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Application of Metrological Approaches in the Design of Calibration Equipment for Verification of Float Level Gauges

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The paper deals with a scientific approach for an increase of accuracy of measurement and possibilities for automation of the standard equipment for calibration and verification of float level gauges. They are applied in high-capacity fuel storage tanks, and they are intended to measure the level of stored liquid hydrocarbons. In the submitted paper, we describe original approaches towards metrological control of float level gauges. Firstly, we present and describe the current ways of control by means of the standard equipment of the first generation with a precision caliper and manual measuring wire with the application of modern scientific and developing processes. A new system, whose design is based on research and development, represents a fully automated measuring system which utilizes the incremental optical encoder with a precision graduated ring and a rewind pulley. The paper deals with the issue of a design of the standard equipment and its measurement system from the standpoint of metrology and construction. Based on scientific procedures, we solve reasons of errors in measurement and their reduction on concrete components of the measurement system. The result is that, following the scientific approach and mathematical description of the determination of measurement uncertainties, constructors are able to design suitable tolerances for the production of components of measuring devices and related materials and technologies.

Keywords: Calibration, verification, accuracy of measurement, precision of measurement, production tolerances, float level gauge, incremental optical encoder.

1. INTRODUCTION

In industrial practices there regularly occur requirements for the measurement of a level of media – liquid or bulk materials in storage tanks. Two types of measurement of the level are applied: contact or contactless [23]. A typical example of the contactless measurement is a radar level sensor. A float level gauge is an example of the contact measurement.

Float level gauges belong to a category of specific measuring devices that are verified at regular intervals [1], [2], [23], [21]. Metrological control of float level gauges was carried out strictly only in laboratories. Regarding measuring ranges (the order of tens of meters) and a vertical working position, common laboratory facilities are integrated into towers or shafts constructed for a specific purpose.

Metrological control in the laboratory requires specific facilities and transportation of the gauge that is not always close to its place of work. That results in, from the standpoint of a customer, finding new alternatives of measurement of the level in stationary storage tanks. In order to meet the customer's needs, Slovak Legal Metrology, n.o. (hereinafter referred to as "SLM"), within its research and development activities proposed a solution and in 2015 it launched a new generation of standard equipment for the metrological verification of float level gauges, so-termed ZOH, which enables measurements right on the customers' premises. (ZOH – the standard equipment for verification of float levelling devices).

In development and design of its prototype, SLM cooperated with scholars from the Faculty of Mechanical Engineering at the University of Žilina. A unique work was the result of long-term experience and theoretical knowledge. The process of development consisted of research of development possibilities and new methods, followed by the identification of affecting factors to define the theoretical model of measurement, quantification of particular sources of measurement uncertainties, definition of parameters and methods of their measurement. Moreover, we defined tasks and principles of particular components in a measuring system from the design, described requirements of accuracy and quality of production. We followed results of prototype production, its testing as well as modifications based on

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experimental results. The final step was validation of the measuring system by its comparison with its reference laboratory represented by the producer Endress&Hauser in Japan with the aim to meet requirements of the standard EN ISO/IEC 17025 [18].

The paper represents a possibility to connect scientific works with applied principles to develop unique metrological systems. In case that standard construction facilities are not utilized in development, scientific approaches must be applied. Before the construction design, a thorough and detailed analysis of metrological requirements must be performed. It is crucial to know how to work with dimensions, tolerances and available technologies and their real capacities in relation with strict and specific requirements for accuracy as it is in the case of the new generation of the standard equipment for metrological verification of float level gauges.

The paper focuses on the requirement for the measuring system applied to the unique principle of the standard measuring equipment, methodology of measurement, and analysis of the original and new solution of the measuring system. Furthermore, it presents the approach to the definition of production tolerances following metrological requirements.

A. Requirement for calibration and verification of float level gauges

The design of the measuring system was based on the requirements of the supplement (automatic level gauges) of the Decree of the ÚNMS SR no. 161/2019 Coll. on measuring instruments and metrological control and the requirements of International Recommendation OIML R 85 (ÚNMS – Slovak Office of Standards, Metrology and Testing) [1], [2], [3].

2. SUBJECT & METHODS

A. Current status

The equipment ZOH1 (the first generation) for calibration and verification of float level gauges was developed based on the utility model no. 166-2013. [5] This measuring system allows very effective verification of the float level meter directly at the customer's premises, without a need for the meter to be transported to the calibration laboratory. Fig.1. presents the scheme of the equipment ZOH1 for calibration and verification of float level gauges. The equipment consists of a movable pulley (P1) hung on the wire (S2) with the diameter of $0.1475^{+0.0075}_{-0.0075}$ mm [4], a tested float level gauge (S1), a fixed pulley (P2), and a container (2) positioned on the scales (4) filled with liquid (3). A displacer (S3) immersed in the liquid (3) is suspended on the axis of a movable pulley (P1, 1), a caliper (5) with the measuring range of 330 mm. Fig.2. shows the schematic detail of the measuring component of the standard equipment ZOH1. The adjusting weighing part consists of a fixed pulley (P3), a movable pulley (P4), and a counterweight (6). The wire (S2) is wound manually on a winding pulley (P5).

To simulate a drop of the level by one step, we need to perform the following operations:

1. To unlock the locking screw and allow a feed of the movable jaw of the caliper.
2. To unlock the movable jaw of the caliper and to displace the open moveable holder to the beginning of the measured distance of the wire.
3. To lock the locking screw.
4. To record the data of the caliper as the beginning of the measured segment - L_p.
5. To unlock the fixed screw of the fixed support.
6. To move a wire from left to right up to the point when the movable jaw reaches the end of the measured segment by a slow and smooth motion of the arm of the caliper.
7. To record the data of the caliper as the end of the measured segment - L_k.
8. To control a fixation of the displacer in the equilibrium position visually.
9. To lock the fixed screw of the fixed support.
10. To record the data of the level meter, scales and measuring time.

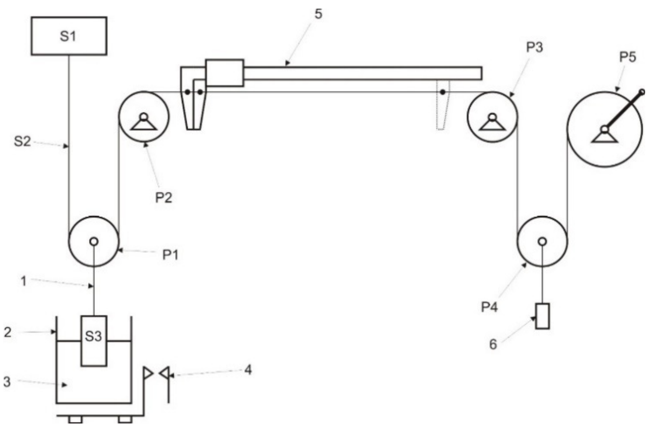

Fig.1. The scheme of the equipment ZOH1.

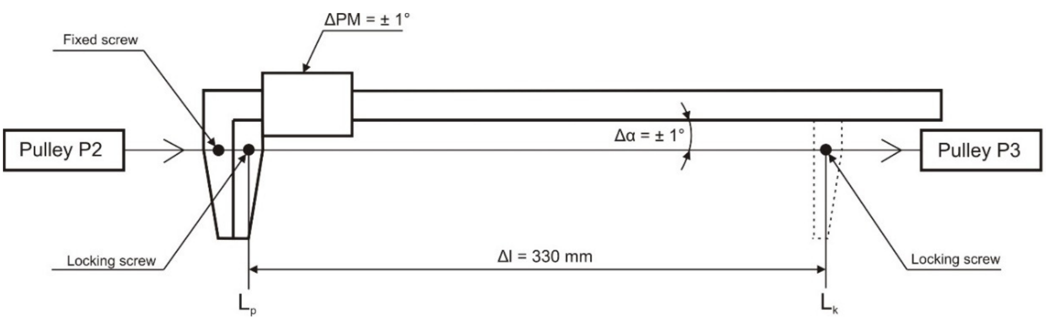

Fig.2. The scheme of the measuring device of the equipment ZOH1.

In case of the measuring range of 26 meters of the float level gauge, it is necessary to perform 64 displacements of the wire from point A to point B.

In practice, the construction of equipment ZOH1 consists of the welded L-profiles. A 500 mm digital caliper (Mitutoyo, type: Absolute Digimatic) with a digital display with the resolution d_s = 0.01 mm and the maximum permissible error *mpe* = 0.03 mm was applied to measure the segment of the length of wire. A portable scale with the capacity of 2 kg was used to measure the liquid container. To be more specific, it was Mettler Toledo, type EL 2001/01 with the division value 0.1 g with the maximum permissible error *mpe* = 0.1 g. The winding of wire was performed manually with an intuitive speed and acceleration. Fig.3. shows the equipment ZOH1 by the verification of a float level gauge. Then, particular data obtained from measurements are transferred into the evaluating program with final results of measurements via a data cable.

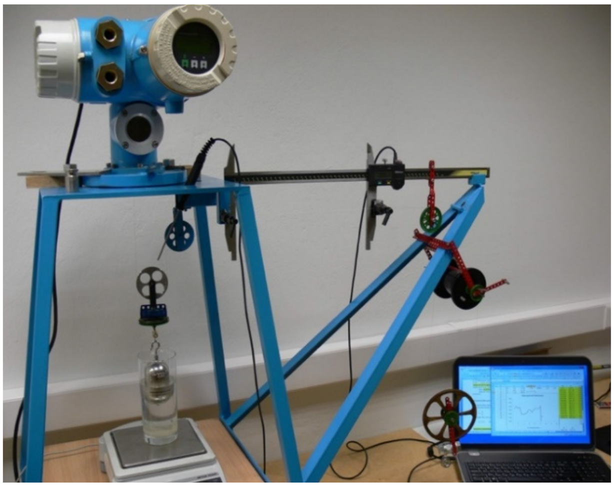

Fig.3. The standard equipment ZOH1 by verification of a float level gauge.

B. *Design of new measuring system*

With the aim to eliminate some adverse effects (they were a part of measurement uncertainty in the original solution), to improve measurement and to prepare a measuring system for the process of automation, we started to design new measuring equipment. The new design is based on the equipment ZOH1 in order to increase the accuracy of the measurement. Therefore, a measuring component with the caliper is substituted by the incremental optical encoder with a precision graduated ring (Renishaw, type: RESM 20, *n* = 23,600, *d* = 20 μm) representing a standard measure of length. [19]. The measurement system provides measurement accuracy of 0.1 arc. sec., it is part of a precision pulley with the diameter 105.2 ± 0.03 mm, in which the wire is positioned with the wrap angle 360°. The design of the measuring system fully meets the criteria for automation. To be more specific, a stepper electric motor with a gear and a belt drive provides wire winding. As a result, there is no need for any manual interference during measurement. The scheme of the equipment with a new measuring system (the optical encoder with the ring) is shown in Fig.4.

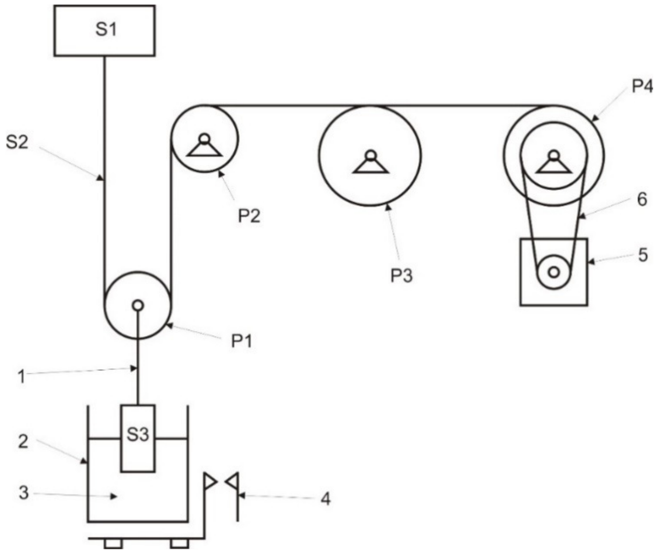

Fig.4. The scheme of the equipment with a new measuring system.

The original solution of the equipment consists of a movable pulley (P1) suspended on the wire (S2) with a diameter of $0.1475^{+0.0075}_{-0.0075}$ mm, a tested float level gauge (S1), a fixed pulley (P2), a container (2) positioned on the scales (4) and filled with liquid (3). A displacer (S3) immersed in the liquid (3) is suspended on the axis of a movable pulley (P1, 1). A part of the new measuring system is a precise pulley (P3). A winding pulley is driven by the stepper electric motor with a gear (5) by means of a V-belt or directly without it.

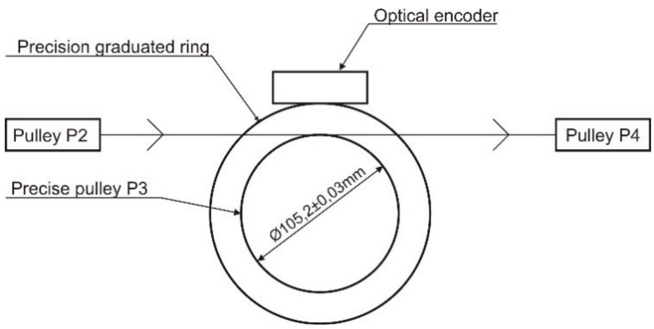

Fig.5. The scheme of the measuring component of the standard equipment.

To simulate a drop of the level by one step, it is necessary to perform one revolution of the measuring pulley. After the revolution, it is important to record the data from the measuring system, the float level gauge and the period of measurement. Fig.6. shows new standard equipment in a verification of the float level gauge. On the left, there is only a manual winding of the rope on the winding pulley. On the right, a stepper electric motor with gear is implemented into the system.

In practice, the construction of the equipment consists of aluminium modular profiles. The stepper motor EMMT-AS-60-L-LS-RMB with the rated power 410 W, the rated speed 3,000 min-1 and torque 1.3 Nm, is used as a drive of the winding pulley. Furthermore, power transfer and speed change are provided by the planetary gear unit EMGA-60-P-G5-EAS-60 with the gear ratio i = 5. The motor is controlled by the servo drive CMMT-AS-C2-3A-PN-S1.

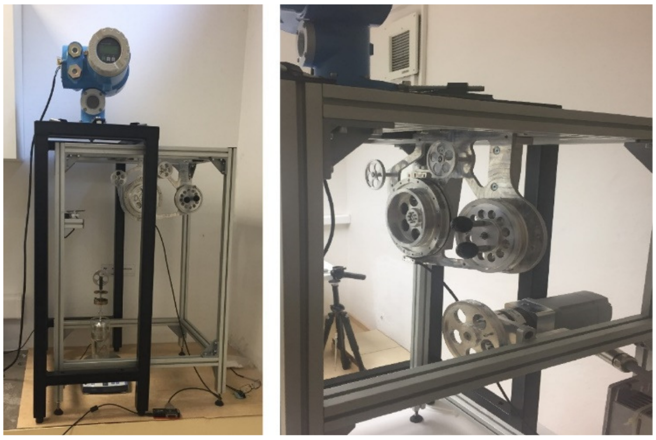

Fig.6. The standard equipment with the new measuring system in a verification of the float level gauge. On the left, with the manual drive. On the right, the system is implemented with a stepper electric motor with a gear.

In design, the drive is based on the analysis of the utilized pulley mechanism. To calculate a minimum torque M_{min}, the formula was applied:

$$M_{min} = I_4\alpha_4 + \left[\left(\frac{1}{2}m_z g + \frac{I_2\alpha_2}{r_2} + \frac{I_3\alpha_3}{r_3}\right)r_4\right]. \quad (1)$$

Where I_4 – moment of inertia of the winding pulley P4, α_4 – angular acceleration of the winding pulley P4, r_4 – radius of the pulley P4, m_z – a weight suspended on the wire S2, g – gravitational acceleration, I_2 – moment of inertia of the fixed pulley P2, α_2 – angular acceleration of the winding pulley P2, r_2 – radius of the pulley P2, I_3 – moment of inertia of the measuring pulley P3 with the measuring system, α_3 – angular acceleration of the measuring pulley P3 with the measuring system, r_3 – radius of the pulley P3.

A slip of the stepper motor takes place at a certain acceleration by pulling the wire through the pulley or the measuring system. To solve this problem, we followed the Euler–Eytelwein formula. The formula states that maximum acceleration of the stepper motor a_{max} equals:

$$|a_{max}| = \frac{\frac{r_3^2 m_z g}{2I_3}}{\left(\frac{1-e^{f\varphi}}{e^{f\varphi}} - \frac{I_2 r_3^2}{I_3 r_2^2}\right)} \quad (2)$$

Where f – friction coefficient, φ – wrap angle.

C. Measurement model and determination of uncertainties

The main issue of the designed solution is that an error occurs every time while using the new measurement system. The error is caused by an inaccuracy in the production of a pulley groove (P3) of the measuring system. The inaccuracy is caused by a permissible tolerance of roundness and roughness of the groove surface [4], [5]. The groove of the measuring pulley in which the wire is placed has the diameter 105.2 ±0.03 mm including the tolerance of roundness ± 0.03 mm. The wire diameter is $0.1475^{+0.0075}_{-0.0075}$ mm. Moreover, a tolerance of the wire of a float gauge also affects an error in measurement. Therefore, for a calculation, we considered geometries of the measuring pulley and its parameters [6], [7], [8]. A wire length, i.e., a length of the measured segment, is determined by a length of a neutral fibre in the wire. As a result, for the calculation of the length of the neutral fiber, a formula for a circle circumference is applied. It is supposed that a position of the neutral fibre varies by a modified diameter of the wire. This results in the fact that the length of the neutral fiber increases with increasing diameter. Fig.7. shows that a circle diameter formed by a wrapped neutral fibre around the pulley D_k equals:

$$D_k = D_L + D. \quad (3)$$

Where D - nominal dimension of the pulley diameter and D_L – nominal dimension of the wire diameter. The wire length and thus one measured segment that unwinds from a wire drum for one revolution of the measuring pulley equals:

$$L = D_k \times \pi. \quad (4)$$

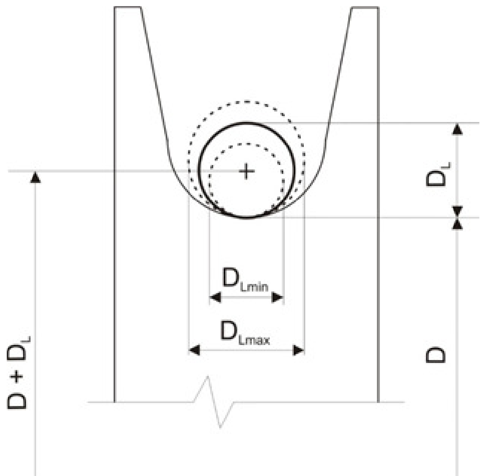

Fig.7. The scheme of the wire placement in the pulley groove.

Fig.7. shows the scheme of the placement of the wire in the groove of the measuring pulley. Where D_k is determined by the relation:

$$D_k = D + D_L \quad (5)$$

Where D is a nominal diameter of the pulley and D_L is nominal dimension of the wire diameter.

D. Uncertainty of Measured Segment

Standard uncertainty of a wire length per one pulley revolution is:

$$u(L) = \pi \times u(D_k) \quad (6)$$

where standard uncertainty of a pulley diameter, considering the relation (5), is

$$u^2(D_\mathrm{k}) = u^2(D) + u^2(D_\mathrm{L}) \tag{7}$$

When we consider that $D_\mathrm{L} \in (0.140; 0.155)$ mm will be in case of the normal distribution of an error of wire diameter (we know the bounds with the probability of 95 %) for an estimation of the wire diameter $\widehat{D_L} = 0.1475$ mm

$$u(D_\mathrm{L}) = \frac{0{,}155 - 0{,}1475}{2} = \frac{0.0075}{2} = 0.00375 \text{ mm}. \tag{8}$$

The pulley diameter (a groove in which the wire is placed) is designed initially as $D = (105.2 \pm 0.03)$ mm. That means the standard uncertainty of the pulley diameter assuming a balanced diameter distribution is

$$u(D) = \frac{0.03}{\sqrt{3}} = 0.0173 \text{ mm}. \tag{9}$$

Therefore, the uncertainty of the circle diameter (see relation (6)) for the design of a pulley with the diameter $D = (105.2 \pm 0.03)$ mm would be

$$u(D_\mathrm{k}) = \sqrt{0.0173^2 + 0.00375^2} = \sqrt{0.000313} = 0.0177 \text{ mm}. \tag{10}$$

In case of 64 revolutions, the uncertainty of the length of the wire (measured segment) is

$$u(L) = \pi \times 64 \times 0.0177 = 3.557 \text{ mm}. \tag{11}$$

Thus, when assuming a normal distribution of the wire length, an expanded uncertainty of the length of a measured segment is

$$U(L) = 2 \times 3{,}557 = 7.12 \text{ mm}. \tag{12}$$

To make an expanded uncertainty of the total measured length $U = 1$ mm (which results from the proposal of designed standard equipment), the standard uncertainty must be $u(L) = 0.5$ mm. Then the standard uncertainty of the length per one revolution

$$u(L_{1rev}) = \frac{0.5}{64} = 0.0078 \text{ mm} \tag{13}$$

And standard uncertainty of a circle per one revolution

$$u(D_\mathrm{k}) = \frac{0.0078}{\pi} = 0.00248 \text{ mm}. \tag{14}$$

That means a permissible error (a permissible expanded uncertainty). In the current design, the considered tolerance (expanded uncertainty) of the pulley is 0.03 mm and tolerance of the wire diameter is 0.0075, which results in an expanded uncertainty of 0.035. Therefore, it is necessary to decrease the tolerance of the wire diameter as well as the tolerance of the pulley diameter.

3. RESULTS

The result of the work is the new equipment ZOH2 for verification of float level gauges based on scientific research in the given field. Particular construction components were produced on the basis of requirements for the minimization of measurement error. The equipment is implemented by an automatic drive system of the winding pulley with own SW and HW solution. Therefore, based on the research of uncertainties of measurement and performed calculations of measurement uncertainties, the measuring pulley was produced with the required dimension (105.2 ±0.0012) mm with a wire tolerance of ±0.0042 mm, what represents the uncertainty of a circle according to the relation (7)

$$u(D_\mathrm{k}) = \sqrt{\left(\frac{0.0012}{\sqrt{3}}\right)^2 + \left(\frac{0.0042}{2}\right)^2} = 0.0022 \text{ mm}.$$

From the standpoint of production technology, it is a very high required accuracy. However, this accuracy can be obtained by modern CNC machines. As a result, the requirement of an expanded uncertainty of a length of a measured segment of 1 mm will be met in the production of a measuring pulley plus uncertainty of the wire length.

During calibration of the designed measuring system when determining the resulting measurement uncertainty, it will be necessary to identify and quantify all significant influencing variables, to determine the uncertainty budget on the basis of experimental calibration data, for further uncertainty contributions arising from the conditions of use of the equipment. The purpose of this paper was to introduce a design of the equipment and accuracy of the production of its components (pulley) in terms of an achievable uncertainty of the measuring equipment.

4. DISCUSSION / CONCLUSIONS

The analysis of a form of measurement uncertainties was performed by the critical element analysis of the measurement system. Before the construction design, we as constructors did not deal with measurement uncertainties sufficiently enough. The result was an incorrect proposal of tolerances. By an application of scientific knowledge from the field of measurement and statistics, the conditions for minimisation of the impact of pulley dimensions on measurement accuracy were set. A definition of the conditions of tolerance in a proposal of metrological equipment must be obtained by an analysis of measurement uncertainties, a definition of critical elements of the measuring system and, consequently, fields of tolerance of individual components must be formed. The work points to the necessity of the scientific knowledge application from the field of measurement and statistics, even in a pre-construction process, to avoid deficiencies in a construction solution, especially in the initial design. It is a lesson for constructors of metrological devices where to start with the process of construction, and how an insufficient analysis may affect the accuracy of the measurement system. Currently, the equipment is in a test operation.

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