Development of Two-Wheeled Balancing Robot Optimal Control System based on Its Feedback Linearization

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***Abstract*—The scope of this research is to compare performance of two main methods of feedback linearization of plants with internal dynamics for the problem of a two-wheeled balancing robot control. The considered methods of linearization include: 1) approximate feedback linearization; 2) partial feedback linearization with stability assessment of the plant internal dynamics using Lyapunov approach. In this case, considering both algorithms, pseudo-control signal value is calculated by an optimal state controller (linear quadratic – LQ – regulator). Experiments with the synthesized nonlinear controllers are conducted using the plant mathematical model in Simulink and the real LEGO EV3 balancing robot. Experiments demonstrate the performance efficacy and the effectiveness of both methods of feedback linearization of the plant under consideration. Taking into consideration that the aim of the future research is to develop an adaptive controller for the robot, the approximate linearization method is chosen as the basis of such regulator, since the partial linearization approach potentially increases its dimension.**

Keywords—nonlinear control; feedback linearization; approximate linearization; partial linearization; balancing robot.

I. INTRODUCTION

A problem of nonlinear optimal control of a two-wheeled balancing robot is considered. Such plants are characterized by several types of nonlinearities, which can be found in their mathematical description. For an instance, the rising of state coordinates to a power, their multiplication and application of trigonometric functions to them [1, 2]. However, existing methods of control of the balancing robots are mostly based on the plant model linearization near a certain point by means of Taylor series expansion. This allows to synthesize linear controllers like PID and state (linear quadratic – LQ) regulators [3, 4], which are able to guarantee the required control quality only in some small neighborhood of the linearization point (as a rule, it is the point of unstable equilibrium) [5]. At the same time, it is known that the application of nonlinear control laws, in some cases, allows to achieve both a significant improvement of the control performance and the expansion of the above mentioned neighborhood around the linearization point in comparison with linear regulators [6, 7]. In particular, considering the balancing robots, the nonlinear controller can stabilize the plant for the high values of a pitch angle, when the influence of nonlinearities is great. The aim of this research is to develop such a nonlinear regulator.

A well-known and developed approach to solve the above considered problem is to use a transformation known as the plant feedback linearization [6, 8]. It implies transition from a nonlinear system to an equivalent linear system, written in the Brunovsky canonical form [9]. In this case, the original control action is replaced by a new pseudo-control, and the state (in particular cases – the output) feedback is applied to the plant. Under such conditions, a regulator forming pseudo-control signal is usually a LQ controller, which parameters are calculated for a linearized plant. The resulting control action is linear for the system in the canonical form, but nonlinear for the initial system. In this paper, the LQ regulator parameters are obtained as a result of analytical optimization by solving the Riccati equation.

In some cases, the development of the nonlinear controller in accordance with the linearization approaches is complicated due to the plant internal dynamics [10, 11]. As a result, the feedback linearization splits the differential equations of the system into the equations of the external (linearized by feedback) and internal (non-linearized by feedback) dynamics. In this case, the validity of the obtained linear pseudo-control law depends on the stability of the internal dynamics [6, 12]

Two-wheeled balancing robots belong to a class of objects with the internal dynamics [10-12]. There are two main methods of such plants feedback linearization. The first is an approximate linearization proposed by Kokotovich in [13-15]. The main idea of this method is to find some output function that depends on state coordinates of the plant and maximizes its relative order. Having differentiated the obtained output function with Lie derivative, the transformation of the state coordinates into the canonical form and the linearization control law can be found. The second approach is a partial linearization [16], in which the linear controller is calculated for the state coordinates describing the linearized dynamics of the plant. Asymptotic stability of the control object internal dynamics is guaranteed by means of an additional regulator developed according to the second Lyapunov method.

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ВЫЧИСЛЕНИЕ ДОПУСТИМОЙ СКОРОСТИ ОБУЧЕНИЯ НЕЙРОСЕТЕВОГО РЕГУЛЯТОРА В ЗАДАЧЕ СТАБИЛИЗАЦИИ БАЛАНСИРУЮЩЕГО РОБОТА

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Ключевые слова: балансирующий робот; нейросетевое управление; устойчивость; скорость оперативного обучения.

Аннотация: В работе решается задача управления балансирующим роботом на основе применения нейронной сети. Они выступает в роли регулятора и формирует на своем выходном слое управляющее воздействие для объекта (напряжения для левого и правого двигателей). Оперативное обучение такой нейронной сети необходимо для улучшения качества управления роботом в условиях изменения его параметров или смены режима работы. При реализации такого обучения актуальным является вопрос о выборе моментов времени, когда оно необходимо, и величины его шага. Именно поэтому в работе была рассмотрена проблема выбора предельной скорости оперативного обучения, непосредственно связанная с оценкой устойчивости изучаемой системы управления, поскольку излишне высокие скорости обучения могут привести к переходу объекта в неустойчивое состояние. В работе предложен подход, основанный на втором методе Ляпунова и позволяющий, не имея модели объекта управления, определять верхний допустимый предел для скорости обучения нейронной сети в текущий момент времени в различных ситуациях.

1. Введение

Ранее, на основе анализа недостатков существующих методов управления двухколесным балансирующим роботом, коллективом авторов данной работы был предложен

Development of Balancing Robot Control System on the Basis of the Second Lyapunov Method with Setpoint-Adaptive Step Size

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Abstract **— The aim of this research is to develop an adaptive control system of a two-wheeled balancing robot based on a reference model and the second Lyapunov approach. Solving this problem, the following questions are considered: 1) a mathematical model of the robot reference dynamics is developed, 2) using the optimal control theory, a calculation of LQ controller parameters is made, 3) applying the second Lyapunov method, an algorithm to adjust the parameters of such controller is proposed. The step size is calculated in accordance with the proposed formula and depends on the current and previous setpoint values of one of the robot state coordinates. A real balancing robot and its model are used to conduct experiments, over the course of which the mass of the robot is increased by several times. The obtained results show that, despite the robot non-stationarity, the developed adaptive control system is able to follow the reference model output keeping the transient quality close to the desired one.**

Keywords — adaptive control system; second Lyapunov method; two-wheeled balancing robot; LQ regulator

I. Introduction

A problem of a two-wheeled balancing robot control is considered in this research. Such plants are unstable, multidimensional, non-stationary and characterized by several types of nonlinearities [1-3]. These facts are to be taken into account in order to develop an effective regulator for such a plant. The existing methods of balancing robots control, in most cases, are based on an assumption that the control object linearized model is known, so the regulator parameters can be calculated using optimal control methods [4, 5]. Such parameters are not adjusted in the process of the robot functioning [6]. These methods guarantee the required transients quality only in a small neighborhood of a point, at which the model linearization has been made (in many cases, this is the point of an unstable equilibrium) [7]. Moreover, such regulators cannot fully compensate the plant non-stationarity (the robot mass variation, center-of-gravity shift, etc.). At the same time, in order to make the balancing robots more widespread in people's everyday life, it is necessary to guarantee their effective control from the points of view of transients quality and energy consumption for a wide range of the robot parameters variation [8, 9].

A possible solution of the problem involved is the application of adaptive control methods [8]. Having excluded from consideration approaches supposing that the balancing robot model and possible variations of its parameters are known, since the identification of such plant in real time is rather a complex task, methods based on the reference model [10] are analyzed. The balancing robot is initially an unstable control object, so the main task is to make it stable. In this regard, the application of the adaptive control method based on the second Lyapunov approach is supposed to be promising [11]. Published books and papers having been analyzed, some works in which the Lyapunov method is applied to stabilize an aircraft and solve the Wing Rock problem were found [12, 13].

In this research, the method involved is proposed to be applied to control the balancing robot. This requires its adaptation and improvement. In particular, the regulator obtained in this study is able to control unstable plants. It adjusts its own parameters in both modes of functioning (stabilization and setpoint tracking), while the version from [12, 13] is able to do that only for the first of them.

The development of such an adaptive controller includes the following steps: 1) calculation of a mathematical model of the robot according to its known physical characteristics (model of the robot initial (nominal) state), 2) calculation of the nominal values of the parameters of the LQ controller for such model, 3) development of a controller online adjustment system with an adaptive step size, which depends on the value of the setpoint. Such system is based on the Lyapunov method and does not require subsequent re-identification of the robot. It is described in details in the following sections.

II. Balancing Robot Description

The kinematics of the balancing robot is shown in Fig.1. Its mathematical model is obtained with the help of the second Eulerian-Lagrangian method [14]. It is linearized in the point of the unstable equilibrium and shown as (1).

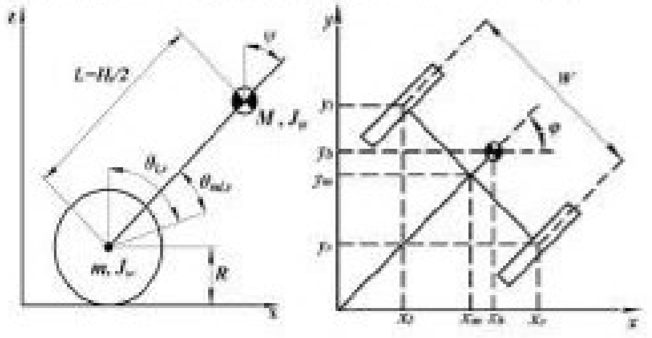

Fig. 1. Balancing robot kinematics.

Full-scale experiments are conducted on the basis of the LEGO EV3 balancing robot.

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Method of Maximum Permitted Learning Rate Calculation for Neural Controller of Balancing Robot

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***Abstract*—This research is to solve a problem of sustainability of a balancing robot controlled by an artificial neural network. The mentioned network acts as a regulator and calculates at its output layer a control action for the plant. Online training of such a network is necessary to improve the quality of the robot control since it changes its parameters or a mode of functioning in the course of operation. Implementing such training, the question of the learning rate limitation arises sharply. It is directly related to the assessment of sustainability of the control system under consideration. That is why a method based on the second Lyapunov approach is proposed to calculate the upper allowable limit of the online learning rate for the neural network controller under various conditions at each moment of its functioning. This method does not require the plant mathematical model. The efficiency of the approach is proved by experiments with a real balancing robot based on the EV3 platform.**

***Keywords*— sustainability, balancing robot, neural network control, learning rate value for online training**

I. Introduction

Among all the challenges of modern control theory, the problems of control and stabilization of mobile robotic systems under the conditions of changes of their parameters and an environment state are becoming more and more actual [1, 2]. This parameters non-stationarity is caused either by uncontrolled external disturbances or change of the mobile robot electrical and electromechanical components parameters during its long-term operation. All such robotic complexes can be divided into several groups according to the method of movement: wheeled, crawler, walking. As far as kinematics is concerned, the most maneuverable and simple to implement are wheeled robots with a small number of wheels N (in this study N =2). But at the same time, the task of their stabilization and position control is very complex since there is the need to control several state coordinates with the help of only one or two actuating mechanisms.

A great number of control schemes and methods for such unstable objects have been developed [3, 4, 5]. In the studies [6, 7] a comparative description of the majority of existing control algorithms for the considered class of objects is given. In most cases, linear quadratic (LQ) and PID controllers are used to solve the considered problem. The values of their parameters are calculated by optimal control methods using the obtained mathematical model of the robot, which parameters are constants calculated on the basis of the geometric dimensions and weight of the robot itself and the nameplate data about the values of the electric motors used to rotate the robot wheels.

As it is mentioned above, the parameters of the robot may change their values over time. In particular, considering a two-wheeled robotic loader, the weight of the transported load may change, as well as, the center of inertia might be shifted. All these can lead to a deterioration in the control quality or even the instability of the robot.

Therefore, it is advisable to use adaptive control systems, which is able to adjust the parameters of the controller in the course of functioning. In general, all such systems can be divided into two large groups: classical and intellectual [8].

Considering application of the classical adaptive systems, it is necessary either to have a reference model or permanently repeat the identification procedure for the plant using test signals. Both ways are difficult to be implemented for an unstable two-wheeled robot.

The disadvantages of the intelligent control methods, which are mostly based on the fuzzy logic and the neural networks [7], are as follows. As for systems using offline training, there is the difficulty of obtaining a training set (either an object model is needed, or samples are formed using an existing controller, but that does not allow to improve accuracy of the regulator). Considering the fuzzy logic, there is the complexity to provide the online adjustment of the normalization parameters used for the fuzzy controller input and output signals. As for systems using the online training, there are no restrictions on the learning rate value. Moreover, such systems do not usually take into account a priori knowledge of the particular control object [7]. Due to these reasons the considered methods can be applied to control models of an inverted pendulum, but not a real one. However, the neural networks are supposed to be the most promising approach because of their ability to both approximate and be trained online.

Having made such an analysis of the shortcomings of the existing control methods for the two-wheeled balancing robots, we have proposed our own direct neural network control algorithm [9, 10]. The network is not trained offline, but online at times that are strictly determined by a system of rules and restrictions, which takes into account the features of the balancing robot operation. A method to adapt the controller to the current robot operation mode is also proposed.

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PI-controller Fuzzy Tuner Based on Transient Quality Estimation to Control DC Drive Speed

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***Abstract*—The quality improvement of a DC drive speed control is the scope of this research. Classical PI-controllers with constant parameters does not provide high quality of transients for all DC drive functioning modes due to the motor nonlinearity and parameters nonstationarity. In this regard, there is a need to develop control systems, which take this fact into account and, to some extent, compensate it. The existing methods to develop DC drive adaptive control system are analyzed. It is concluded that the most promising way to solve this problem is to apply fuzzy logic to implement a PI-controller parameters adjuster. A comparison of the existing fuzzy tuners is made, and their shortcomings are found. A new fuzzy tuner is proposed and implemented taking into consideration the transients quality requirements. A model of a DC drive of NI-ELVIS II test bench is developed to conduct experiments. Full-scale experiments are also performed using this test bench. The results show that the proposed tuner, which uses an overshoot and a transient time estimation as input variables, is able to reduce the overshoot value by 15% comparing to the classical speed PI-controller and by averagely 10% in comparison with the exiting tuners under the conditions of the DC drive parameters nonstationarity, while the transient time remains the same.**

***Keywords*—DC drive, PI-controller, fuzzy tuner, overshoot, transient time**

I. Introduction

Classical PI-regulators with constant parameters are the most commonly used industrial controllers [1]. At the same time, they have a significant drawback due to the fact that they are linear, while most real control objects are nonlinear [2]. For example, the nonlinearity of DC drives is usually caused by parameters value change of a motor and a thyristor converter, the drive mechanics wear, etc. The above mentioned controllers application to such drives often eventually results in energy consumption increase and control quality deterioration, which is characterized by high values of overshoot, steady-state error and transient time [3].

Effective control of the DC motor to meet the high transients quality requirements is possible through the use of adaptive control systems. So, the development of such a system is an actual problem. The existing methods to solve it are analyzed in the following section.

II. Analysis of Existing Methods

A DC drive adaptive drive control system can be developed either by changing the standard P and PI algorithms to a new (nonlinear) one or taking them as base ones to implement online adjustment of their parameters. Both ways are considered further.

For an instance, methods to develop robust controllers using adaptive observers of state coordinates are shown in [4, 5]. Their disadvantage is the need to have an adequate model of the control object, which identification is a difficult task under real production conditions.

Fuzzy controllers are also used as an alternative to classic PID-regulators [6-8]. In these papers studies are presented to compare the effectiveness of the classical PI-controller and the fuzzy PI-controller. Their authors justify the relevance of the fuzzy regulators application by the fact that the classical PI-controller does not provide high control quality due to the electric drives nonlinearity [8]. In this case, the functioning of the PI-controller is characterized by a high value of overshoot and low quality of disturbances rejection. The fuzzy PID controller provides a better control quality for complex systems, which is reflected in good dynamic response, low overshoot value and transient time [6]. At the same time, neither test signals, nor control object model are required. In each of the studies under consideration the simulation results show the advantages of the fuzzy controller comparing to the classical PI-controller.

However, it is difficult to implement these results in practice. The fact is that the use of the adaptive regulators as an alternative to classical PI-regulators is complicated due to design features of electric drives, which do not allow such a replacement in most cases. The structure of the control system is usually fixed-programmed and cannot be changed. But it is possible to adjust the parameters of the controllers integrated into the drive. Their values can be transmitted to the drive from a programmable logic controller (PLC). So it can be concluded that the most appropriate way to develop the DC drive adaptive

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СИНТЕЗ СИСТЕМЫ УПРАВЛЕНИЯ БАЛАНСИРУЮЩИМ РОБОТОМ НА ОСНОВЕ ВТОРОГО МЕТОДА ЛЯПУНОВА[*]

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Введение

В работе решается задача управления двухколесными балансирующими роботами. Рассматриваемый класс объектов характеризуется неустойчивостью и наличием в математическом описании нескольких видов нелинейностей: возведение фазовых координат в степень и применение к ним тригонометрических функций [1]. Кроме того, при прикладном использовании подобных объектов возникает изменение значений его параметров (массы, положения центра масс и коэффициента трения колес о дорожную поверхность), что, в целом, и определяет необходимость применения адаптивных алгоритмов управления.

Применяемые на сегодняшний день системы управления балансирующими роботами, а в большинстве случаев это оптимальные LQ-алгоритмы и ПИД-регуляторы, не способны обеспечить компенсацию существенных параметрических возмущений, хотя и обладают определенной робастностью по отношению к ним [2].

Для решения данной проблемы в работе предлагается система адаптивного управления, основанная на втором методе Ляпунова [3] и использовании эталонной модели [4]. Для построения такого регулятора в исследовании: 1) получено математическое описание эталонной динамики робота (при номинальных значениях его параметров), 2) выполнен расчет LQ-регулятора, 3) на основе второго метода Ляпунова разработан алгоритм адаптации параметров регулятора, не требующий знания значений элементов матрицы коэффициентов усиления объекта.

Описание системы адаптивного управления

Полученная в исследовании система автоматического управления представлена на рис.1.

Рис. 1. Структурная схема контура управления

[*] Исследование проведено при финансовой поддержке РФФИ (грант № 18-47-310003 р_а).

Её структурная схема состоит из эталонной модели, блока регулятора и контура адаптации. В качестве эталонной модели применена замкнутая система

$$\begin{cases} \dot{x}_m = (A - BK)x_m + BKr \\ y_m = Cx_m \end{cases}, \quad (1)$$

состоящая из математической модели робота [5], полученной при его номинальных параметрах и, ввиду неустойчивости рассматриваемого объекта, LQ-регулятора, рассчитанного для стабилизации такой системы посредством решения уравнения Риккати. Здесь K – матрица коэффициентов LQ-регулятора.

Для вывода вида закона управления и адаптации было получено уравнение в отклонениях

$$\dot{e}_m = A_m e_m + B\left(\tilde{k}_x x + \tilde{k}_r r\right), \quad (2)$$

где e_m – разница между выходом объекта и эталонной модели. Здесь $\tilde{k}_x = k_x^* - k_x$ и $\tilde{k}_r = k_r^* - k_r$ – разница между идеальными и реальными коэффициентами регулятора.

Векторы состояний для объекта x и эталонной модели x_m содержат по семь координат, описание которых приведено в [5].

Для получения закона управления и адаптации выберем функцию Ляпунова

$$V = e_m^T H e_m + |B|\left(\frac{1}{2}\tilde{k}_x^T \Gamma \tilde{k}_x + \frac{1}{2}\tilde{k}_r^T \Gamma \tilde{k}_r\right), \quad (3)$$

зависящей от ошибки e_m и разницы между идеальными и реальными коэффициентами регулятора. Здесь Γ – положительно определенная диагональная матрица. Для выбора значений ее элементов был предложен алгоритм, зависящий от текущего и предыдущего значений задания. Матрица H найдена как решение уравнения Ляпунова

$$A_m^T H + HA_m = -I. \quad (4)$$

Производная выбранной функции Ляпунова будет отрицательной при справедливости равенств

$$u = k_x e, \quad (5)$$

$$\dot{k}_x = -sgn(B)\Gamma^{-1} e_m^T He \quad (6)$$

и $\dot{k}_r = -\dot{\tilde{k}}_x$.

Тестирование системы на модели балансирующего робота

Экспериментальная проверка разработанной системы адаптивного управления была проведена на модели балансирующего робота в среде Matlab Simulink. Сравнение качества управления адаптивного регулятора производилось с оптимальным LQ-регулятором. При проведении таких экс-

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НЕЙРОСЕТЕВАЯ НАСТРОЙКА РЕГУЛЯТОРА СКОРОСТИ ПРИ УПРАВЛЕНИИ ЭЛЕКТРОПРИВОДОМ НА БАЗЕ SINAMICS DCM*

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Введение

Электроприводы постоянного тока до сих пор широко используются в промышленности, несмотря на известные недостатки [1]. К их числу можно отнести наличие щеточно-коллекторного узла, низкий КПД и необходимость частого обслуживания. Однако простота управления и возможность создания высокомощных приводов позволяет по-прежнему применять их, например, в металлургическом и горнодобывающем производствах. Зачастую это приводы, разработанные в 70 – 80-е гг. На многих заводах в настоящее время проводится их модернизация, однако она, как правило, затрагивает только систему управления, оставляя силовую часть таких приводов без изменений [1]. В свою очередь, наличие современных цифровых регуляторов дает возможность построения адаптивных систем управления для рассматриваемых электроприводов с целью компенсации их нелинейности и нестационарности.

Можно выделить два основных класса методов построения подобных систем: классические [2] и интеллектуальные [3]. В данной работе рассматривается применение одного из интеллектуальных методов (нейросетевого настройщика) [4] в системе управления промышленного электропривода. В отличие от других подходов, он не требует наличия модели объекта управления или явной эталонной модели, учитывает опыт инженера АСУТП и способен обучиться оперативно, выбирая шаг настройки автоматически.

Ранее [4] нейросетевой настройщик был реализован в среде Matlab и апробирован на модели электропривода. Задачей данной работы является его адаптация к системе управления электроприводами Sinamics DCM для возможности его последующего промышленного применения.

Система управления SINAMICS DCM

Электропривод постоянного тока Sinamics DCM фирмы Siemens является одним из наиболее распространенных современных приводов. По принципу подчинённого регулирования в него интегрированы контур регулирования тока и внешний по отношению к нему контур регулирования скорости. Цифровая система управления позволяет линейно изменять параметры K_p и T_n регулятора скорости в зависимости от величины, выбранной с помощью технологии Binector – Connector. Это может быть внешний сигнал. В данном случае к Sinamics DCM через Profibus был подключен контроллер Simatic S7-300. В его память помещен настройщик, выход которого передается на Sinamics DCM в виде телеграммы.

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Нейросетевой настройщик параметров ПИ-регуляторов

В целом настройщики не требуют изменения структуры системы регулирования. Адаптация достигается с помощью изменения параметров используемых регуляторов. В данном случае речь идет о ПИ-регуляторе скорости. Общая структура настройщика изображена на рис. 1.

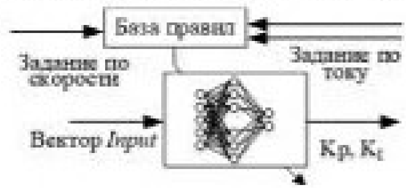

Рис. 1. Структурная схема настройщика (KI = KP / Tn)

База правил необходима для определения момента времени, когда качество переходного процесса отклоняется от требуемого (оценивается перерегулирование, статическая ошибка, колебательность). Также она вычисляет скорости оперативного обучения для каждого нейрона выходного слоя сети, которая, в свою очередь, вычисляет на своих выходах значения параметров ПИ-регулятора скорости. Ее входы – это вектор *Input*, включающий значения задания по скорости, ее фактическое и задержанное значения и текущий выход настраиваемого регулятора. Устойчивость системы управления с настройщиком оценивается с помощью метода, представленного в [5].

Результаты экспериментов

В качестве исследуемого электропривода в составе экспериментального стенда используется Sinamics DCM . На верхнем уровне автоматизации находится контроллер Simatic S7-314C 2 DP. Связь между контроллером, электроприводом и персональным компьютером построена с помощью сети Profibus DP. Для передачи данных управления используются SIEMENS Telegram. Электропривод Sinamics DCM инициализировал параметры регуляторов в ходе процесса ввода в эксплуатацию. Параметры регулятора контура тока (K_p = 0,43; T_n = 0,019 с) настроены с помощью измерения параметров якорной цепи (сопротивления и индуктивности), а параметры регулятора скорости (K_p = 2,51; T_n = 0,166) – при снятии кривой разгона. Перерегулирование в контуре скорости при такой настройке составило 13,5 %. Это же значение было внесено в

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ОЦЕНКА ВЛИЯНИЯ НЕЛИНЕЙНОСТЕЙ НА КАЧЕСТВО УПРАВЛЕНИЯ БАЛАНСИРУЮЩИМ РОБОТОМ

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EVALUATION OF NON-LINEARITIES INFLUENCE ON BALANCING ROBOT CONTROL QUALITY

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Аннотация. *Разработка автоматических систем управления обычно проводится по линеаризованным дифференциальным уравнениям, которые адекватно описывают реальный нелинейный объект управления только в малой окрестности точки линеаризации. Отсутствие учета влияния нелинейностей при практическом применении полученных систем управления часто приводит к невозможности эффективного управления в режимах работы и состояниях реального объекта, в которых наиболее существенное влияние на динамику оказывают нелинейности. В этой связи в данной работе проводится оценка влияния нелинейностей на качество управления балансирующим роботом, выделены классы вхождения нелинейностей в математическое описание робота и выбраны подходы к формированию закона управления, способного учитывать и компенсировать влияние нелинейностей.*

Ключевые слова: балансирующий робот, нелинейные объекты, моделирование, управление.

Abstract. *Automatic control systems are usually developed using linearized differential equations, which adequately describe a real nonlinear control object only in a small neighborhood of a linearization point. Considering practical application of the obtained control systems, unconsidered nonlinearities contribution often leads to impossibility of the plant effective control in such functioning modes and states, which are mostly influenced by such nonlinearities. In this regard, this paper scope is to evaluate the influence of the nonlinearities on the control quality of the balancing robot. Nonlinearities in the mathematical description of*