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EXPERIMENTAL STUDY OF DYNAMIC CALIBRATION IN GRAVITATIONAL WEIGHING SYSTEMS FOR BULK MATERIALS

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The issue of dosing and weighing materials will remain relevant for many years to come. The need to measure a required amount of material can be found in almost every area of activity – from microscopic substances to massive materials, compounds, and aggregates. Therefore, the search for the most optimal and efficient solutions in this field remains a constant and pressing task.

The primary characteristics of a weighed material are the accuracy of its weighing and the speed of the weighing process. The presented gravitational feeder is a high-performance device that ensures continuous material weighing in flow, without interruptions or stoppages. However, its weighing accuracy depends on many design features, especially the main working body – the curvature radius that receives the material flow. Accordingly, conducting experiments to calibrate the gravitational feeder allows one to understand how static and dynamic operating conditions affect measurement accuracy, which can characterize the system's behavior during real-world operation.

The aim of the study is to configure an experimental setup for conducting tests to optimize the design, determine the optimal parameters of the curved working body, and identify the most effective tilt angle of the working element relative to the vertical axis.

This work provides a detailed description of the construction of the experimental setup, methods of material feeding, parameters of the variable tilt angle of the feeder's working plane, as well as the methodology for collecting and processing experimental data.

Special attention is paid to the dynamic feeding mode, in which the load on the measuring element – the strain gauge sensor – changes. Key issues arising in this mode are identified: signal fluctuations, the influence of the tilt angle, and the physical and mechanical properties of the bulk material. A comparative analysis of measurement results under different conditions was conducted, calibration curves were constructed, and the dependencies between mass and voltage were interpreted.

Based on the results of the study, recommendations were developed for adjusting the feeder control system considering changes in technological conditions. The methodology can be implemented in automated production lines, particularly in the food, chemical, and pharmaceutical industries. The presented data have practical value for process engineers, equipment developers, and researchers in the field of conveying and dosing systems.

Key words: *gravitational feeder, calibration, bulk materials, strain gauge, dynamic dosing, tilt angle.*
Eq. 3. Fig. 7. Table.2. Ref. 19.

1. Problem formulation

In modern conditions of automation and digitalization of technological processes, it is important to ensure accurate, stable and continuous dosing of bulk materials. It is the accuracy of dosing that directly affects the quality of finished products, production efficiency and reduction of raw material losses. Gravity feeders are simple in design devices that use gravity to feed bulk components – often used in continuous feed systems for equipment in the food, chemical, construction and pharmaceutical industries.

Despite their structural simplicity, the effectiveness of such dispensers depends on correct calibration, i.e. establishing a functional relationship between the mass of the material and the signal of the measuring device (usually the voltage from a strain gauge). Mismatch of the calibration characteristic with the actual feed conditions leads to errors in dosing, which can cause recipe deviations, overconsumption or shortage of components.

Dynamic calibration is particularly difficult when the material is in motion – in such conditions the strain gauge signal undergoes fluctuations due to vibrations, changes in pressure on the sensor, as well as the physical properties of the material (humidity, granulometry, angle of natural slope). Therefore, it is important to develop an experimental technique that will allow not only to obtain accurate calibration dependences in static mode, but also to take into account the influence of design and operational factors in dynamic conditions.

Thus, the study of the calibration process of a gravity batcher in a flow aims to increase the accuracy of dosing, ensure the reproducibility of results in different operating modes, and create prerequisites for the implementation of automated adaptive control systems for the supply of bulk materials.

2. Analysis of recent research and publications

The scientific literature presents numerous studies devoted to the development, improvement and calibration of dosing devices for bulk materials. In particular, a significant part of the works is focused on screw and centrifugal feeders, which are characterized by stable feed, but require complex maintenance [5, 7, 17, 19].

The works of Osiptsov A.A. [1] and Johanson J.R. [2] analyze the influence of the geometry of the working bodies and the phenomenon of segregation in the flows of bulk materials. Peleg M. [3] describes methods for assessing the fluidity of powders, which affect the accuracy of dosing.

Studies in [4–6] focus on the effects of pressure, rotation speed, and tilt angle on the efficiency of centrifugal and gravity feeders. They confirm that the physical and mechanical properties of the material (moisture content, density, granulometry) critically affect the measurement result.

In [7, 8], the use of strain gauge systems in continuous flow was investigated and how dynamic forces can cause signal fluctuations was shown. It was found that the optimal tilt angle depends on the balance between accuracy and material feed rate.

System approaches to calibration described in the works Zhang et al. [9] and Gupta i Sharma [10], take into account complex flow dynamics and propose adaptive control algorithms.

Recent studies, including a paper in Applied Sciences (MDPI, 2024) [11], demonstrate the use of hybrid DEM–CFD models for particle flow simulation and precision weighing. They also propose a method for accounting for particle interaction forces and the influence of the gravitational field on strain gauge performance.

Also discussed are practical self-calibration methods (Hardy Solutions [12]), recommendations for calibration accuracy (PTB [13]), and implementation of embedded models in Thayer Scale dispensers [14]. The use of feedback methods, modeling of bulk solids motion in MATLAB/Simulink [15], and calibration through parametric model identification [16] are promising directions for automation.

Despite numerous studies, the issue of calibration of gravity feeders in dynamics remains poorly studied. Most experiments are conducted under static conditions, while industrial applications involve the feeding of material in a flow. This gap between laboratory conditions and production determines the need for new experimental approaches.

Thus, the relevance of the study is due to the need for accurate calibration of gravity feeders in dynamic conditions, which will allow creating more efficient and adaptive dosing systems for industrial applications. Most of the works are devoted to screw and centrifugal feeders [5, 7, 17]. Some authors focus on the influence of the geometry of the working elements [1], while others focus on ways to compensate for the influence of the physical and mechanical properties of bulk materials [4].

It is known that the accuracy of dosing significantly depends on the calibration relationship between the mass of the material and the sensor signal. In this case, calibration in dynamic flow conditions is particularly difficult, when the movement of the material causes instability of the signal. Works [2, 3, 18] demonstrate the advantages of using electronic strain gauge systems in combination with mathematical modeling to build calibration curves.

3. The purpose of the article

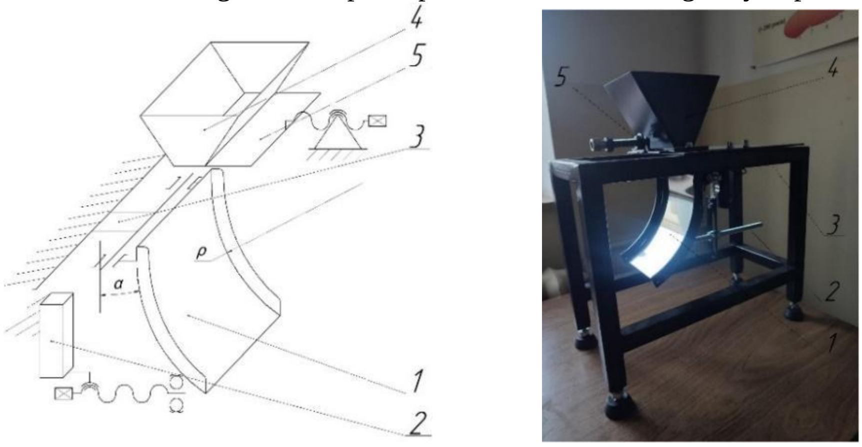
The purpose of the study is to substantiate and implement an experimental method for constructing static and dynamic calibration characteristics of a gravity feeder for bulk materials in a flow.

The objectives of the study are to analyze the influence of the mass and angle of inclination of the dispenser on the output voltage of the strain gauge; to construct the "mass – voltage" relationships in static and dynamic conditions; to assess the influence of feed modes on the stability of calibration; to formulate recommendations for implementing the results in automated dispensing systems.

4. Results and discussion

The study is conducted with the aim of setting up the experimental setup, determining the indicators in static and dynamic calibration, and comparing their characteristics. The comparative characteristic will be the basis for initial optimization of the main parameters, the curvature of the working body, and the angle of inclination to the vertical.

The research is carried out using the developed experimental model of the gravity dispenser, presented (Fig. 1).



a ***b***

Fig. 1. Gravity feeder for bulk materials:
a – diagram of a gravity feeder; b – general view; 1 – working body of curvature radii; 2 – strain gauge; 3 – frame; 4 – filling hopper; 5 – flow gate;

To carry out the calibration process, a laboratory setup was developed, with power supplies, strain gauge amplification, strain gauge sensor, and signal processing (Fig. 2).

Fig. 2. General view of laboratory equipment:
1 – power supply; 2 – reference mass; 3 – gravity feeder; 4 – strain gauge; 5 – oscilloscope

The research methodology is as follows. I set the maximum and minimum angle of inclination of the working body to the vertical, (Fig. 3). The maximum is 40°, the minimum is 10°.

a ***b***

Fig. 3. View of the angle of inclination of the working body to the vertical: a – 40°; b – 10°

I take as a basis the average value of the angle of inclination of the working body to the vertical of 20° and perform static calibration of the installation (Fig. 4).

I record the voltage signal data from the oscilloscope depending on the weight of the reference mass (Table 1).

During dynamic calibration, measurements were taken of the reference mass at three positions of the working body angle to the vertical: 40°, 20°, and 10°.

I record data from the oscilloscope in a dynamic stream, depending on the weight of the reference mass (Table 2).

Fig. 4. Static calibration

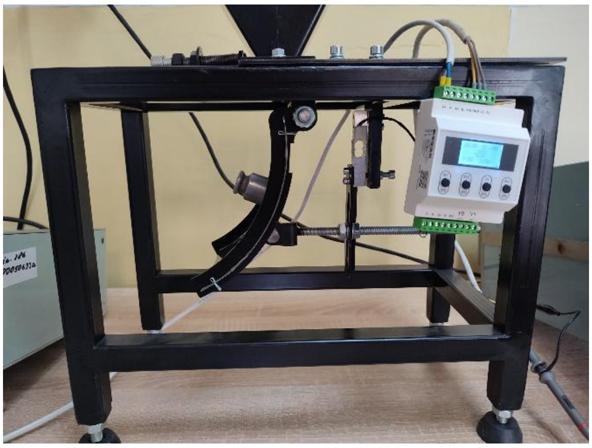


Fig. 5. Dynamic calibration

According to the results of laboratory research, the following data were obtained, calibration of the gravity feeder, presented in the tables.

Table 1

Static calibration

Reference mass, g	Voltage, V
50	0,25
100	0,52
150	0,78
200	1,01
250	1,28
300	1,53
350	1,79
400	2,03
450	2,29
500	2,51
550	2,76
600	3,01
650	3,27
700	3,53
750	3,79
800	4,06
850	4,34
900	4,51
950	4,72
1000	5,05

Table 2

Dynamic calibration

	Reference mass, g	The angle of inclination of the working body to the vertical, α		
		40	20	10
Voltage, V	50	0,4	0,8	1,35
	100	0,7	1,03	1,5
	150	1	1,27	1,65
	200	1,3	1,5	1,8
	250	1,6	1,73	1,95
	300	1,9	1,97	2,1
	350	2,2	2,2	2,25
	400	2,5	2,43	2,4
	450	2,8	2,67	2,55
	500	3,1	2,9	2,7
	550	3,29	3,09	2,92
	600	3,48	3,28	3,14
	650	3,67	3,47	3,36
	700	3,86	3,66	3,58
	750	4,06	3,85	3,8
	800	4,25	4,04	4,02
	850	4,44	4,23	4,24
	900	4,63	4,42	4,46
	950	4,82	4,61	4,68
	1000	5,01	4,8	4,9

Based on the data obtained, I build graphs of static and dynamic dependences of the calibration of the gravity feeder.

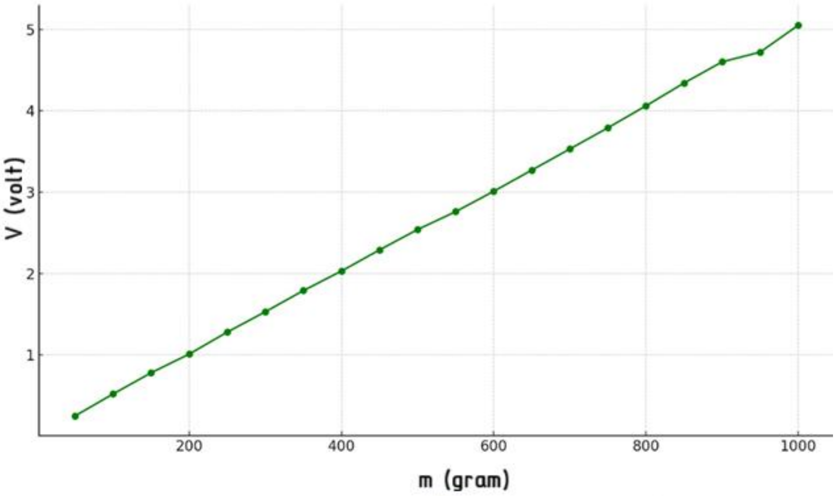


Fig. 6. Calibration graph of voltage dependence on reference mass

Static calibration showed a nearly linear relationship between mass and voltage (correlation coefficient over 0,99). This allows for the use of a simple linear approximation in automated control systems.

The resulting curve graph of the dependence of voltage on the reference mass is described by the method of least squares, according to the following equation:

$$U = a_i \cdot m + a_0, \tag{1}$$

where the coefficients are: $a_i = 0{,}0050, a_0 = 0{,}0138$.

we get:

$$U = 0{,}0050 \cdot m + 0{,}0138$$

where U – value of the reference mass voltage; m – value of the reference mass.

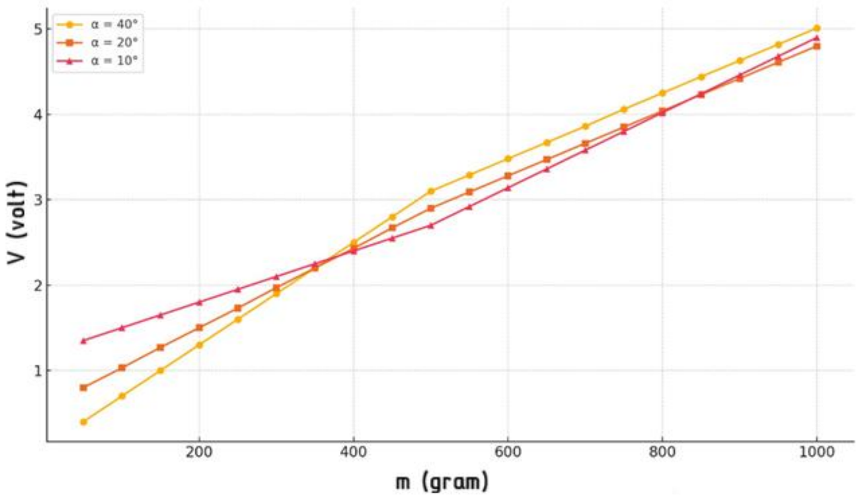


Fig. 7. Calibration graph of voltage dependence on reference mass, for three different angles of the working body to the vertical

Dynamic calibration showed that as the tilt angle increases from 10° to 40°, the voltage decreases for the same mass. This is due to the decrease in material pressure on the sensor's working surface.

For the obtained tabular and graphical data, an optimization function can be derived that will allow determining the optimal tilt angle, which affects the differences between static and dynamic calibration, and this, in turn, is one of the components of the material weighing accuracy indicator.

$$L(\alpha) = \frac{1}{n}\sum_{i=1}^{n}(U_{dyn}^{(i)}(\alpha) - U_{stat}^{(i)})^2, \tag{2}$$

where U_{stst} – voltage during static calibration, V; U_{dyn} – voltage during dynamic calibration, V; α – angle of inclination of the working body to the vertical.

and accordingly:

$$\alpha_{opt} = \arg\min_{\alpha} L(\alpha)\,, \tag{3}$$

As a result of the analysis of experimental data, it was found that at inclination angles from 10° to 15° the smallest error is observed (less than 3%), therefore, this range is the most acceptable for accurate dosing in motion.

5. Conclusion

As a result of the research, a calibration method for a gravity feeder for bulk materials, which operates in both static and dynamic feed modes, was developed and experimentally substantiated. The experiment showed that even in simple systems, a significant role is played by the precise adjustment of operating parameters and the correct consideration of the influence of external factors, in particular the angle of inclination of the dosing plane and the physical properties of the material.

The obtained calibration curves allow predicting the strain gauge signal with a high degree of reliability when the material mass changes, which provides the possibility of integrating the system into modern automated lines with real-time control. Dynamic experiments have proven that with a change in the angle of inclination, there is a systematic decrease in voltage at the same mass, which is associated with inertial and contact effects between material particles and the sensor surface.

The key result is the establishment of empirical dependencies that allow signal correction in accordance with current operating conditions. Thus, it is possible to ensure high dosing accuracy even under variable conditions – which is critically important for industrial applications, where the stability of the mixture composition determines the quality of the final product.

In order to optimize the operation of the dispenser, the optimal range of the inclination angle (10°– 15°) was determined, at which the root mean square error between the dynamic and static data is minimal (less than 3%), which is confirmed by calculations using formulas 2–3.

The proposed method is universal and can be adapted to different types of dispensers. It has prospects for implementation in adaptive process control systems in the chemical, food, pharmaceutical and construction industries.

References

1. Osiptsov, A.A. (2017). Modeling of granular material flow on rotating surfaces. *Powder Technology, 316*, 456–468. DOI: https://doi.org/10.1016/j.powtec.2017.04.045. [in English].
2. Johanson, J.R. (2002). Particle segregation and what to do about it. *Chemical Engineering Progress, 98*(1), 43–50. [in English].
3. Peleg, M. (2005). Flowability of food powders and methods for its evaluation – A review. *Journal of Food Process Engineering, 1*(1), 7–20. [in English].
4. Berthold, F., & Scherer, J. (2020). Design and performance evaluation of centrifugal feeders for powder dosing applications. *Powder Technology, 366*, 256–265. DOI: https://doi.org/10.1016/j.powtec.2020.02.013. [in English].
5. Zhang, L., Yan, C., Wu, Q., & Wang, T. (2019). Effect of pressurized feeding on powder flow and dosing performance in continuous processing. *Chemical Engineering Research and Design, 147*, 229–238. DOI: https://doi.org/10.1016/j.cherd.2019.05.020. [in English].
6. Thakur, A., Chandel, R., & Kumar, A. (2024). Gravimetric dosing dynamics under inclined feed. *Applied Sciences*, *14*(16), 7373. DOI: https://www.mdpi.com/2076-3417/14/16/7373. [in English].
7. Gupta, M., & Sharma, V. (2021). Advances in continuous powder mixing technologies for pharmaceutical manufacturing. *International Journal of Pharmaceutics, 598*, 120361. DOI: https://doi.org/10.1016/j.ijpharm.2021.120361. [in English].
8. Aguilera, J. (2014). Dynamic weighing for gravimetric flowmeter calibration. *Flow Measurement and Instrumentation, 37*, 100–108. DOI: https://doi.org/10.1016/j.flowmeasinst.2014.01.008. [in English].
9. Zhang, H., Li, Y., & Wang, J. (2023). DEM calibration procedures for cohesive particles. *Powder Technology*. DOI: https://doi.org/10.1016/j.powtec.2023.119999. [in English].
10. Berkenbusch, M., & Brendel, L. (2019). Hybrid CFD–DEM modelling of particulate systems. *Granular Matter, 21*(3), 68. DOI: https://doi.org/10.1007/s10035-019-0920-3. [in English].
11. Thayer Scale. (n.d.). *Gravimetric Feeders*. Retrieved October 26, 2025, URL: https://www.thayerscale.com/. [in English].
12. Hardy Process Solutions. (n.d.). *Calibration and preventive maintenance*. Retrieved October 26, 2025, URL: https://www.hardysolutions.com/. [in English].

13. Physikalisch-Technische Bundesanstalt (PTB). (n.d.). *Dynamic weighing recommendations*. Retrieved October 26, 2025, URL: https://www.ptb.de/. [in English].
14. Liu, K., Zhao, H., & Tan, J. (2022). Real-time DEM simulation in material feeding processes. *Advanced Powder Technology*, *33*(5), 103426. DOI: https://doi.org/10.1016/j.apt.2022.103426. [in English].
15. Platonov, I. V. (2018). *Teoriia ta praktyka vymiriuvannia masy u pototsi* [Theory and practice of mass measurement in flow]. Kharkiv: NTU "KhPI". [in Ukrainian].
16. Nienhaus, K., Müller, F., & Kruggel-Emden, H. (2018). Parameter identification for powder flow modeling. *Computers & Chemical Engineering*, *115*, 324–335. DOI: https://doi.org/10.1016/j.compchemeng.2018.04.017. [in English].
17. Melnyk, O. I. (2020). *Automated systems for dosing bulk materials*. Kyiv: Tekhnika. [in Ukrainian].
18. Platonov, I. V. (2018). *Theory and practice of mass measurement in flow*. Kharkiv: NTU "KhPI". [in Ukrainian].
19. Bembenek, M., Dmytriv, V., Banha, V., Horodniak, R., & Pawlik, J. (2024). A mathematical model for conical hopper mass efficiency. *Applied Sciences*, *14*(16), 7373. DOI: https://doi.org/10.3390/app14167373. [in English].

ДОСЛІДЖЕННЯ ВПЛИВУ КУТА НАХИЛУ РОБОЧОГО ОРГАНУ НА ТОЧНІСТЬ КАЛІБРУВАННЯ ГРАВІТАЦІЙНОГО ДОЗАТОРА

Питання дозування, та вимірювання ваги матеріалів, матиме актуальність на довгі роки вперед. Вимірювання, необхідної ваги матеріалу, можна зустріти майже в кожній галузі діяльності. Від дрібних, мікроскопічних речовин, до над величезних мас, речовин, агрегатів, матерій. Тому шукати найоптимальніші та найефективніші рішення, з цих напрямах є постійним сьогоденним питанням.

Основною характеристикою зваженого матеріалу є, точність його зважування, та швидкість процесу зважування. Представлений гравітаційний дозатор, є високопродуктивним пристроєм, що забезпечує зважування матеріалу в потоці, без перерв та зупинок. Але точність його зважування, залежить від багатьох конструктивних особливостей, головного робочого органу радіусу кривизни, який сприймає потік матеріалу. Відповідно проведення експериментів, з калібрування гравітаційного дозатора, дає змогу зрозуміти, як статичні, і динамічні умови експлуатації, впливають на покази точності, що може охарактеризувати поведінку системи під час реальної роботи.

Метою дослідження є налаштування експериментальної установки, для виконання дослідів, по оптимізації конструкції, визначенні оптимальних параметрів робочого органу установки кривизни, визначення найбільш ефективного кута нахилу робочого органу до вертикалі.

У роботі детально описано побудову експериментальної установки, способи подачі матеріалу, параметри змінного кута нахилу робочої площини дозатора, а також методологію збору та обробки експериментальних даних.

Особлива увага приділена динамічному режиму подачі, при якому змінюються навантаження на вимірювальний елемент – тензометричний датчик. Зазначено ключові проблеми, що виникають у такому режимі: флуктуації сигналу, вплив кута нахилу, фізико-механічні характеристики сипкого матеріалу. Проведено порівняльний аналіз результатів вимірювань у різних умовах, побудовано калібрувальні криві та надано інтерпретацію залежностей між масою та напругою.

За результатами дослідження розроблено рекомендації щодо налаштування системи керування дозатором з урахуванням зміни технологічних умов. Методика може бути впроваджена у виробничі лінії з автоматизованим керуванням, зокрема в харчовій, хімічній та фармацевтичній промисловості. Представлені дані мають практичну цінність для інженерів-технологів, розробників обладнання та дослідників у галузі транспортних і дозуючих систем.

Ключові слова: *гравітаційний дозатор, калібрування, сипкі матеріали, тензодатчик, динамічне дозування, кут нахилу.*

Ф. 3. Рис. 7. Табл. 2. Літ. 19.

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