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Non-Invasive Ultrasonic Measurement of Piston Position in High-Pressure Hydraulic Cylinders

J. Elsner[1] *and K.S. Drese*[1]
[1]*Coburg University of Applied Sciences and Arts, ISAT – Institute of Sensor and Actuator Technology, Coburg, Bavaria, Germany*
jakob.elsner@hs-coburg.de

Abstract: This work introduces a non-invasive ultrasonic method for accurate piston position measurement in high-pressure hydraulic cylinders. By analyzing time-of-flight shifts using externally mounted transducers, it enables precise tracking without coming into contact with the pressurized fluid. This prevents sealing issues, minimizes contamination risks, and reduces maintenance effort. The method achieves sub-millimeter accuracy over an 80 mm stroke. Experiments confirm its robustness and industrial applicability.

Keywords: ultrasonic position sensing, piston position measurement, high-pressure hydraulic cylinders, non-invasive monitoring, time-of-flight analysis

Introduction

High-pressure hydraulic cylinders are critical components in industrial automation, especially in systems requiring reliable control and high-precision motion feedback. In many applications, such as automated cable cutting, piston position must be determined with high accuracy and robustness to ensure safety and process quality. Conventional position measurement techniques, such as magnetic field sensors or magneto-inductive methods [1], [2], often require significant changes to the cylinder design and may be susceptible to electromagnetic interference. Optical distance sensors [3], though externally mountable, are sensitive to contamination and reflective disturbances, limiting their suitability in harsh environments. Existing ultrasonic methods [4]–[6], while promising, typically rely on structural modifications such as windows or recesses in the cylinder wall, which are unsuitable for high-pressure applications.

To address these limitations, we present a novel non-invasive ultrasonic method for real-time piston position tracking that eliminates the need to access the hydraulic fluid directly. The approach relies on externally mounted piezoelectric transducers that generate and detect ultrasonic waves propagating through the piston rod and cylinder structure. This method requires no modifications to the pressure chamber, enabling easy integration into existing hydraulic systems while withstanding variable pressure and temperature conditions common in industrial environments. A robust algorithm and a stand-alone hardware enable real-time measurement and end-position detection of the hydraulic cylinder, offering a promising alternative to traditional invasive and non-invasive measurement techniques.

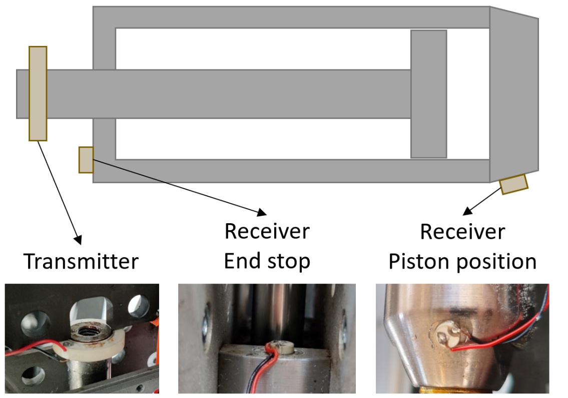

Fig. 1: Schematic representation of the experimental setup of the piston, including the positions of the three acoustic transducers.

The main objectives of this work are:

- To achieve real-time, sub-millimeter accurate piston tracking over the full stroke.
- To enable robust mechanical end-stop detection under varying environmental conditions.

Materials and Methods

The method employs piezoelectric ultrasonic transducers arranged on the exterior of the piston rod and the cylinder, as shown in Fig. 1. Two transducers are used in a transmitter-receiver configuration. The ultrasonic wave generated by the first transducer travels along the piston rod, propagates through the seal region, and is partially transmitted to the piston head, which guides the wave toward the second transducer. As the piston moves, the acoustic path length changes,

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resulting in a measurable shift in the time-of-flight (ToF) of the received signal. The piston position can be calculated based on this shift.

Due to hardware constraints of the final stand-alone electronics, the transmitted signal was designed as a sequence of five rectangular pulses at a center frequency of 330 kHz. This frequency was chosen because it yielded the highest signal amplitude during preliminary testing, resulting in an optimal signal-to-noise ratio. However, other tested frequencies within the range of 100 kHz to 500 kHz showed comparable performances.

The spectral components outside the central frequency - particularly low- and high-frequency components introduced by the rectangular pulses - were subsequently filtered from the received signal using a Butterworth band-pass filter centered around 330 kHz.

The transmission was performed using a function generator (Agilent 33521A) with an amplitude of 20 V_{pp}. The received signals were first amplified by 20 dB and then recorded using an oscilloscope (LeCroy HDO6034).

Data acquisition was carried out at intervals of 25 ms, resulting in 800 individual measurements over a total duration of 20 s. During this period, the piston advanced, pressure was built up to its maximum value, and the piston subsequently retracted.

The reference measurement of the piston position was taken using a linear potentiometer, which was measured synchronously with the ultrasonic data.

An example of the measured time-domain signal is shown in Fig. 2a. The eight zero-crossings used to determine the time-of-flight shift are marked. As shown in Fig. 2b, there is an approximately linear relationship between the actual piston position and the measured ToF shift.

Temperature also influences the speed of sound, and therefore affects the signal's time-of-flight. In the temperature range considered here (-5° C to 50 °C), the effect can also be approximated as linear. Based on this, the following linear model is used to estimate piston position from the ToF shift:

$$x_{lin}(t_0, ..., t_7) = \frac{1}{\gamma_t} \cdot \tau_{mean}$$

$$\text{with } \tau_{mean} = \frac{1}{8}\sum_{i=0}^{7} t_i - \frac{i}{f} - \alpha_T \cdot T - t_{0,\,0°C}$$

Here, t_i denotes the position of the i-th zero-crossing. The ToF gradient $\gamma_t = 0.39\,\frac{\mu s}{mm}$, the temperature correction coefficient $\alpha_T = 0.014\,\frac{\mu s}{°C}$, and the zero-crossing position $t_{0,\,0°C} = 57.1\,\mu s$ at 0 °C were determined from experimental data using a least-squares fit. The parameters were optimized for the extending stroke of the piston, as this part is the more

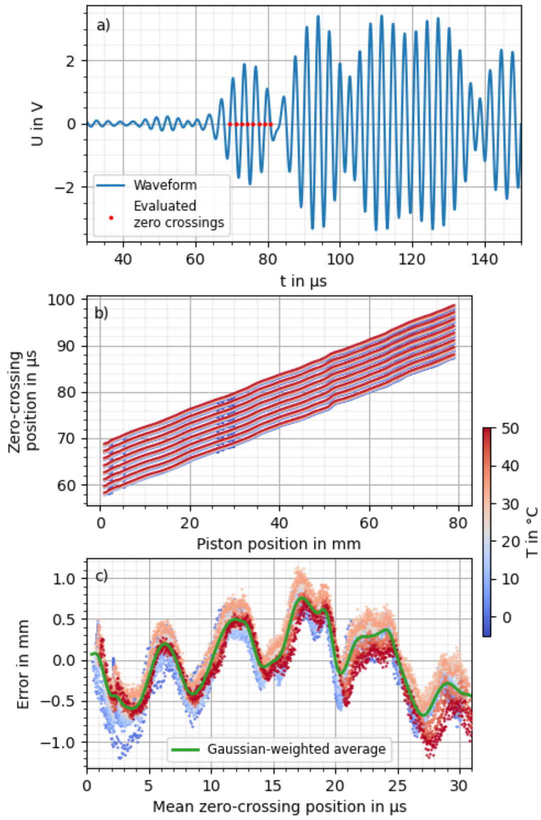

Fig. 2: a) Representative measurement signal used to determine the piston position, with indicated zero-crossings utilized for evaluation. b) Position of the evaluated zero-crossings as a function of piston position and temperature. c) Error of the linear model for piston position estimation as a function of zero-crossing displacement and temperature, including the Gaussian-weighted average of this error.

safety-critical motion. For the excitation frequency f, a value of 330 kHz was used, corresponding to the signal frequency applied during transmission. The resulting coefficient of determination, $R^2 = 0.9997$, indicates excellent agreement between the model and the observed measurements, showing that piston position can already be predicted with high accuracy.

The residuals of this linear model are shown in Fig. 2c. It can be seen that the residuals are nearly independent of temperature, which confirms that the linear temperature correction generalizes well. However, the residuals are not randomly distributed but follow a wave-like pattern. This trend is also visible in the oscillations of the ToF shift in Fig. 2b.

To improve prediction accuracy, the linear model was extended by adding a nonlinear component $K(\tau_{mean})$, resulting in a hybrid model. To estimate the nonlinear part, a weighted moving average of the

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residuals was calculated for each piston position using a Gaussian kernel with a standard deviation of 0.3 µs. This correction term is shown in green in Fig. 2c and is added to the linear model.

The final hybrid model is thus defined as:

$$x_{hyb}(t_0, ..., t_7) = x_{lin}(t_0, ..., t_7) + K(\tau_{mean})$$

The prediction accuracy of this model is analyzed in more detail in the following section.

A third transducer was added near the mechanical end-stop of the piston stroke for clear identification of the piston reaching its limit position. The detection of the mechanical end stop using the third ultrasonic transducer proved to be more reliable than estimating it indirectly through the piston position. Position-based detection is always subject to some measurement uncertainty, which makes it difficult to clearly distinguish between a position close to the end stop and the actual contact.

The end stop is detected by analyzing the root mean square (RMS) of the received signal, representing the signal energy. When the piston hits the end stop, additional acoustic paths are created on the rear side of the piston, in addition to the existing sound transmission through the piston seal. These additional paths increase the acoustic excitation of the cylinder, which results in a noticeable increase in the measured signal energy and the system can reliably detect the end-of-stroke condition, which is crucial in safety-critical processes such as cable cutting.

The selected time window of the ultrasound signal was optimized to meet two criteria: first, to maximize the difference in RMS values between the two states to be distinguished, and second, to make the window as large as possible to improve robustness against noise. Both conditions are best fulfilled with a time window ranging from 0 to 80 µs.

Results

The dual-transducer setup, combined with optimized signal processing and the hybrid model, demonstrated high accuracy and repeatability. Within the tested stroke range of 80 mm, the final model achieved a maximum absolute error of 0.78 mm and a standard deviation of 0.18 mm during the extending stroke.

As the model was optimized for the piston's extending stroke, slightly higher deviations were observed during the return stroke. The maximum absolute error in this case was 1.04 mm, with a standard deviation of 0.23 mm. These error distributions are shown in Fig. 3a. Additionally, the return stroke error distribution exhibits an offset of approximately 0.22 mm. This hysteresis-like behavior can also be observed in the position-dependent model error illustrated in Fig. 3b and 3c.

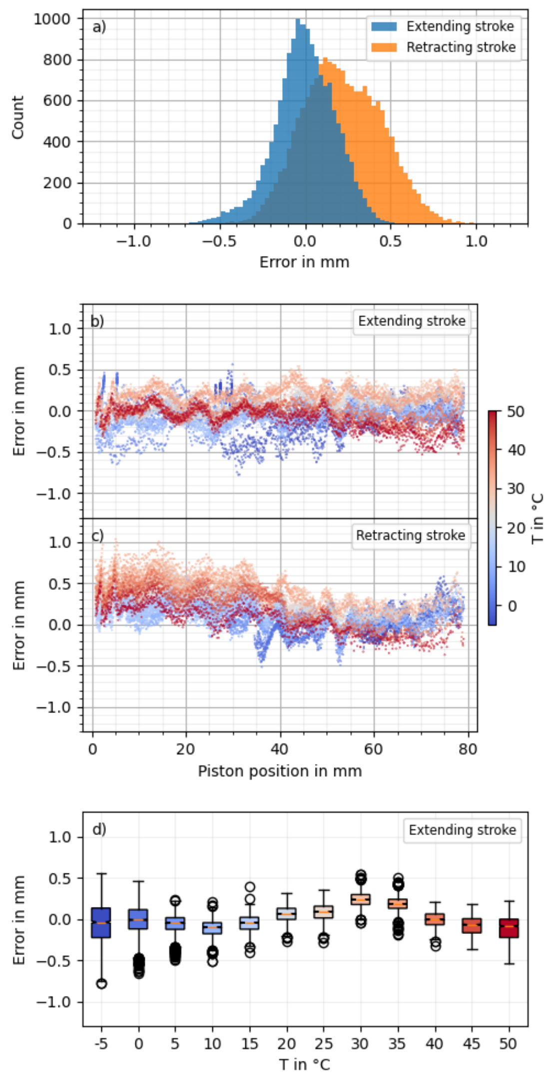

Fig. 3: a) Error distribution of the piston position predicted by the hybrid model for the extending and retracting stroke. b) & c) Error distribution of the predicted piston position as a function of the actual piston position and temperature for the extending (b) and retracting stroke (c). d) Boxplot of the prediction error of the hybrid model during the extending stroke as a function of temperature.

This is likely caused by mechanical play or slight deformation of the piston seal due to the direction of motion. This leads to a minor offset in the signal response for identical piston positions, depending on the motion direction.

As shown in the temperature-dependent error distribution in Fig. 3d, the model performs best at typical ambient temperatures around 20 °C, where a standard deviation of 0.09 mm and a maximum absolute

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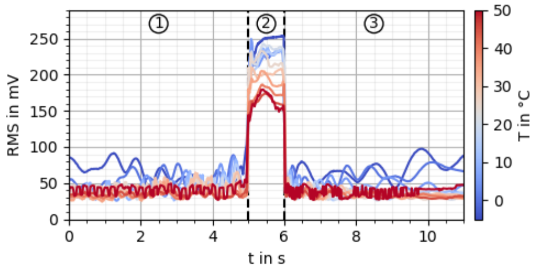

Fig. 4: RMS value of the end-stop receiver as a function of time and temperature. Three phases are highlighted: (1) Initial piston position and extending stroke, (2) Reaching the end-stop and pressure buildup in the piston, (3) Retracting stroke of the piston with partial return to the initial position.

error of 0.32 mm were observed. At the temperature extremes of -5 °C and 50 °C, the prediction accuracy decreases slightly, with standard deviations of 0.24 mm and 0.11 mm, and maximum absolute errors of 0.78 mm and 0.54 mm, respectively. Therefore, for most practical applications, the actual accuracy is even better than the overall error values reported above.

Incorporating temperature as an additional input to the nonlinear error correction term $K(\tau_{mean}, T)$ could potentially improve performance at the extremes. However, a temperature-independent correction was chosen to simplify calibration and implementation.

The detection of the mechanical end-stop was based on RMS signal energy, which increased significantly when the piston made contact with the cylinder boundary. As shown in Fig. 4, the difference in RMS levels between contact and non-contact states was pronounced and consistent across all tested temperatures.

However, the absolute RMS values decreased with rising temperature. To maintain detection reliability, a temperature-dependent threshold was implemented, which dynamically adjusts the RMS threshold RMS_{thr} based on real-time temperature.

$$RMS_{thr} = 157\,\mathrm{mV} - 1\,\frac{\mathrm{mV}}{\mathrm{°C}} \cdot T$$

This approach enabled a highly reliable binary classification of end-stop states over the full tested temperature range from -5 to 50 °C.

Conclusion

This work presents a fully non-invasive ultrasonic measurement system capable of accurately determining the position of a piston in a high-pressure hydraulic cylinder. The method, based on externally mounted bulk wave transducers, avoids fluid contact and eliminates the need for structural modifications.

The key contributions of this work are:

- A dual-sensor ToF-based measurement approach with sub-millimeter accuracy.
- A temperature-compensated hybrid model for improved accuracy.
- Reliable end-stop detection through RMS signal energy analysis and dynamic thresholding.

The system was experimentally validated under variable thermal conditions and demonstrated excellent reliability, paving the way for industrial application in safety-critical systems. Its low maintenance, high accuracy, and modularity make it particularly attractive for retrofitting existing hydraulic systems without requiring structural changes.

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