the sensor would be assembled behind the cylinder end wall (right side in Figure 1.1) outside the cylinder. This setup has some advantages for the cylinder manufacturer. Unfortunately, in this case about 95% of the wave amplitude is reflected at the boundary between the steel end wall and oil inside the cylinder (chapter 2.2). Consequently, the wave will travel back and forth inside the end wall and will superimpose on the piston echo. This will lead to a degradation in the quality of the measurement. Therefore, an immersive setup was finally chosen (Figure 1.1).

Additional measures have been taken to reduce the reflections at the boundary between the piezo element and the oil. However, a detailed description is beyond the scope of this publication.

2.6. Performance and limitation of the ultrasonic position sensor

The ultrasonic position sensor provides a selectable analogue voltage or current output (0…10V or 4…20 mA) and an IO-Link interface [7]. IO-Link is predestined as a digital, bidirectional, peer-to-peer communication system to support the configuration of the sensor and the transmission of sensor data [8] [9]. Table 2 lists the performance characteristics of the ultrasonic position sensor.

The limitation of the measurement range to currently < 100 mm is caused by attenuation of the ultrasonic wave, which leads to decreasing signals for long strokes. The maximum measuring rate is limited by the time-of-flight inside the cylinder. A new measurement cycle can be started after the arrival of the previous echo only considering the maximal measuring range. Noise will also limit the effect of the temperature and pressure compensation because short pressure peaks which appear in the hydraulic system must be acquired without filtering or averaging.

Performance characteristic	Value
Measuring range	0…80 mm
Pressure rating max.	350 bar
Burst pressure	455 bar
Dimension	∅ 30 x 30.9 mm
Sensor housing material	1.4104
Measuring rate max.	500 Hz (digital) 1000 Hz (analog)
Non-linearity max.	± 250 µm
Repeat accuracy	± 50 µm
Temperature drift max.	5 % full scale

Table 2: Performance characteristics of the ultrasonic position sensor [7]

The typical output characteristic at room temperature is shown in figure 2.5.

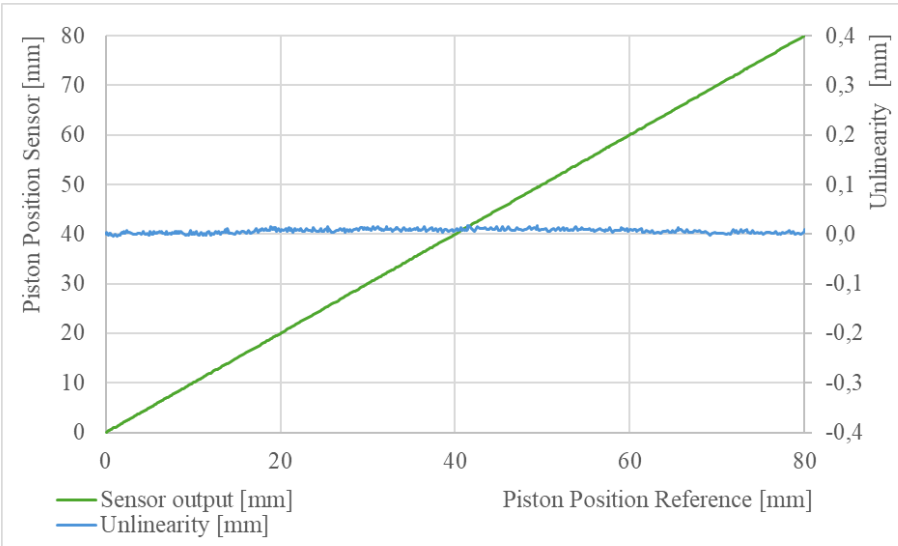

Figure 2.5: Output characteristic during travel over the full piston stroke of 80 mm. Piston position sensor [mm] (green curve) and unlinearity [mm] (blue curve)

3. APPLICATIONS FOR SWING CLAMPING CYLINDERS

Figure 3.1 represents a typical swing clamping cylinder. The hammer at the upper end of the piston rotates by 90° during its vertical movement to allow the workpiece to be placed in the "open position". The ultrasonic position sensor provides information of the clamping status for high-efficiency PLC-controlled manufacturing in machining centers (figure 3.2).

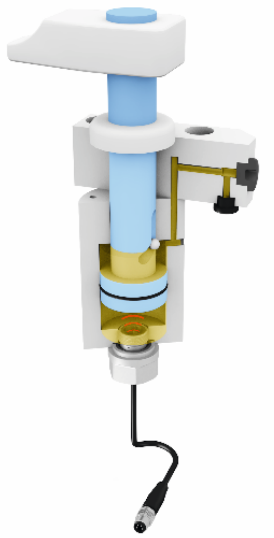

Figure 3.1: Swing clamping cylinders: The ultrasonic position sensor is attached to the end face. The piston is equipped with a hammer to clamp the workpiece.

The automated manufacturing process consists of the main following steps:

1. Picking of the raw workpiece by the worker, a robot or an automated device from a tray or another container
2. Transport of the workpiece into the workspace and placement on the workbench of the machining center
3. Clamping of the workpiece by the clamping cylinder. The clamping cylinder should travel from its "open position" until "clamped with workpiece" which causes a mechanical stop.
4. Machining process such as milling, grinding or drilling. High forces and torques are applied to the workpiece during this step.
5. Releasing of the workpiece by the movement of the clamping cylinder to the "open position"
6. Picking of the processed workpiece by the worker, a robot or an automated device from the workbench
7. Transport of the workpiece out of the workspace and placement into a container of the processed workpieces

Several possible situations may occur after the clamping in step 3:

a. The workpiece is correctly inserted and clamped. The clamping position of the clamping cylinder (“clamped with workpiece”) is in the predefined range. Step 4 may be executed.
b. The workpiece is not placed at all due to faulty execution of the preceding steps. The clamping cylinder travelled too far to a position “clamped without workpiece”. The preceding steps 1 and 2 must be repeated.
c. The workpiece was placed at the wrong position and is consequently not clamped correctly
d. An incorrect workpiece was placed and is consequently not clamped correctly.
e. The workpiece is placed at the correct position but was not clamped.

Cases c, d and e may cause severe damage of the workpiece and the machining center in step 4 and leads to production downtime and high reject rates. By monitoring the entire clamping process, it is also possible to detect pressure fluctuations in the hydraulic unit, defects in the swivel mechanism and defective seals. Thus, the integration of the ultrasonic position sensor can help to prevent damage and downtime in the daily production process.

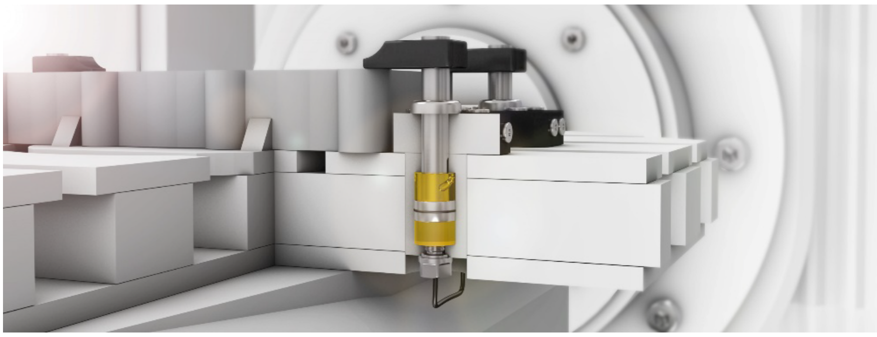

Figure 3.2: Machining center: Two swing clamp cylinders integrated in the workbench are visible. The cylinders are in the position “clamped with workpiece”

Polymer injection molding machines are another application for ultrasonic position sensors. Block cylinders are used in these machines to eject the molded part or to move inserts during the molding process. Ultrasonic position sensors can monitor this movement for process quality improvements and condition monitoring.

4. CONCLUSION

Ultrasonic sensing is a suitable principle for continuous, accurate and quick detection of piston position for short stroke cylinders. Modern electronic components, materials and compensation algorithms enable a compact and cost-efficient design for applications in machining centers and other automated machines. IO-Link makes it possible to achieve an excellent user experience during commissioning and configuration of the ultrasonic position sensor. The performance characteristics that are achieved have the potential to make this new type of sensor a game changer in position detection of short-stroke hydraulic cylinders and condition monitoring of the clamping process in factory automation.

5. REFERENCES

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Biographies

Markus Fritton completed his apprenticeship successfully in communication electronics with Balluff GmbH, Neuhausen, Germany, in 1993. He received the qualification as state certified technician in communication engineering from the DAA-Technikum, Würzburg, Germany, in 1998. He is currently working as a senior engineer at the Innovation Department of Balluff GmbH.

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Albert Dorneich received the degree of Dipl.-Phys. in physics from University of Stuttgart in 1998. He is employed as a Technology Strategy Manager at the Innovation Department of Balluff GmbH in Neuhausen, Germany. He has been a member of the IEEE for 18 years and is currently a senior member. He serves as a member of the board of trustees of the Institut für Mikroelektronik Stuttgart (IMS Chips). His R&D activities include new and well-known sensor principles such as inductive, radar and ultrasonic as well as industrial RFID and wireless communication for use in production. He is the author of several reviewed conference and journal papers and holds various patents.