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INFLUENCE OF THE DESIGN FEATURES OF ELECTROMAGNETIC FORCE COMPENSATION BALANCES ON THEIR METROLOGICAL PERFORMANCE

Key words

Electronic balance, moisture sorption, parallelogram stiffness.

Abstract

This paper shows the basic design of the laboratory balances that operate according to the principle of electromagnetic force compensation. The study of factors adversely affecting the weighing accuracy was carried out. The effect of moisture sorption on weight change of the electromagnetic actuator of the coil was explored as well as the influence of the compliant joint geometry on the stiffness of a model parallelogram mechanism guiding the weighing pan of the balance. The change in mass of the coil was studied using the gravimetric method, and mechanism stiffness was analysed using the FEM method. It was found that the adsorption has a significant contribution in weight increase of the electromagnetic coil and the force resulting from the stiffness of the parallelogram system in the load of the weighing pan has also a significant contribution.

Introduction

Poland is among the leading manufacturers of scales and balances in the world. Depending on the application, balances can be divided into industrial, warehouse, medical and laboratory balances. Laboratory balances are the largest group. They have to meet strict requirements for precision and the stability of the weighing result in different environmental conditions. This group includes precision balances (with the readability of d ≥ 1mg and capacity of M ≥ 100 g), analytical balances (d = 0.1 mg, M = 50 to 500 g), semi-micro balances (d = 10 µg, M = 30 to 200 g), microbalances (d = 1 µg, M = 1 to 25 g), and ultra- microbalances (d = 0.1 µg, M ≤ 10 g). The resolution of analytical balances reaches 5 · 106 and ultra-micro balances even 100 · 106.

Laboratory balances with a resolution greater than 100 · 103 are equipped with weighing modules (weighing cells) based primarily on electromagnetic force compensation. The measurement of the mass m is based on balancing the force of gravity G (G = m · g, where g is the acceleration of the Earth) of the weighed object with the compensation force generated in the electromagnetic force transducer. By neglecting the influencing factors, the compensating current (or any other electric value), required to achieve balance, is proportional to the mass of the object to be weighted. The relationship between the loading of the pan and the measurement signal from the force transducer is determined in the adjustment process of the balance with the use of the mass standards.

Figure 1 shows a typical construction and the principle of operation of the balance with electromagnetic force compensation.

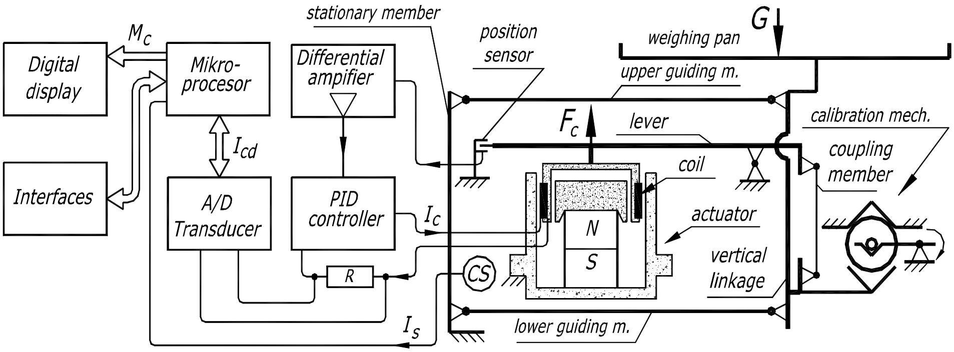


Fig. 1. Construction and principle of the operation of the balance with electromagnetic force compensation

The figure shows the electronic measuring system without any electrical power supply and the weighing module (weighing cell) containing the electromagnetic actuator (force transducer) with the permanent magnet. It also shows the position sensor, the mechanism of the force transmission from the weighing pan to the actuator and, usually used, internal calibration mechanism. The force transmission mechanism includes the parallelogram mechanism guiding the weighing pan, the lever mechanism (usually with one or two levers), and the coupling element linking both mechanisms. The coupling element is bendable, mainly in the plane of the parallelogram. The parallelogram mechanism has a stationary part rigidly attached to the balance housing, and, parallel to it, vertically movable linkage with the weighing pan are attached. Both elements are connected with two parallel guiding parts (upper and lower) with flexure hinges at their ends forming the compliant joints. The parallelogram mechanism prevents tipping and eliminates or reduces the measurement deviation (corner error) caused by the eccentric loading of the pan.

The lever mechanism with the lever supported pivotally on the flexible hinge is used to reduce the weight force transmitted from the pan to the actuator. Typically, there is an actuator with a cylindrical permanent magnet and the pole piece in the shape of a cup.

In the air gap created between the poles of the permanent magnet, a cylindrical electromagnetic coil connected to the longer lever arm is submerged. The compensation current Ic flows through the coil with the value needed to generate the compensation force Fc in the actuator that balances the vertical component of the measured load acting on the weighing pan. Loading or unloading the pan causes the change of the angular position of the lever with the attached coil. The inclination of the lever is detected by a position sensor that is usually optoelectronic [1]. The signal from the position sensor that is proportional to the lever deflection is transmitted to the PID control device with the feedback that controls the current in the coil in such a way that the lever returns to its original (starting) position.

The compensating current is converted into a voltage on a precision measuring resistor with the resistance of R. This voltage is applied to the analogue-digital converter (A/D). The digital measuring signal is then transmitted to the microprocessor-based data processing unit for further processing (including digital filtering of the measurement signal). Digital signals Isc from the sensors (indicated in Fig. 1 with the symbol CS) placed at different locations inside the balance housing are also transmitted to this unit. On their basis, the parameters are developed, which are dependent or independent from the loading of the weighing pan that corrects the effects of influencing factors (such as temperature, humidity and atmospheric pressure) on the measuring signal [2]. The compensated (typically only in terms of temperature and non-linearity) measuring signal Mc is transmitted to the system presenting the weighing result, which is usually the liquid crystal display.

Modern balances are equipped with interfaces to transfer the measurement signal to the process controller, monitoring device, computer, mobile phone, or other similar devices. They usually use the following communication standards: RS232, RS485, Ethernet, WiFi, Bluetooth, USB, Profibus, DeviceNet, and Can.

The relationship between the measurement signal and the mass of the weighed object is determined based on the calibration of the balance with the external calibration mass standard or using the internal calibration system.

In balances with high resolution, the environmental conditions have a significant impact on the weighing results [3, 4, 5]. The accuracy and repeatability of the mass measurement depend on the type of the object to be weighed, weighing methodology (operator), and on the measuring device. The design features of the balance, in particular the weighing cell, have a significant influence on its metrological characteristics (resolution, non-linearity, zero drift, sensitivity, temperature coefficient of sensitivity and eccentric load deviation).

This paper presents the results of a study aimed at examining the influence of the moisture sorption by the coil of the electromagnetic actuator and the influence of the design features of the horizontal parallel guides in the force transmission mechanism on potential mass measurement deviations.

1. Moisture sorption by the coil of the electromagnetic actuator

The compensation force Fc (the Lorentz force), balancing the force G, is described by the following formula:

$$F_c = G \cdot \frac{b}{a} = I_c \cdot B \cdot l \tag{1}$$

where: B – the induction in the air gap of the magnetic circuit of the actuator, L – the length of the coil windings, a and b – the length of the longer and shorter lever arm respectively.

Therefore, the loading of the balance linearly depends on the product of the current flowing through the coil, the induction in the air gap and on the length (number) of coil windings. Increasing of the length of the windings (increasing their resistance R) and of the compensation current in particular is associated with the increased heat generation in the coil. The power Pc (Pc = Ic2 · R) generated in the electromagnetic coil, that is converted to heat, depends on the load G. This causes a change in temperature of the coil itself and the change in temperature of the components of the weighing cell within its environment. The changes in temperature initiate a number of adverse effects, such as changes in the air buoyancy force, variable airflows around the coil, or changes in the moisture sorption. One of the best ways to increase the loading of the balance is to increase the induction B by reduction of the air gap volume in the actuator.

The coil is usually wound on an aluminium coil former. The coil wire has a polymer insulation (polyurethane, polyamide, or polyamidimide). Organic materials, to which winding insulation belongs, absorb moisture from the surrounding air. Simultaneously with the phenomenon of the moisture absorption, the adsorption phenomenon occurs that extends to the coil elements made of inorganic materials. A change of the moisture content in the coil can lead to a leakage of the current between the windings; changes in the mutual position of windings caused by a volume change of the wire insulation absorbing moisture, and above all, a change in the weight of the coil. These elements contribute to the change of the sensitivity and cause a drift of the zero-balance indication. The adverse effects of the sorption phenomena concern all moving parts of the mechanism.

In order to limit the penetration of moisture into the coil, various solutions are applied, such as, covering the coil windings with a polymer layer (varnish) that has a low coefficient of moisture absorption, encapsulation using an aluminium ring embedded on the aluminium coil former, covering the coil with the polymer layer alignment and closing the gaps between the windings and then covering it entirely with a layer or multiple layers of an inorganic material [6]. The first solution works in balances with less strict requirements on sensitivity and accuracy. The third solution is applied to balances with the highest sensitivity and accuracy requirements. Its implementation, however, requires the use of the advanced vacuum technology [7]. Therefore the second solution is the most commonly used solution, which is based on the encapsulation using an aluminium ring, which is the subject of this study. These are shown in Fig. 2.

Fig. 2. Electromagnetic coil: a) non-encapsulated, b) encapsulated, c) coil former, and d) sealing ring

Coils with the sealing ring, however, require a wider air gap in the actuator, which is a drawback of this solution.

Table 1 shows the test results illustrating the sorption of moisture by the non-encapsulated coil (CNH), the encapsulated coil (CH), the coil former (anodized - CFA and non-anodized - CFNA) and the sealing ring (non-anodised - SNA). A mass gain of each element was tested after changing a relative humidity between 40 to 60%. In both cases, the temperature was maintained at about 25 °C and the conditions were stabilized for 24 hours.

From the results shown in Tab. 1, it can be seen that the non-encapsulated coil absorbs about four times more moisture than the encapsulated coil. The anodized former exhibits a large percentage of mass gain. The research also indicates that aluminium elements with a low surface roughness (Ra ≈ 1.5 μm) and polished absorb up to half as much moisture as the non-polished ones.

Table 1. Sorption of moisture by the coil and its elements

i	CNH	CH	CFA	CFNA	SNA
Δm [μg]	2000	500	400	20	18
$[\Delta m/A_i]$ μg/cm^2	31	7.6	6	0.44	0.37
$(\Delta m/m_i)\cdot 10^{-4}$[%]	96	19	73	8	5.6

The adhesive sealing the output wires of the coil also participates in a mass gain. A polymer with low moisture absorbency and a temperature expansion coefficient similar to that of aluminium is desired. The anode of the coil former provides the electrical insulation. In coils with a non-anodized former, electrical short circuits often occur. Figure 3 shows changes in weight of the encapsulated coil over time.

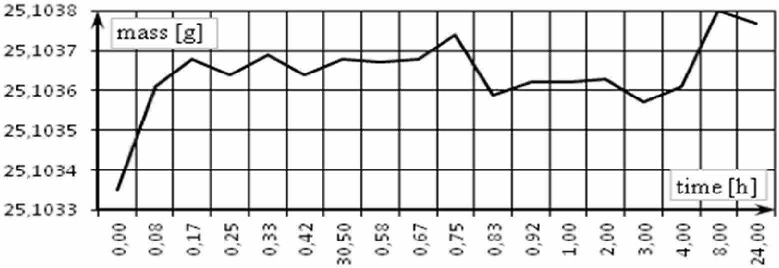


Fig. 3. Mass changes over time of the compensating coil (humidity RH = 45 to 65%, temperature 25°C)

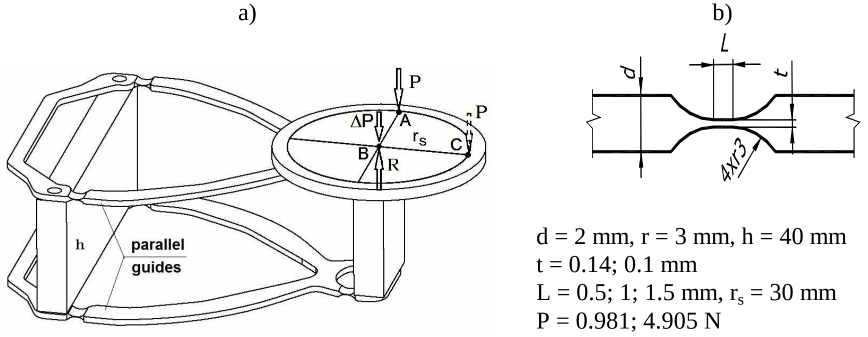
Figure 3 shows that the mass gain reaches the value close to the maximum only after 12 minutes. The phenomenon of adsorption is therefore dominant.

Within the space between the coil windings and the sealing ring, the air is enclosed. When the temperature changes the changes of balance sensitivity might occur caused by the absorption or desorption of moisture by the winding, despite encapsulation of the coil. In order to limit the impact of this phenomenon, the vacuum impregnation of coil windings in an epoxy-impregnating compound was done prior to the encapsulation. After reaching sufficient pressure in the vacuum chamber, the coil was immersed in the impregnating polymer. The operation was performed in the residual atmosphere of nitrogen. After removing the coil from the vacuum chamber, the encapsulating ring was set at the total immersion of the coil in the epoxy. The introduction of nitrogen was to remove any remaining air from the space between the coils. The investigations of changes in sensitivity of the balance did not show the intended advantages over the previously illustrated method of the encapsulation of the coils. Furthermore, the production implementation of this method is challenging.

Another equally important problem, especially in the case of the high-resolution balances, is the stiffness of the elastic joints of the force transmission mechanism.

2. Stiffness of the parallelogram mechanism guiding the weighing pan

The error of the position sensor and deformations caused by temperature change and mechanical loads cause the deformation of the assumed geometry of the force transmission mechanism. One of the manifestations of these deformities is the angular deviation of the horizontal parallel guides in combination with the vertical movement of the pan. The analysis showed that the movement of the pan, up or down, can be up to several micrometres. In the elastic flexure hinges of parallel guides, the reaction moments therefore arise. The resulting vertical component of the reaction force is summed up with the measured load of the weighing pan. Its value depends on the stiffness of the parallel guides. This stiffness in turn depends on the shape and dimensions of the elastic joints creating the compliant hinges [8]. In order to examine this relationship, the stiffness of the model parallelogram with monolithic parallel guides was determined using the FEM method. Figure 4 shows the adopted loading of the weighing pan and a typical shape and dimensions of the constrictions formed in the guides forming the elastic joints.



d = 2 mm, r = 3 mm, h = 40 mm
t = 0.14; 0.1 mm
L = 0.5; 1; 1.5 mm, r_s = 30 mm
P = 0.981; 4.905 N
ΔP = (1 do 9)$\cdot 10^{-5}$ N

Fig. 4. Model of the parallelogram mechanism: a) force on the pan, b) shape and dimensions of the flexible joints

Horizontal guides made of aluminium alloy have a thickness of 2 mm, and the constrictions have two circular portions having a radius of 3 mm and a fillet portion with a length of L and thickness of t. All elements of the system were assumed as weightless and rigid, with the exception of the horizontal guides. The pan was loaded with the vertical force P (P = 0.981 N or P = 4.905 N) successively at points B, A, C or simultaneously at points A and C. At point B, the balancing force R was applied. Then, at point B, the setup was loaded with the force ΔP and the vertical displacement Δf of the pan was examined. The application of the force at points A or C causes the system to be loaded with a torque or bending moment (M = P rs). Within the scope of this research, the parameter values as shown in Fig. 4b were analysed. The displacement of the centre point of the pan at the load of $\Delta P = 9 \cdot 10^{-5}$ N and t = 0.14 mm has not exceeded 2 µm. A sample of the test results is shown in Fig. 5.

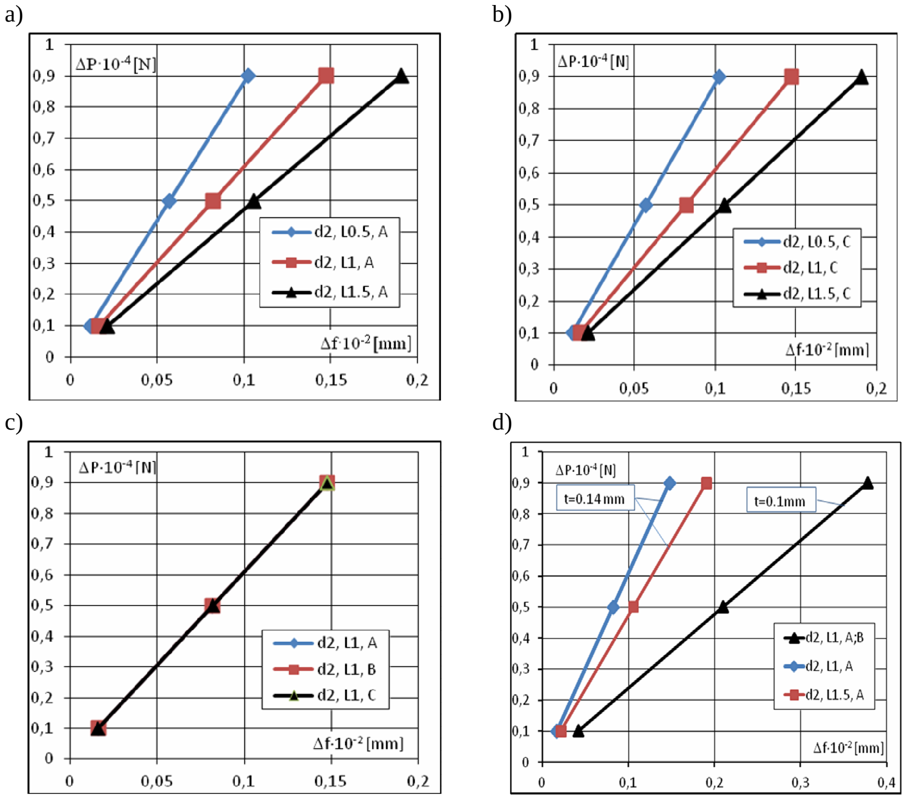


Fig. 5. The characteristics of stiffness of the parallel guides system for loads applied successively at points A, B, and C (d2 – d = 2 mm, L0.5(1,1.5) – L= 0.5 (1, 1.5) mm): a,b,c) P = 0.981 N and P = 4.905 N, t = 0.14 mm d) P = 0.981 N.

The research results show that the relationships between the loading of the parallel guiding system and the vertical displacement of the weighing pan are approximately linear within the range tested. Regardless of the point of the applied force, the stiffness of the system, for L = 1 mm and t = 0.14 mm, is $c = \Delta P / \Delta f \approx 0.061\ N \cdot mm^{-1}$. Assuming the vertical displacement of the pan of 1 μm, the measurement deviation of the mass is about 6 mg, which with a weighing mass on a pan of 100g, is 60 ppm. This deviation is counteracted by adjusting the balance, but not always in its entirety. For L = 0.5 mm, the stiffness of the system increase by about 44%, while for L = 1.5 mm reduces by about 23%. Therefore, the stiffness of the system non-linearly depends on the length of the fillet portion of the flexible joint. Changing the thickness of the fillet portion of the hinge with the length of L = 1 mm, from t = 0.14 to t = 0.1 mm, resulted in a decrease of the stiffness of the system by about 61% (for t = 0.1 mm $c \approx 0.023\ N \cdot mm^{-1}$).

The shape and the dimensions of the hinge depend on the strength of the material used as well as on the technology of shaping and assembly of the guide. If dimension L of the fillet portion of the hinge is too large, it is not advantageous because it increases the ambiguity of the position of the pivot axis at the angular displacement of the system.

Conclusions

To summarize the following conclusion can be made:

1. The encapsulated coil sorbs about four times less moisture than the non-encapsulated coil.
2. The anodized coil former has a significant share in the weight increase of the electromagnetic coil.
3. Aluminium elements with low surface roughness (Ra ≈1.5 μm) and polished absorbs up to half as much moisture as the non-polished ones.
4. The stiffness of the tested system with monolithic guides does not depend on the loading of the weighing pan (in the range tested).
5. The stiffness of the parallelogram with monolithic guides depends non-linearly on the length of the fillet portions of the compliant joints.
6. The vertical component of the force resulting from the stiffness of the parallelogram has a significant share in the weight force of the weighed object.

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Wpływ cech konstrukcyjnych wag z elekromagnetyczną kompensacją siły na ich właściwości metrologiczne

Słowa kluczowe

Waga elektroniczna, sorpcja wilgoci, sztywność równoległoboku.

Streszczenie

W pracy przedstawiono budowę elektronicznych wag laboratoryjnych działających zgodnie z zasadą elektromagnetycznej kompensacji siły. Dokonano analizy szkodliwych czynników wpływających na dokładność ważenia. Przeprowadzono badania wpływu sorpcji wilgoci na zmianę masy cewki siłownika elektromagnetycznego oraz wpływu geometrii podatnych łączników na sztywność modelowego mechanizmu równoległoboku prowadzącego szalkę wagi. Zmianę masy cewki analizowano metodą wagową, a sztywność mechanizmu równoległoboku analizowano, korzystając z metody MES. Stwierdzono istotny udział zjawiska adsorpcji w przyroście masy cewki oraz znaczący udział siły wynikającej ze sztywności układu równoległoboku w obciążeniu szalki wagi.