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CONTROL OF THE MAGNETIC LEVITATION USING A PID CONTROLLER WITH ADAPTATION BASED ON LINEAR INTERPOLATION LOGIC AND GENETIC ALGORITHM

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Abstract. *This paper presents a magnetic levitation system in which the position of a steel ball is obtained at a desired level by controlling the coil current. The object's behavior was approximated using a mathematical model, considering the inductance's dependence on the ball's position. Then, simulations were carried out in the MATLAB/Simulink environment, and the results were compared with data obtained from a physical bench, confirming the accuracy of the simulation model. As part of the work, two variants of the control system were realized: a classic PID controller and an adaptive version, in which the PID parameters are determined using a genetic algorithm. In addition, linear interpolation logic was introduced, enabling smooth adaptation of the settings depending on the current operating conditions. Experimental tests carried out for step and sinusoidal excitation showed a significant improvement in control quality, reduced rise time, and reduced overshoot in the system using the genetic algorithm and linear interpolation logic compared to a classically tuned PID.*

Keywords: electromagnetism, magnetic levitation, PID control, genetic algorithms, fuzzy logic

STEROWANIE LEWITACJĄ MAGNETYCZNĄ ZA POMOCĄ REGULATORA PID Z ADAPTACJĄ OPARTĄ NA LINIOWEJ INTERPOLACJI I ALGORYTMIE GENETYCZNYM

Streszczenie. *W niniejszym artykule przedstawiono system lewitacji magnetycznej, w którym pozycja stalowej kuli utrzymywana jest na żądanym poziomie poprzez sterowanie prądem cewki. Przybliżenie zachowania obiektu dokonano za pomocą modelu matematycznego, uwzględniającego zależność indukcyjności od położenia kuli. Następnie przeprowadzono symulacje w środowisku MATLAB/Simulink, a ich wyniki porównano z danymi uzyskanymi na fizycznym stanowisku, potwierdzając dokładność modelu symulacyjnego. W ramach prac zrealizowano dwa warianty układu sterowania: klasyczny regulator PID oraz wersję adaptacyjną, w której parametry PID wyznaczane są z zastosowaniem algorytmu genetycznego. Dodatkowo wprowadzono logikę interpolacji liniowej, umożliwiającą płynną adaptację nastaw w zależności od aktualnych warunków pracy. Badania eksperymentalne zrealizowane dla wymuszeń skokowych i sinusoidalnych wykazały wyraźną poprawę jakości regulacji, skrócony czas narastania oraz zredukowany uchyb w układzie z algorytmem genetycznym i logiką interpolacji liniowej w porównaniu z klasycznie strojonym PID.*

Słowa kluczowe: pole elektromagnetyczne, lewitacja magnetyczna, sterowanie PID, algorytmy genetyczne, logika rozmyta

Introduction

With technological progress, there is a growing focus on reducing losses and optimizing energy consumption. One type of loss is mechanical resistance. Friction generates heat and accelerates the wear of mechanical components, which requires regular maintenance and, in the long term, replacement. One of the solutions to minimize losses caused by friction is to eliminate direct mechanical contact. This is possible through magnetic levitation, which allows an object to be suspended without mechanical contact using magnetic forces.

Magnetic levitation finds applications in many areas – from transportation (Maglev trains) to industry (contactless transport systems) and even medicine (levitating bearings in blood pumps) [5]. This technology reduces friction, improves precision and reliability, and lowers maintenance costs.

A modern example of such an application is the XPlanar system by Beckhoff, which uses magnetic levitation principles to transport manufacturing components. This solution allows for complete freedom of movement, independent operation of multiple elements on a single track, and significantly reduces mechanical wear.

The operating principle of many levitation-based systems – such as Maglev trains or magnetic bearings – relies on similar physical foundations. A notable example is the magnetic bearing, which supports a rotating shaft without mechanical contact (Fig.1). This type of bearing can serve as a helpful reference point for the levitating ball project, as its operation is quite similar: electromagnetic force maintains the object in a stable position, dynamically responding to its movements.

Due to the rapid development of this technology, we decided to build a simple magnetic levitation system based on an electromagnet and a steel ball controlled by a PID controller [9]. This setup allows for a practical understanding of feedback control and the behavior of dynamically unstable systems.

Fig. 1. Magnetic bearing [4]

Genetic algorithms (GAs) are optimization techniques inspired by natural selection and evolution, particularly useful in control systems for solving complex problems [6]. They excel in tasks such as controller design and tuning, system identification, and multiobjective optimization, where they optimize parameters and structures for better performance, identify model structures and parameters, and balance conflicting performance metrics. Their adaptability and ability to handle complex problems make GAs versatile tools in control engineering, applicable across diverse domains like robotics and aerospace [1].

1. Description of the test stand

The magnetic levitation phenomenon was investigated on the specially built test stand consisting of an electromagnet and a ferromagnetic ball. The first step in preparing the magnetic levitation system was computer simulations with FEMM 4.2 [7] software to calculate the geometrical parameters of the electromagnet. Parametric computer simulations allowed us to choose the electromagnet's geometrical parameters and number of turns for the coil. Dimensions of the final version are presented in Fig. 2. The 'E' shape of the electromagnet was used deliberately to limit the leak of the magnetic field, which is especially important when the inductive proximity sensor measures the position of the ferromagnetic ball.

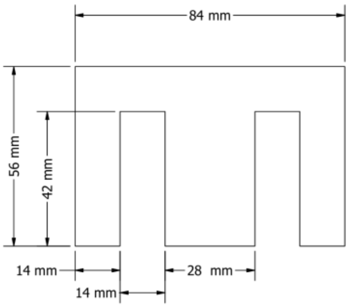

Fig. 2. Dimensions of the electromagnet

The cross-section area of the coil equals 588 mm^2. Therefore, it was possible to wound 348 turns with a wire of 0.789 mm^2 area. Fig. 3 presents the magnetic field distribution for the ball spaced from the electromagnet about 10mm.

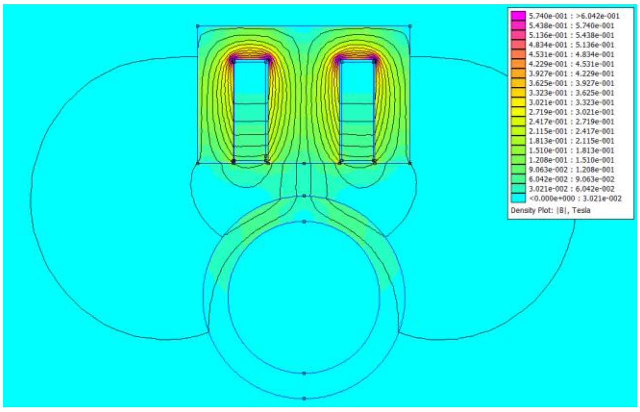

Fig. 3. Magnetic field distribution of the levitating ball prepared in FEMM 4.2

Fig. 4 presents the photo of the test stand, which consists of an electromagnet, ferromagnetic ball, inductive proximity sensor BAWM30ME-UAC10B-S04G manufactured by Balluff [2], two DC power supplies, H-bridge, and personal computer with installed board DS1140 for fast prototyping [3].

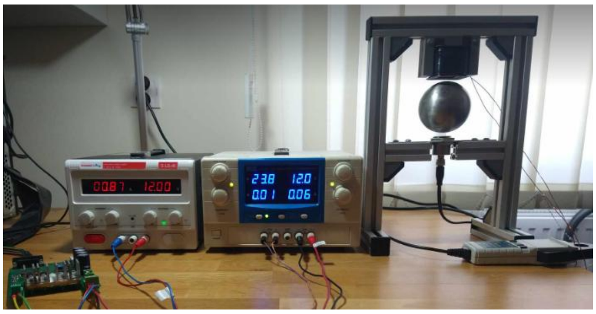

Fig. 4. Photograph of the test stand

2. Mathematical model of the levitation system

A mathematical model of the levitation system was used for tuning purposes. The mathematical model was built in MATLAB/Simulink software based on the following equations:

$$m\frac{d^2x}{dt^2} = F_x(x,i) - mg \quad (1)$$

$$\frac{di}{dt} = \frac{(u-Ri)}{L(x,i)} \quad (2)$$

where: L – coil inductance [H], m – mass of the ball [kg], i – coil current [A], g – acceleration of gravity [m/s^2], u – supply voltage [V], R – coil resistance [Ω], x – position of the sphere [m].

The value of the ferromagnetic ball and the coil resistance are constant and equal to m = 0.238 kg and R = 2.2 Ω. On the other hand, the value of the coil inductance and the magnetic force depend on the ball position and the coil current. Fig. 5a and 5b present characteristics of the coil inductance $L(x, i)$ and the magnetic force $F_x(x, i)$ in the function of the rotor position x and the coil current i obtained from the FEMM 4.2 software based on parametric simulations.

Fig. 6 presents an implementation of the simulation model in MATLAB/Simulink software, where characteristics of the coil inductance $L(x, i)$ and the magnetic force $F_x(x, i)$ are included as lookup tables.

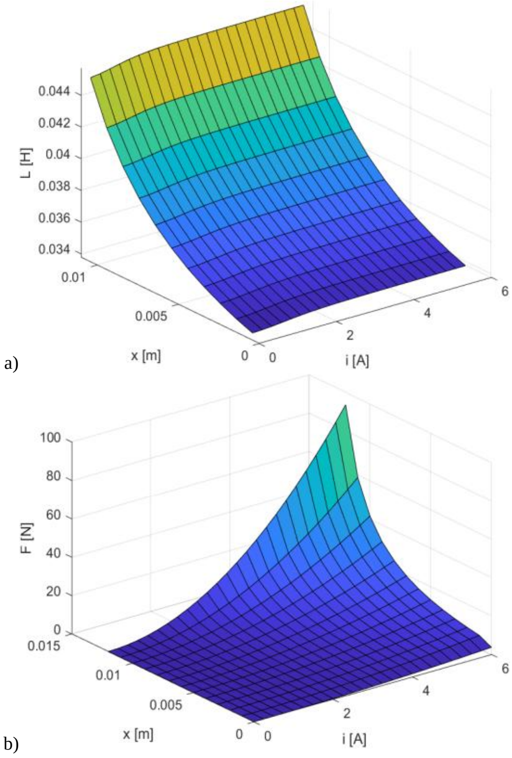

Fig. 5. Characteristics of the coil inductance L(x, i) (a) and the magnetic force $F_x(x, i)$ (b) in the function of the rotor position x and the coil current i

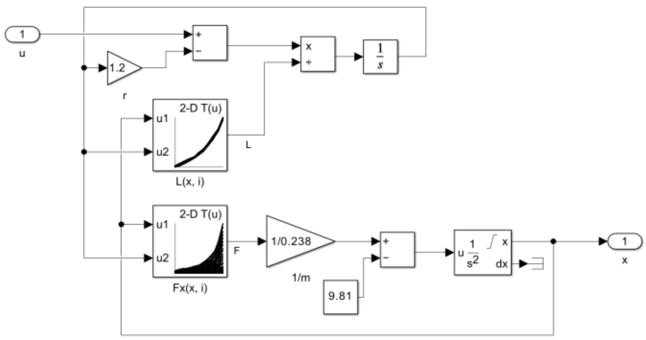

Fig. 6. The simulation model implemented in MATLAB/Simulink software

The following research step consisted of testing the simulation model's accuracy. For that purpose, a series of measurements were carried out on the test stand equipped with a PID controller. The simulation model and the real object were compared for various positions of the ball x and the same parameters of the PID controllers.

In Fig. 7 is presented the required position of the ball (href), the position obtained from the simulation (simulation), and the position obtained from the measurement (measurement).

It can be seen that results obtained from the real object have higher overshoot values than the simulation results. In Fig. 8, errors between the set position of the ball and the positions obtained from simulation and measurement are presented. The maximal values of errors occur when the sphere change its position. The visible triangle interferences in the position signal of the real object are caused by the H-bridge used to supply the coil.

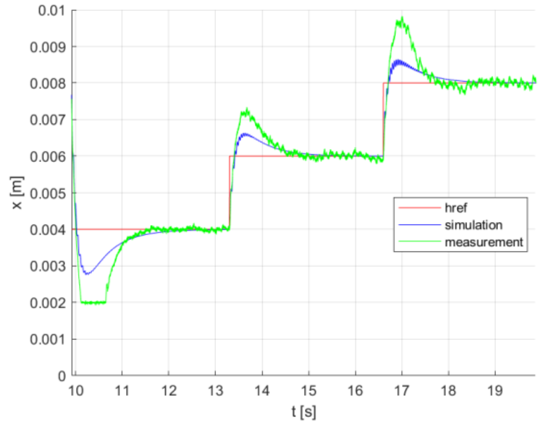

Fig. 7. Position of the ball obtained from the simulation and measurement

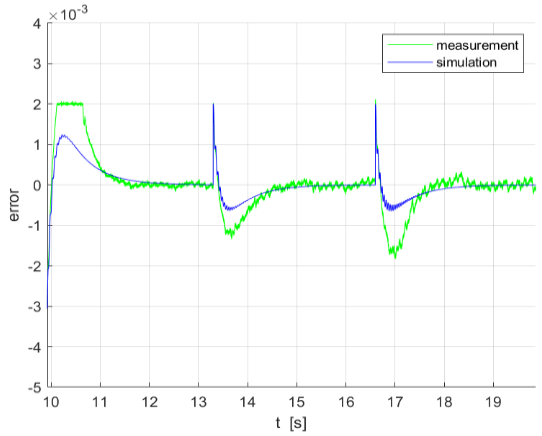

Fig. 8. Comparison of the position error obtained from the simulation and measurement

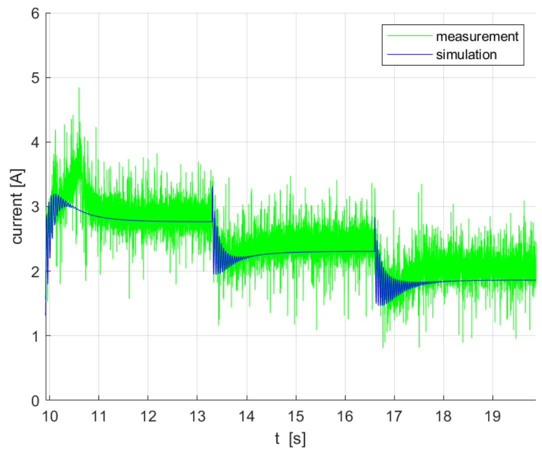

Fig. 9. Comparison of measured and simulated current

3. Description of the control system

Fig. 9 presents the model created in MATLAB/Simulink software, which was used to simulate the ball position. The discrete PID controller was used in the first step of the control system's design. The control system (Fig. 9) consists of the simulation model for the levitation system, the feedback loop with the discrete PID controller, the block for the set value, the saturation block to limit the value of the duty cycle, and an addition block to add to the control signal duty cycle 50%.

The parameters of the PID controller were determined using an engineering method. Since the results of such control are unsatisfactory, the issue of designing a more complex controller was addressed to achieve better results. An algorithm was developed using genetic algorithm technology, PID controller, and linear interpolation. The combination of these solutions allowed better results to be achieved [8].

The genetic algorithm was used to determine the PID controller settings, which works by iterative selection, crossover, and mutation of a population of solutions. An additional parameter, which is an indicator of quality, is the integral of the square value of the error. Once the results were obtained, the quality indicator was checked successively in the model and then on the real object. The first population was entered as initial conditions to minimize the number of mathematical operations. The parameters from the manual tuning were entered first, followed by the data obtained from the first calculation of the genetic algorithm. Parameters of the PID controller were determined for three operating points, that is, for the minimal, the center, and the maximal positions of the ball. The obtained results were fed into a suitable algorithm based on linear interpolation logic, approximating the PID controller settings over the entire operating range of the system (Fig. 10). The task of this algorithm was to select the gains of the individual PID controller parameters depending on the reference value. This combination of different solutions resulted in an adaptive controller, which calculated settings are based on the model (Fig. 11).

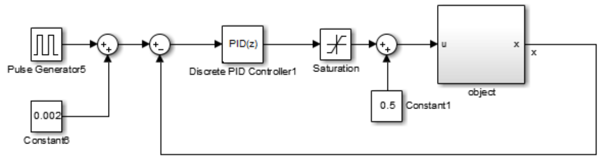

Fig. 9. Control system with traditional PID(z)

To assess the correct operation of the proposed controller and compare it to a classic PID controller, the integral of the square value of the error was used. As shown in the graph in Fig. 12, the overshooting of the system with settings selected by the genetic algorithm is similar to the manual settings. At the same time, the settling time is visibly lower for the system with settings chosen by the genetic algorithm. The oscillations in the vicinity of the reference value for the settings determined by the genetic algorithm are slightly larger but relatively small compared to the target value. The integral of the square value of the error (ISE) and the integral of the absolute value of the error (IAE) are larger for the manual settings (Tab. 1), which is mainly due to the different settling times. This can be seen from Fig. 13.

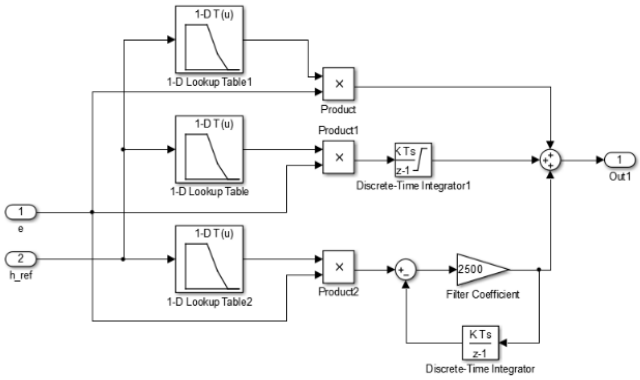

Fig. 10 Construction of the PID controller with linear interpolation

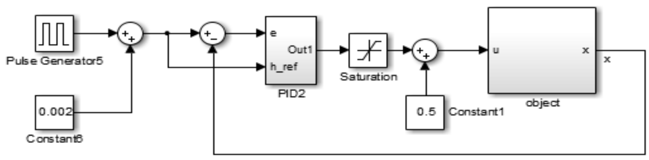

Fig. 11. Control system with PID controller and linear interpolation

Table 1. Integral quality indicators

PID tuning method	ISE [m]	IAE [m]
Manual	0.15626	118.9311
Genetic algorithm with linear interpolation/PID	0.073273	72.6039

In the case of manual settings, the overshoot takes longer than in the case of settings obtained from the genetic algorithm, with a reference value of 8 mm, with the genetic algorithm having a higher number of oscillations.

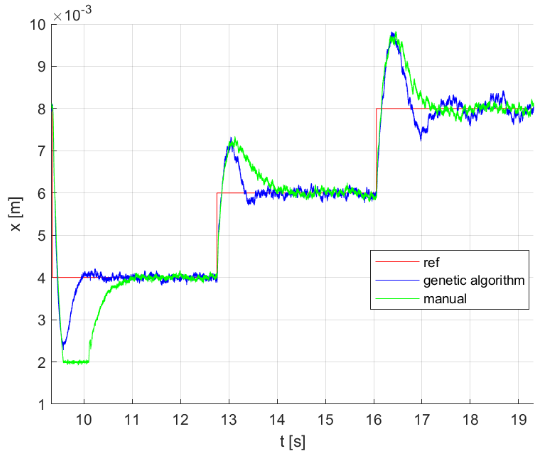

Fig. 12. Comparison of the ball position for the PID controller with parameters set manually (manual) and generated by the GA for the step change of the ball position

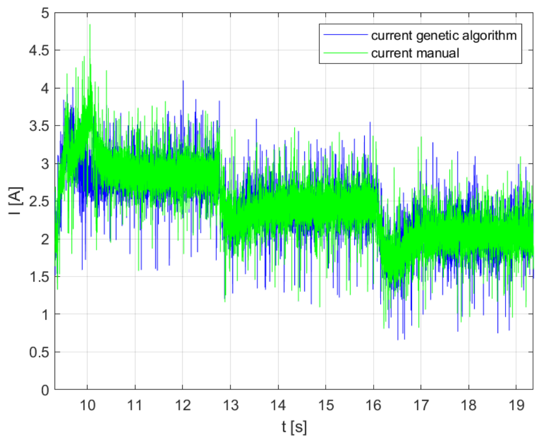

Fig. 13. Comparison of the coil current for the PID controller with parameters set manually (manual) and generated by the GA for the step change of the ball position

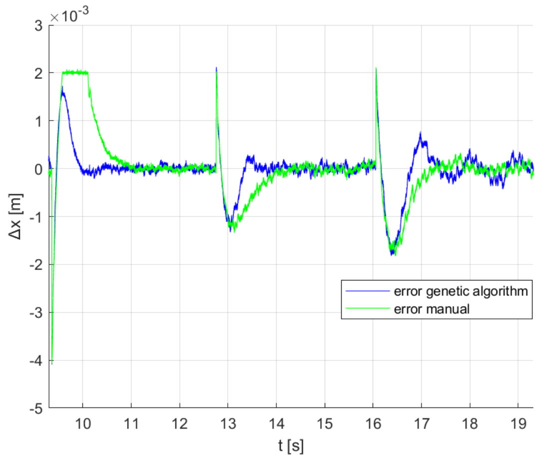

Fig. 14. Comparison of the position error Δx for the PID controller with parameters set manually (manual) and generated by the GA for the step change of the ball position

For the sinusoidal reference signal, illustrated in Fig. 15, similar to the stepped signal, the PID controller parameters obtained from the genetic algorithm are better than the parameters selected by the engineering method. The average value of the position controlled by the regulator with parameters tuned using a genetic algorithm is approximately equal to the reference position. In the case of manual settings, the position of the ball is slightly offset from the set position. In addition, the position error Δx is significantly higher for manual settings, as shown in Figure 16.

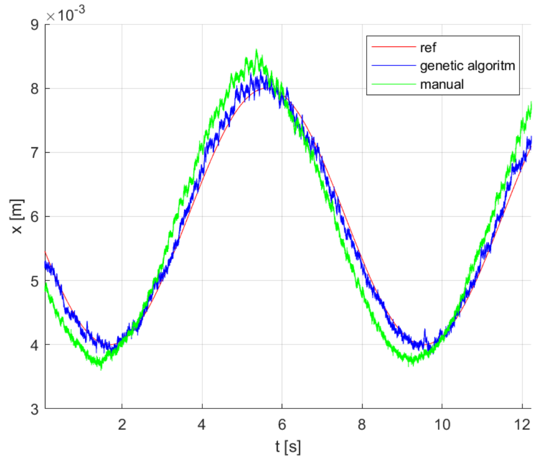

Fig. 15. Comparison of the ball position for the PID controller with parameters set manually (manual) and generated by the GA for the sinusoidal change of the ball position

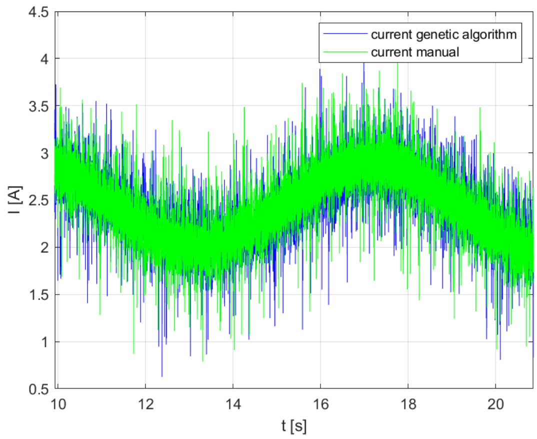

Fig. 16. Comparison of the coil current for the PID controller with parameters set manually (manual) and generated by the GA for the sinusoidal change of the ball position

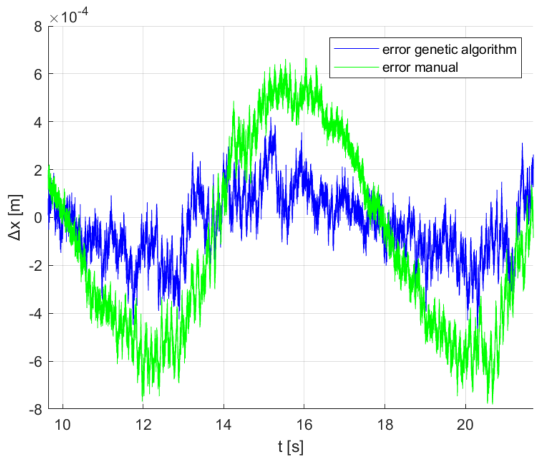

Fig. 17. Comparison of the position error Δx for the PID controller with parameters set manually (manual) and generated by the GA for the step change of the ball position

4. Summary

This paper presents a design for a control system for the levitating ferromagnetic ball using PID controllers. The first approach was to determine the settings using an engineering method. The second method used the genetic algorithm to determine the PID controller parameters. Additionally, linear interpolation logic was used to change the settings for the different operating points smoothly. Once the controllers were obtained, verification tests were carried out. The second controller performs much better. Fig. 12 clearly shows that the error decreases faster for all operating points, where overshot is the same. Fig. 15 shows that, for a sinusoidal reference signal, the second controller also performs better. The integral from the square value of the position error and the integral from the absolute value of the position error were also calculated and are presented in Table 1. These results clearly show that the controller with the settings determined by the genetic algorithms is better.

References

[1] Fleming P. J., Purshouse R. C.: Genetic Algorithms in Control Systems Engineering. Unbehauen H.: Control systems, robotics and automation. Volume XVII. Eolss Publishers Co. Ltd., Oxford 2009.

[2] https://www.balluff.com/pl-pl/products/BAW002W (available: 21.05.2025)

[3] https://www.dspace.com/en/pub/home/products/hw/singbord/ds1104.cfm (available: 21.05.2025)

[4] https://www.kamansensors.com/industry/magnetic-bearings/ (available: 12.04.2025).

[5] Hyung-Woo Lee, Ki-Chan Kim, Ju Lee: Review of maglev train technologies. IEEE Transactions on Magnetics 42(7), 2006, 1917–1925 [https://doi.org/10.1109/tmag.2006.875842].

[6] Lambora A., Gupta K., Chopra K.: Genetic Algorithm- A Literature Review. International Conference on Machine Learning, Big Data, Cloud and Parallel Computing (COMITCon), Faridabad, India 2019.

[7] Meeker D.: FEMM 4.0, User's Manual. University of Virginia, Virginia, 2004.

[8] Płoszajski G.: Automatyka. WSiP, Warszawa 1995.

[9] Unbehauen H.: System Analysis and Control: Classical Approaches. Unbehauen H.: Control systems, robotics and automation. Volume II. Eolss Publishers Co. Ltd., Oxford 2009.

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