UDC 629.359, 681.513.1

Experimental study of stabilizing the position of a device for transporting small-sized cargo

Yuriy Romasevych[1], *Oleksandr Zarivnyi*[2]

[1, 2]National University of Life and Environmental Sciences of Ukraine,
15, Heroiv Oborony St., Kyiv, Ukraine, 03041
[1]romasevichyuriy@ukr.net, https://orcid.org/0000-0001-5069-5929,
[2]alex-zar@ukr.net, https://orcid.org/0009-0006-3532-9393

Received: 24.02.2025; Accepted: 28.03.2025
https://doi.org/10.32347/gbdmm.2025.105.0302

Abstract. An experimental study of the stabilization process of a small cargo transportation device is required to confirm the applicability of the theoretical method for synthesizing optimal motion control of such a device in practice. This paper describes the methodology for conducting such an experiment and the methods for evaluating the quality of such stabilization.

The expected outcome was to obtain experimental data verifying the quality of the developed control system for 11 sets of PID-controller coefficients. The controller coefficients that provided the best stabilization performance were selected. Additionally, experimental data with minimal error compared to theoretical data needed to be obtained.

The experimental study was conducted using a physical model of a two-wheeled transportation device for small cargo. The quality of position control was tested for eleven sets of PID-controller coefficients. Experimental data sets of the device's performance were collected, compared with theoretical data, and used to evaluate the quality of the stabilization process.

A comparison of theoretical and experimental data provided values for maximum and root-mean-square errors of the device's tilt angle, as well as errors in the maximum and root-mean-square angular velocity of the tilt. The damping decrement of oscillations ranged from 0.25 to 2.11. Among all the solutions, the best set of PID-controller coefficients from a practical point of view was selected (proportional k_1=-2,112, integral k_2=-1,756, derivative k_3=-1,38·10^{-7}). This result corresponds to the highest damping decrement (λ=2.11). The obtained results provide grounds for considering the optimal control synthesis methodology adequate and the experimental validation successfully completed.

Keywords: experimental study, two-wheeled device, motion control, unstable dynamic system, PID-controller, position stabilization.

INTRODUCTION

Transportation is one of the primary processes in any field of human activity. Transport means can be classified by weight, type, and the distance over which goods are moved. This article focuses on a two-wheeled device designed for transporting small cargo within residential areas, warehouses, or manufacturing premises [1].

As is known, two-wheeled vehicles are unstable dynamic systems that require constant control to maintain stability. A two-wheeled transport device, such as a scooter, lacks a mechanism to maintain stability when stopping. Therefore, the developed device includes a balancing mechanism that works on the principle of shifting the center of mass relative to the support points.

There are numerous approaches and methods for synthesizing optimal control for this class of devices. To solve this task, an adequate mathematical model of the device is required, along with the selection of a controller type, the formulation of a cost function, and the optimization of the controller's parameters to achieve the desired control outcome. From a practical standpoint, the goal is to apply theoretical results experimentally, namely, to experimentally verify the device's operation.

In [2], an experimental validation of the optimal control of the position of a two-wheeled device of the Segway type was conducted. The quality of control with LQR and SDRE was compared using a physical model of the device. A gyroscope-accelerometer was used to measure the pitch angle, with experimental data recorded at a frequency of 50 Hz. All calculations for the control process were performed on a computer, and the device contained only the module with sensors and drivers. Disturbances of the device's angular velocity (yaw angle) were applied. The results were evaluated graphically without additional calculations. The graphs showed the presence of disturbances and residual oscillations.

In [3], experimental studies of a Segway-type two-wheeled device were conducted in equilibrium position maintenance mode. The device also contains a weight-shifting mechanism to maintain balance when stopping. The results of the device's operation were presented in the form of graphs of the tilt angles and angular velocities of the device and the balancing mechanism. The criterion for evaluating control quality was the energy consumed during stabilization. Similar experimental studies were conducted in [4], but the obtained graphs of the tilt angle showed a significant level of disturbances that distorted the actual movement of the device in stabilization mode.

In [5], the study object was a two-legged wheeled device. Due to the two-jointed articulated legs, it can perform tilts and change its height. Accordingly, the control of such a device must account for these changes and adapt. For this, an LQR controller with a fuzzy observer was applied. The first stabilizes the equilibrium position, while the second adjusts the coefficients of the LQR controller according to the change in the device's height. A PID-controller was also used to change the device's height. Experimental studies of the device's stabilization were conducted using a physical model, a control board, and a gyroscope-accelerometer sensor (MPU9250). The quality of operation was assessed solely based on the graphs. Some graphs displayed significant disturbances, complicating their analysis.

In [6], experimental studies of the quality of control of a Segway-type two-wheeled device were carried out. An LQR controller was applied as the control doctrine. Optical encoders on the wheel axes and an inclinometer on the platform were used as sensors. The experiment was conducted in three device modes: translational motion with different loads, rotational motion, and movement on an inclined plane. The sensors were polled at a frequency of 1 kHz. The results were presented in the form of device motion graphs (tilt angle, tilt angular velocity, and linear displacement relative to the surface). The study results were shown in graphs and numerical parameters: maximum deviations in the tilt angle, transient process time parameters, and actual linear displacement data.

In [7], experimental studies were conducted on the quality of operation of a two-legged wheeled device in different operating modes. The device contained an inertial position sensor and encoders on the wheel axes. The actuators consisted of two-wheel drives and two drives for adjusting the length of the device's legs. The data collection frequency and program calculations were 400 Hz, and only the built-in filter of the inertial sensor was used. The quality of the obtained data was assessed visually from the device operation plots.

In [8], the research focused on the controlled sliding (drifting) of wheels on a physical model of a car scaled 1:10. A distinctive feature of this work was the dual control of the measured quantities. The experimental data of the device's operation were obtained both from the device's sensors and externally through an optical camera with computer vision. The results were presented as graphical dependencies of theoretical and experimental data, along with the difference between them. A qualitative and quantitative analysis of the results was performed.

In [9], experimental validation of theoretical research results on the control of the motion of a Segway-type two-wheeled device was conducted. The physical model was implemented using ready-made Lego EV3 modules. The results were presented as graphical dependencies and controllability matrices. Numerical results were presented in terms of the critical tilt angles at which the device maintains equilibrium.

In [10], the methodology for conducting and collecting experimental data on the operation of a robot manipulator in a desired motion trajectory mode was well demonstrated. The control quality was assessed based on plots and tabular numerical values of the settling time and overshoot levels for each experiment. A similar methodology for experimental studies was applied to a six-legged wheeled platform model [11]. The experiments were conducted in motion planning modes using LIDAR, infrared cameras, and a height sensor. Two personal computers and a microcontroller were used for data collection and device operation. The obtained data were presented as plots, and the analysis was performed using numerical data from the device's operation.

PURPOSE OF THE PAPER

For 11 sets of PID-controller coefficients, conduct an experimental study on the quality of device control in the stabilization mode. Collect experimental data and evaluate the quality of position stabilization. Based on the obtained data, the best results in terms of theoretical compliance and operational performance will be selected.

MATERIALS AND METHODS

The experimental study utilized a physical model of the device [1] (Fig. 1a). The key parameters of the device's operation include its tilt angle α (Fig. 1b), deviation angle of the balancing mechanism β (Fig. 1c), and their time derivatives.

A PID-controller is used to stabilize the position of the device:

$$\beta = k_1 \cdot \alpha(t) + k_2 \cdot \int \alpha(t)dt + k_3 \cdot \dot{\alpha}(t), \quad (1)$$

where k_1, k_2, k_3 are the proportional, integral, and derivative coefficients of the controller, respectively.

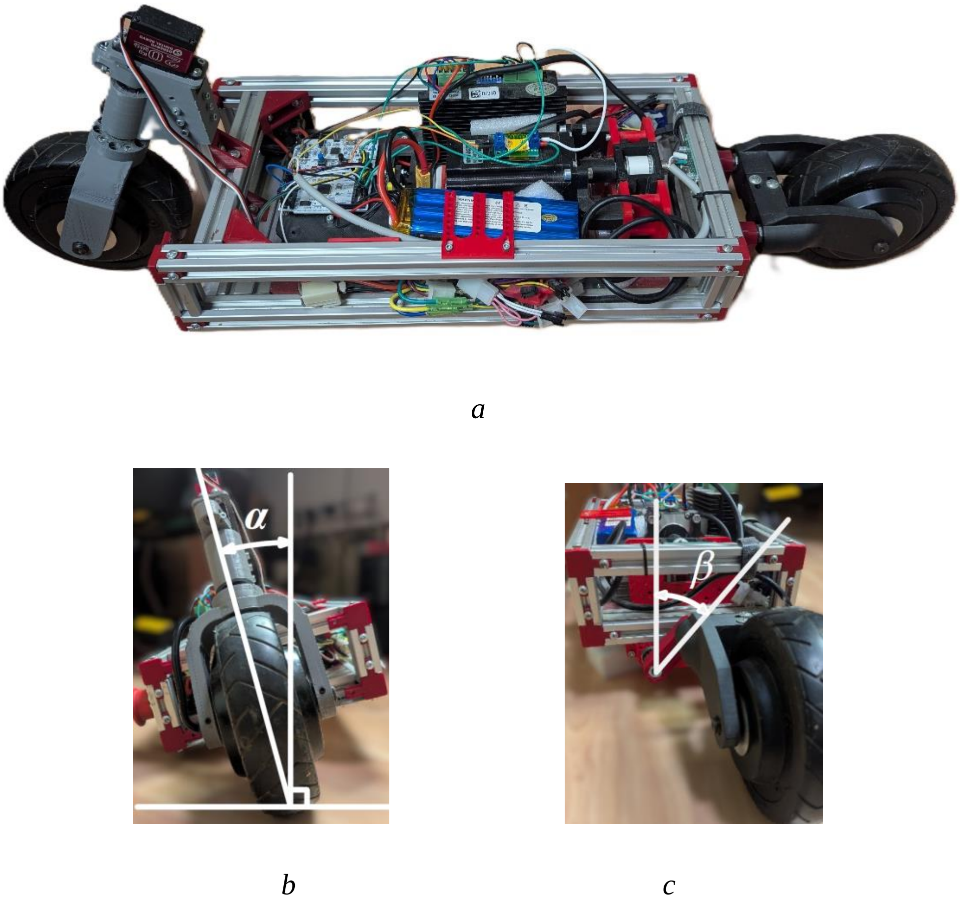


Fig. 1. Physical model of the device for transporting small-sized cargo: a) general view; b) designation of the device tilt angle α; c) designation of the inclination angle of the balancing mechanism β

The theoretically obtained controller coefficients, which are presented in Table 1, are subject to experimental verification. These coefficients were derived through the synthesis of optimal control using the mathematical model of the device [12], the optimization criterion, and the VCT-PSO optimization method [13].

During the experiments, a series of disturbances (impulses) were applied to the device in equilibrium, activating the balancing mechanism to maintain stability.

During the experiment, data on the tilt angle and angular velocity of the device were recorded at a frequency of 333 Hz using the COM-port monitor of a computer. As a result, sets of experimental data were collected for the device operating in stabilization mode according to the computed solutions for 11 different sets of controller coefficients.

The experimental data were filtered using a finite impulse response (FIR) low-pass filter [14] with a cutoff frequency of 30 Hz.

The conformity of experimental and theoretical data was assessed based on the computed error of the tilt angle (E_α) and angular velocity of the device ($E_{d\alpha}$). The tilt angle error arrays were calculated using the following formula:

$$E_\alpha = A_{\exp} - A_{theor}, \tag{2}$$

where A_{ex}□ – the array of experimental tilt angle values of the device; A_{theor} – the array of theoretical tilt angle values of the device.

Next, from the obtained error array, the root mean square ($E_{\alpha.RMS}$) and maximum ($E_{\alpha.\max}$) errors were determined using the following formulas:

$$E_{\alpha.RMS} = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} E_{\alpha.i}^2}, \tag{3}$$

$$E_{\alpha.\max} = \max\left(\left|E_{\alpha.i}\right|\right), \tag{4}$$

where $E_{\alpha.i}$ – is the i-th error value from the array E_α; i – is the index that runs from 1 to n (the size of the experimental data).

Similar calculations (2-4) were performed on the arrays of experimental and theoretical angular velocity data. As a result, numerical values for the maximum ($E_{d\alpha.max}$) and root mean square ($E_{d\alpha.RMS}$) errors of angular velocity were obtained.

Logarithmic decrement of oscillation damping was used to estimate the stabilization speed of the device's position. It shows how quickly the initial disturbance decreases with each oscillation period. The decrement is denoted by the symbol λ and is calculated using the following formula:

$$\lambda = \ln(A_t / A_{t+T}), \tag{5}$$

where A_t – is the amplitude of oscillation (tilt angle of the device) at time t; A_{t+T} is the amplitude of the oscillation that occurred at a time T after the previous one.

RESEARCH RESULTS

Table 1. Theoretical PID-controller coefficients

Controller Coefficients	Numerical values for different parameter sets										
	1	2	3	4	5	6	7	8	9	10	11
k_1	-2.103	-2.121	-2.112	-2.103	-2.114	-2.123	-2.117	-2.105	-2.120	-2.113	-2.126
k_2	-1.015	-1.725	-1.756	-0.658	-1.691	-1.755	-1.747	-0.845	-1.742	-1.747	-1.693
k_3	$-2.19\cdot10^{-5}$	$-5.13\cdot10^{-6}$	$-1.38\cdot10^{-7}$	$-1.62\cdot10^{-5}$	$-5.58\cdot10^{-7}$	$-1.32\cdot10^{-6}$	$-5.72\cdot10^{-8}$	$-1.33\cdot10^{-5}$	$-6.10\cdot10^{-6}$	$-4.92\cdot10^{-6}$	$-2.96\cdot10^{-7}$

Table 2. Results of the comparison of theoretical and experimental data regarding the dynamics of the PID-controller for device position stabilization

№	Numerical values of the evaluation indicators				
	$E_{\alpha.\max}$, rad	$E_{\alpha.RMS}$, rad	$E_{d\alpha.\max}$, rad/s	$E_{d\alpha.RMS}$, rad/s	λ
1	0.00386	0.00178	0.0412	0.0128	1.58
2	0.00392	0.00235	0.0404	0.0165	1.47
3	0.00940	0.00443	0.0396	0.0142	2.11
4	0.00652	0.00283	0.0537	0.0208	0.76
5	0.008036	0.00386	0.0341	0.0143	0.64
6	0.005917	0.00251	0.0425	0.0150	0.25
7	0.00325	0.00155	0.0218	0.00997	0.90
8	0.00860	0.00310	0.0405	0.0170	0.28
9	0.00585	0.00308	0.0404	0.0176	0.45
10	0.0112	0.00487	0.0782	0.0238	1.55
11	0.00378	0.00199	0.0235	0.00669	0.59

The results of the comparison between experimental and theoretical data that were obtained are entered into Table 2. Among the results, the smallest error in the deviation of theoretical and experimental data corresponds to the sets of coefficients of the PID-controller No. 7 and No. 11.

According to the oscillation damping decrement, solution No. 3 has the best indicator (λ=2.11). This makes the solution the most attractive for use as a controller in the device's position stabilization mode. In addition, plots of the tilt angle and angular velocity of the device's movement in the equilibrium position stabilization mode were built (Fig. 2).

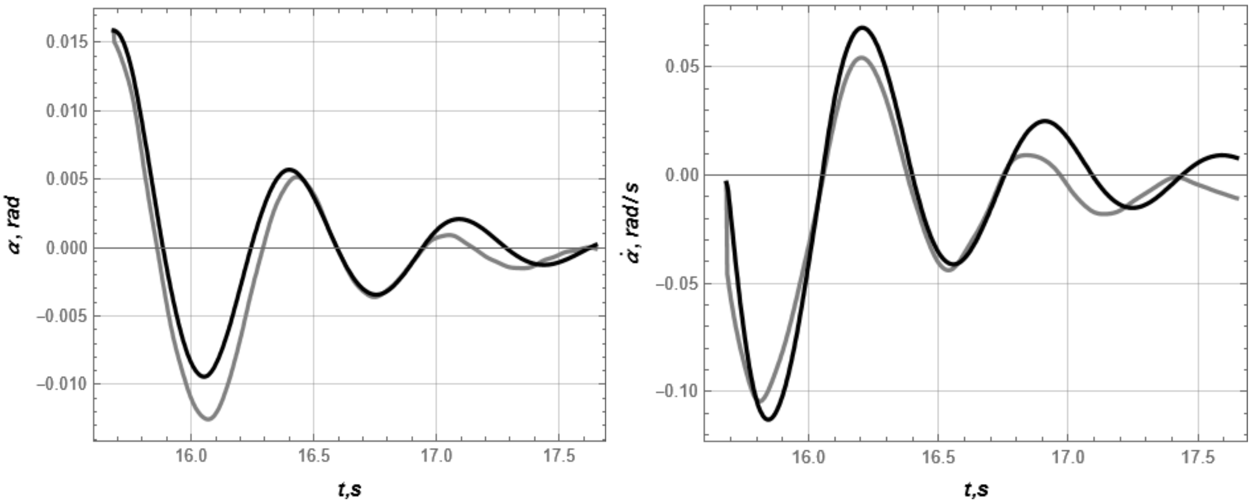
The obtained plots and numerical data demonstrate partial agreement between experimental results and the mathematical model of the device's position stabilization, influenced by multiple factors.

The dynamic parameters of the model (moments of inertia of the frame, wheel, and motor) are determined approximately and are considered constant during the device's operation. In reality, the moment of inertia of the frame changes due to the change in the distance from the pivot point to the center of mass of the frame.

To simplify the calculations, it was assumed that the device's frame has a uniform mass distribution and that there is no imbalance in the design, which does not fully reflect the actual situation. Another factor affecting the deviation of experimental data from theoretical values is that the wheel contacts the surface at a single point (for a more complete description, the contact patch should be considered).

When considering the software part of the device, unaccounted factors include the processing speed of the computational and execution electronic components, namely the speed of reading and processing data from the gyro-accelerometer and the execution of the main program code in the microcontroller core.

Despite all the inaccuracies, the goal has been achieved, namely, the development of optimal motion control for the device in position stabilization mode, which shows good implementation quality.



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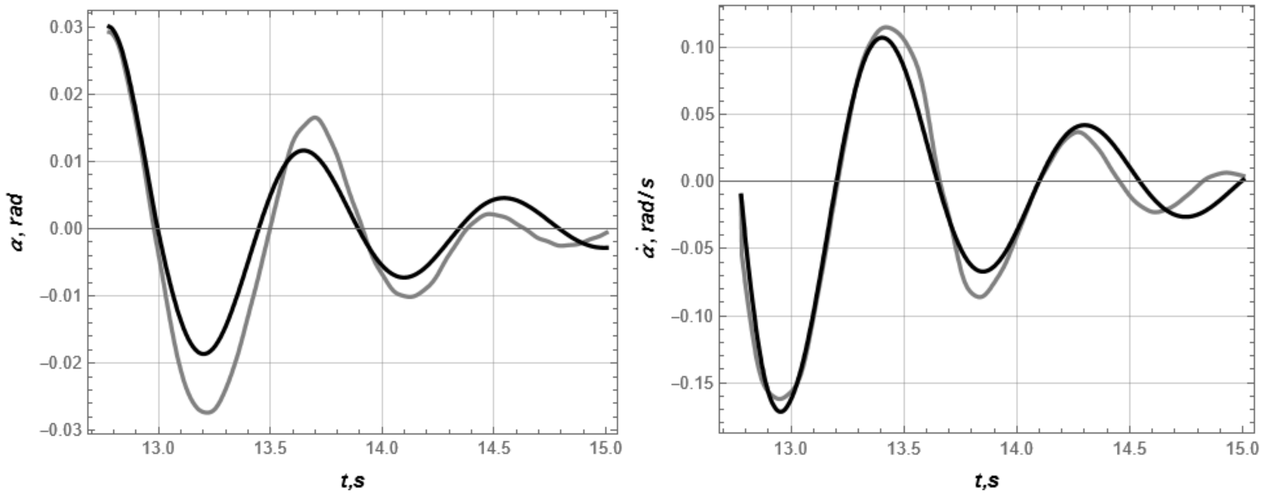

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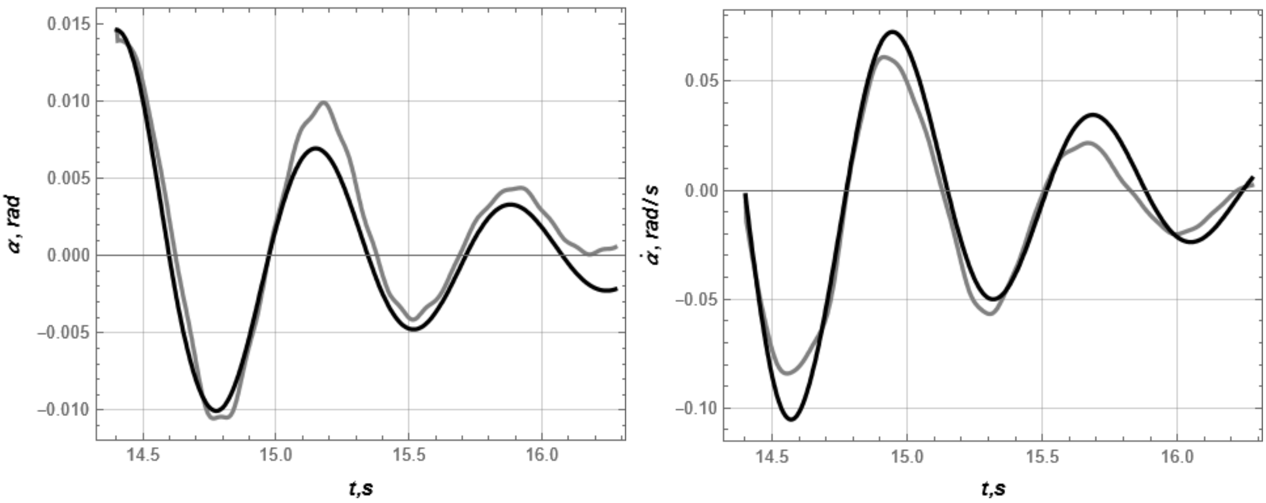

c

Fig. 2. Plots of the changes in experimental (black color) and theoretical (gray color) tilt angles and angular velocities of the device during the stabilization of its position: *a* - experiment No. 1; *b* - experiment No. 3; *c* - experiment No. 7

CONCLUSIONS

When comparing theoretical and experimental data, the values for the maximum (0.00325…0.0112 rad) and root mean square (0.00155…0.00487 rad) errors of the device's tilt angle, as well as the maximum (0.0218…0.0782 rad/s) and root mean square (0.00669…0.0238 rad/s) errors of the device's angular velocity, were obtained. The oscillation damping decrement ranged from 0.25 to 2.11. Among all the solutions, the best from a practical perspective is the result in No. 3, which has the most significant oscillation-damping decrement. The obtained result provides grounds for considering the methodology for synthesizing optimal control effectively and the task of experimentally verifying the device's position stabilization as accomplished.

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Експериментальне дослідження стабілізації положення пристрою для переміщення малогабаритних вантажів

Юрій Ромасевич[1], *Олександр Зарівний*[2]

[1,2]*Національний університет біоресурсів і природокористування України*

Анотація. Для підтвердження застосовності теоретичного методу синтезу оптимального керування рухом пристрою для транспортування малогабаритних вантажів постає питання проведення експериментального дослідження такого керування на практиці. В даній роботі описано методику проведення експериментального дослідження процесу стабілізації положення пристрою для транспортування малогабаритних вантажів та методи оцінки якості такої стабілізації.

Очікуваним результатом було отримати експериментальні дані перевірки якості розробленого керування для 11 наборів коефіцієнтів ПІД-регулятора. Надалі з них обрано коефіцієнти регулятора, які найкраще себе показали в процесі стабілізації положення пристрою. Також отримано експериментальні дані роботи пристрою з мінімальною похибкою при порівнянні з теоретичними даними.

При проведенні експериментального дослідження використано фізичну модель двоколісного пристрою для транспортування малогабаритних вантажів. Було перевірено якість реалізації регулювання положення пристрою на одинадцяти наборах коефіцієнтів ПІД-регулятора. Зібрано масиви експериментальних даних роботи пристрою, проведено порівняння з теоретичними даними та проведено оцінку якості процесу стабілізації положення пристрою.

При співставленні теоретичних і експериментальних даних отримано показники максимальних та середньоквадратичних похибок кута нахилу пристрою, показники похибок максимальної та середньоквадратичної кутової швидкості нахилу пристрою. Декремент згасання коливань знаходився в межах 0,25…2,11. Серед усіх розв’язків обрано найкращим з практичної точки зору є результат набору наступних коефіцієнтів ПІД-регулятора: пропрорційний k_1=-2,112, інтегральний k_2=-1,756, диференціальний k_3=-1,38·10^{-7}. Цей результат відповідає найбільшому декременту згасання коливань (λ=2,11). Отриманий результат дав підстави вважати методику синтезу оптимального керування дієвою, а задачу експериментальної перевірки виконаною.

Ключові слова: експериментальне дослідження, двоколісний пристрій, керування рухом, нестійка динамічна система, ПІД-регулятор, стабілізація положення.