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The Measurement Method of a Piston Fall Rate

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Abstract: The accurate determination of the piston fall rate is one of critical parameters in dead-weight testers and piston gauges, as it confirms a quality of machining, instrument accuracy class, and long-term stability. This study introduces a method for determining piston fall rate using two triangulating laser distance sensors. This approach offers versatile applicability, in high-precision standards as well as in regular-class instruments, and is robust in accommodating variations in measurement ranges, pressure transmitting mediums, materials of weights, and weight diameters. The method utilizes two laser sensors symmetrically positioned under the primary weight of the piston pressure gauge, allowing for seamless measurements without the need for sensor adjustments. The data collected from these sensors are processed to calculate the average displacement of the primary weight. The method's effectiveness is demonstrated with high linearity and precision in determining the piston weight fall rate. This approach can lead to improvements in fluid dynamics analysis and metrology of precise pressure balances. The method's advantages include error mitigation and reduced operator intervention, making it highly suitable for applications requiring accurate piston descent velocity measurements, particularly in older measuring instruments. The establishment of a reference dataset can enhance the accuracy of periodic examinations of piston-cylinder assemblies, thereby reducing costs and improving measurement quality.

Keywords: piston fall rate, pressure balance, piston gauge, piston-cylinder unit

1. Introduction

One of the crucial parameters of piston-cylinder assembly used in dead-weight testers and piston gauges is the piston fall rate. Specified intervals of this element prove the machining quality, determine the instrument's accuracy class and confirm long-term stability [11]. Fall rate characteristic indicates range [3] and construction of piston-cylinder assembly, and is used to verify the results obtained from calculations using analytical mathematical methods [5]. This parameter is inseparably correlated with the flow of the medium transmitting pressure in the gap between the piston and the cylinder of the measuring assembly [9, 10]. Proper determination of piston fall rate makes cross-float calibration more precise and repeatable but is also crucial for determining effective cross-sectional area using other methods [7, 8].

This study aims to introduce a method of determining piston fall rate utilising two triangulating laser distance sensors. As a result, it enables data analysis for convenient and versatile implementation in a wide range of routine calibrations. The proposed solution can be applicable in maximum cases concerning standards of the highest precision and regular class instruments. The method's functionality is robust to the diversity associated with measurement ranges, pressure transmitting medium, materials of which weights are manufactured, different weights' diameters and so forth. This article covers the technical idea for a measurement system, data processing methods, and final result evaluation.

2. State of the art

There are several acknowledged methods of piston fall rate determination. Visual-based methods involving image analy-

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sis are fairly universal [2]; nevertheless, they lack precision, resulting in difficult-to-estimate measurement errors and relatively high uncertainty. On the other hand, various distance sensors (i.e., capacity, laser or confocal sensors) offer exquisite accuracy, but their application is much narrower [1]. Usually, they demand certain technical conditions for proper measurement, and need to fit ideally for various design solutions among piston gauges. Moreover, their use is inconvenient in many cases during practical application since moving the sensor along with applying subsequent weights is required [9].

The most commonly employed solution for sensor displacement positioning involves placing the measuring device in a manner that enables measurements along the axis of the measuring piston rotation above the primary weight [10, 11]. This approach ensures that imperfections in the fabrication of the weights utilised at subsequent pressure measurement points have no impact on the measurements – wobble is minimised. However, the primary drawback is the operational complexity of the load-piston pressure gauge. It necessitates the frequent disassembly and reassembly of the sensor when applying reference weights due to the relatively limited operational range of the length sensor. Consequently, this extends the measurement process and potentially introduces unknown errors caused by the risk of altering the measurement axis at each successive measurement point. Furthermore, as the stack of reference weights grows, the length sensor must be progressively elevated, which compels the adoption of the intermediate component to define the reference point, thereby introducing additional possibilities of errors arising from the nonlinearity of the length sensor.

3. Methodology

The general idea of the proposed method for piston fall rate measurement is presented in Figure 1a, whereas the photography of the measuring stand is presented in Figure 1b. The measuring stand consists of the pressure pump (3), standard cut-off valve (4) and pressure balance under test (6).

The method is based on utilising two laser-based triangular length sensors (type: optoNCDT, model: ILD1420-25, producer: Micro-Epsilon Messtechnik GmbH & Co. KG) positioned beneath the primary weight of the piston pressure gauge, as it is presented in figure 2. These sensors are symmetrically arranged in relation to the piston axis. This configuration of measuring sensors ensures that the operation of the pressure gauge does not require any adjustments to the working position of the length sensors. Consequently, subsequent measurement points can be executed seamlessly without the risk associated with displacing the length sensors.

Laser sensors employed in the measurement setup feature a measurement range of 0–25 mm with a readout capability at a frequency of 4 kHz. Such a measurement range allows the setup to be utilised for examining practically any piston gauge.

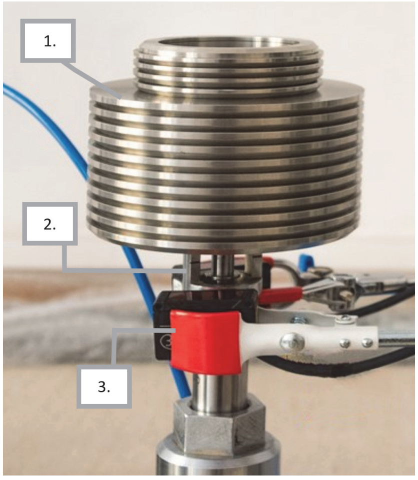

Fig. 2. Sensors close-up presenting location: 1 – pressure balance under test, 2, 3 – laser distance sensors
Rys. 2. Zbliżenie umiejscowienia czujników: 1 – badany ciśnieniomierz obciążnikowo-tłokowy, 2, 3 – laserowe czujniki przemieszczenia

Sensors are connected to a dual-channel controller, which enables uniform control of the sensors and ensures synchronised data collection. It also interfaces with the computer, allowing the LabVIEW application to conveniently manage the entire measurement system.

Average displacement D_a of the primary weight of the piston pressure gauge can be calculated as:

$$D_a = (D_1 + D_2)/2 \tag{1}$$

where D_1 and D_2 are the measuring signals from the first and second laser positioning sensor respectively.

It should be highlighted that combining readings collected from two independent laser positioning sensors located on the opposite sides of the primary weight of the piston pressure gauge, considering calibration corrections, will ensure the elimination of systematic errors arising mostly from the shaft

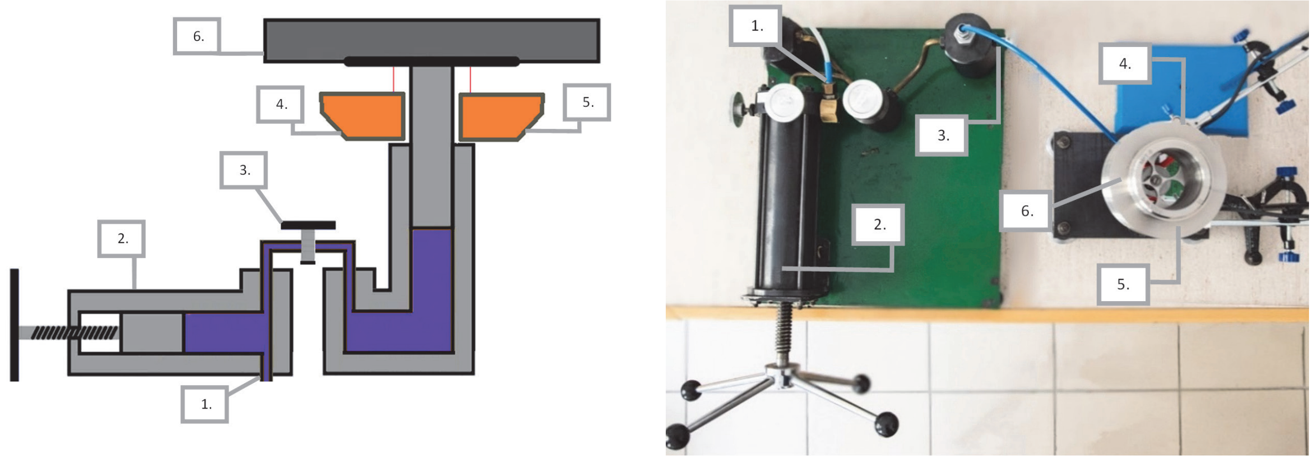

Fig. 1. Measurement stand: a) schematic diagram, b) photography. 1 – pressure inlet, 2 – pressure pump, 3 – standard cut-off valve, 4, 5 – laser sensors (under weights), 6 – pressure balance under test
Rys. 1. Stanowisko pomiarowe: a) schemat, b) zdjęcie. 1 – ciśnienie zasilające, 2 – pompa, 3 – zawór odcinający, 4, 5 – czujniki laserowe (pod obciążnikami), 6 – badany ciśnieniomierz obciążnikowo-tłokowy

position errors and runout, shape imperfections of the primary weight and the hysteresis effect.

4. Results

The measurements were conducted using different piston gauges with a simple piston-cylinder assembly, without a drive mechanism, utilising gas or oil medium. The data has been gathered using a computerised system controlled by LabVIEW software. Figure 3 presents an example of data collected from two laser sensors D_1 and D_2, positioned symmetrically with respect to the piston rotation axis and with starting point correction applied.

The data obtained from two individual sensors can be further examined either separately or averaged as an outcome by interpreting correlated data. In the second scenario, the potential exists to attain error correction effects originating from the geometry of the basic weight. Figure 4 shows the averaged displacement D_a registered by two separate sensors D_1 and D_2. It is clearly visible that signals D_1 and D_2 exhibit shaft position errors and runout together with shape imperfections. The systematic error observed in signals D_1 and D_2 presents the phase inversion (clearly visible in Figure 3) caused by the rotation of the weight of the piston pressure gauge. These errors are suspended by the averaging of the D_a signal. As a result, a more smoothed plot is shown, which demonstrates that the combination of signals can largely eliminate repetitive irregularities on the lower surface of the base weight.

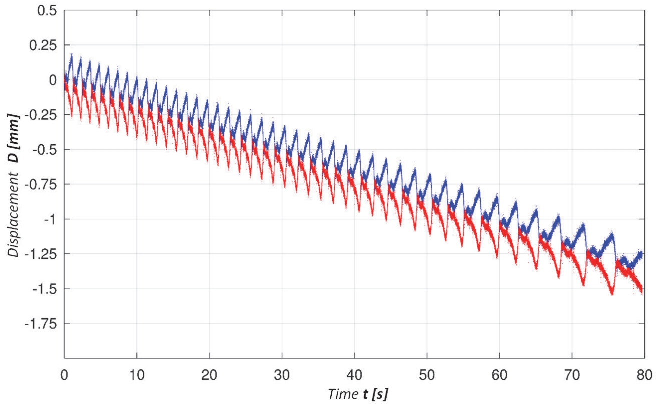

Fig. 3. Results of displacement measurements during the experimental setup operation: red – the first position sensor D_1, blue – the second position sensor D_2

Rys. 3. Wyniki pomiarów przemieszczenia podczas działania eksperymentalnego układu: czerwony – pierwszy czujnik przemieszczenia D_1, niebieskie – drugi czujnik przemieszczenia D_2

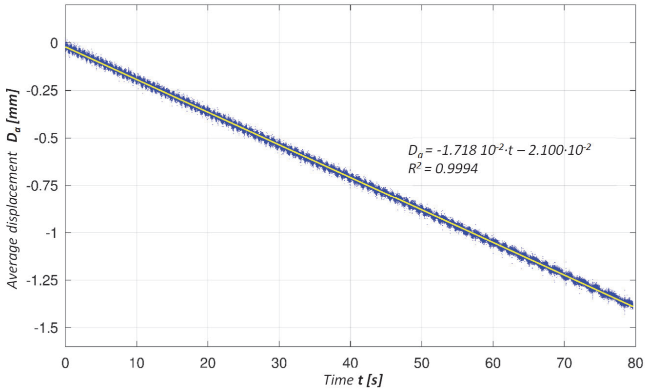

Fig. 4. Average displacement D_a from both position sensors (blue) and its linear approximation (yellow)

Rys. 4. Średnie przemieszczenie D_a z obu czujników położenia (niebieski) i jego liniowa aproksymacja (żółty)

It should be highlighted that averaged displacement D_a exhibits strong linearity, confirmed by determination coefficient R^2 exceeding 0.9994. For this reason, on the results presented in Figure 4, the piston weight fall rate can be precisely determined as $1.718 \cdot 10^{-2}$ m/s. Linearity of the D_a signal together with the possibility of precise determination of the piston weight fall rate, enables further analyses of fluid dynamics and metrology of precise pressure balances.

5. Conclusion

The proposed method of measurement of piston weight fall rate utilising two laser-based positioning sensors provides improved reliability and shorter measurement time, making it well-suited for applications requiring precise and dependable piston descent velocity measurements. The key strength and advantage of the selected solution is the ability to mitigate systematic errors associated with shaft position errors and runout, together with shape imperfections and hysteresis effects. Another advantage is limiting the manual labour of the operator, and reduction of adjustment time for different measured pistons. The method proposed in this article has never been presented in the literature before.

The results presented in the paper confirmed the high effectiveness of the applied fall rate measurement solution, even for older measuring instruments, whose calibration is relatively most widespread. Furthermore, the acquired results can undergo subsequent numerical processing to accurately determine the parameters of the piston fall rate, considering both the average and single sensor signal. The implementation of such an approach holds the potential to enable the detection of irregularities in the operation of the examined piston gauge, such as deformation, leak, proper levelling or cleanliness.

Ultimately, gathering comprehensive data concerning all measurement piston gauge parameters enables the establishment of a reference dataset that can be employed for the assessment conducted during periodic examinations of piston-cylinder assemblies. This will reduce costs and increase the accuracy of required periodic examinations.

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Metoda pomiaru prędkości opadania tłoka

Streszczenie: Prędkość opadania tłoka stanowi jeden z kluczowych parametrów w zespołach pomiarowych ciśnieniomierzy obciążnikowo-tłokowych, ponieważ świadczy o jakości wykonania, klasie dokładności urządzenia oraz rzutuje na stabilność długoterminową. Niniejsza praca przedstawia metodę określania prędkości opadania tłoka za pomocą dwóch triangulacyjnych laserowych czujników przemieszczenia. To podejście cechuje wszechstronna przydatność, zarówno we wzorcach o najwyższej precyzji, jak i w przyrządach roboczych, jak również jest uniwersalne bez względu na zakresy pomiarowe, rodzaje mediów przekazujących ciśnienie, materiały obciążników i ich wymiary. Metoda ta wykorzystuje dwa czujniki laserowe, umieszczone symetrycznie pod obciążnikiem podstawowym ciśnieniomierza, co pozwala na pomiary bez konieczności regulacji ustawienia czujników. Dane zbierane przez te czujniki są przetwarzane w celu obliczenia średniego przesunięcia obciążnika podstawowego, a co za tym idzie tłoka. Skuteczność metody jest potwierdzona wysoką liniowością i precyzją w określaniu prędkości opadania tłoka. Zaletami metody są eliminacja błędów oraz ograniczenie ingerencji operatora, co sprawia, że jest ona szczególnie odpowiednia do zastosowań wymagających dokładnych pomiarów prędkości opadania tłoka, zwłaszcza przy starszych przyrządach pomiarowych.

Słowa kluczowe: prędkość opadania tłoka, ciśnieniomierz obciążnikowo-tłokowy, zespół tłok-cylinder

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