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A cascade pid controller design with cuckoo optimization algorithm (COA) and input shaping (IS)

Guguk kuşu optimizasyon algoritması (coa) ve giriş şekillendirme (IS) ile kaskat bir PID kontrolcü tasarımı

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A Cascade PID Controller Design with Cuckoo Optimization Algorithm (COA) and Input Shaping (IS)

Highlights

- *Controller Design with Cuckoo Optimization Algorithm*
- *Input Shaping for Performance Improvement*
- *Comparison of Classical Tuning Methods and Cuckoo Optimization Algorithm with Shaper*

Graphical Abstract

The Cuckoo Optimization method, which is commonly used in coefficient optimization of PID controllers, and input shaping have been cascaded. This proposed controller has yielded the optimal system response compared to ad hoc tuning methods and COA itself.

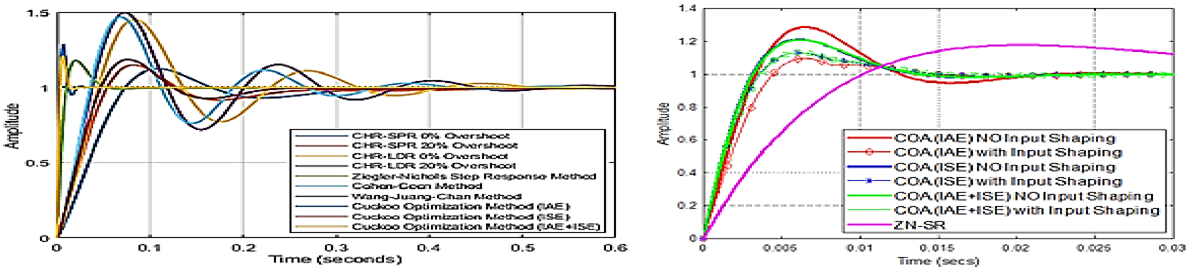

Figure. (a) Step response of classical methods and Cuckoo Optimization Algorithm, (b) reduced overshoot by Input Shaping

Aim

A cascade PID controller, optimized using the Cuckoo Optimization Algorithm (COA) and incorporating input shaping, has been designed to achieve faster response times and reduced overshoot.

Design & Methodology

The Cuckoo Optimization Algorithm has been used to optimize PID parameters, while the Input Shaping method has been employed to reduce overshoot in the system response.

Originality

The Cuckoo Optimization Algorithm, commonly used for PID optimization, has been combined with input shaping technique.

Findings

It has been observed that the controller optimized using the Cuckoo Optimization method exhibits more overshoot compared to the Ziegler-Nichols step response method, which is the best method among ad hoc tuning methods.

Conclusion

The proposed optimized cascade controller performed the best result in terms of IAE, ISE and ITAE, with the smallest overshoot and settling time.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

A Cascade PID Controller Design with Cuckoo Optimization Algorithm and Input Shaping

Araştırma Makalesi / Research Article

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ABSTRACT

From past to present, Proportional-Integral-Derivative (PID) controllers stand out as the most widely used types of controllers. Due to the high-performance requirements, experimentally determined controller coefficients necessitate the application of modern optimization techniques. In this study, Ziegler-Nichols, Chien-Hrones-Reswick, and Cohen-Coon methods, which allow parameter calculation through the open-loop system's step response method, were compared with the Cuckoo Optimization Algorithm for PID controllers designed for a brush-commutated DC motor with unknown parameters in the Matlab environment. The comparison was based on Integral of Absolute Error (IAE), Integral of Square Error (ISE), Integral of Time-weighted Absolute Error criterion. Similarly, the performance of the Cuckoo Algorithm was discussed in terms of stability margins and stability peaks. In this comparison, it was observed that the PID controller optimized with the Cuckoo Algorithm operated with high proportional and integral coefficients to minimize the cost function, resulting in overshoot in the system response. Input shaping, a commonly used method in open-loop control of both brushed and brushless DC motor systems, was integrated into the system to mitigate this overshoot. The hybrid controller achieved the best performance in terms of IAE, ISE and ITAE in the system response, with less overshoot compared to the other mentioned methods.

Keywords: Cuckoo optimization algorithm, PID controller, input shaping, classical controllers.

Guguk Kuşu Optimizasyon Algoritması (COA) ve Giriş Şekillendirme (IS) ile Kaskat Bir PID Kontrolcü Tasarımı

ÖZ

Geçmişten günümüze en çok kullanılan kontrolcü tiplerinin başında Oransal-Toplamsal-Türevsel (PID) gelmektedir. Katsayıları deneysel yöntemlerle hesaplanmış kontrolcüler, yüksek performans gereksinimleri sebebiyle modern optimizasyon tekniklerine ihtiyaç duymaktadır. Bu çalışma kapsamında, açık döngü sistemin adım cevabı yöntemiyle parametre hesabı yapılabilen Ziegler-Nichols (ZN), Chien-Hrones-Reswick (CHR) ve Cohen-Coon (CC) yöntemleri ile Guguk Kuşu Optimizasyon Algoritması (COA), parametreleri bilinmeyen fırçalı bir DA motor için tasarlanacak PID kontrolcüler üzerinden Toplam-Mutlak-Hata (IAE), Toplam-Karesel-Hata ve (ISE, Toplam- Zaman ağırlıklı-Mutlak Hata (ITAE) referans alınarak Matlab ortamında karşılaştırılmıştır. Benzer şekilde, kararlılık payları ve hassasiyet tepesi açısından Guguk Kuşu Algoritmasının performansı tartışılmıştır. Bu kıyaslamada, Guguk Kuşu yöntemiyle optimize edilen PID kontrolcünün, maliyet fonksiyonunu minimize etmek için yüksek oransal ve toplamsal katsayı ile çalıştığı ve sonucunda sistem cevabında aşıma sebebiyet verdiği gözlemlenmiştir. Açık döngü fırçalı ve fırçasız DA motor kontrolünde sıklıkla kullanılan bir yöntem olan giriş şekillendirme, oluşan bu aşımı azaltmak için sisteme entegre edilmiştir. Bu hibrit kontrolcü ile sistem cevabında IAE, ISE ve ITAE açısından en iyi performans elde edilmiş olup, bahsedilen diğer yöntemlere kıyasla daha az aşım olduğu gözlemlenmiştir.

Anahtar Sözcükler: Guguk kuşu algoritması, PID kontrolör, giriş şekillendirme, klasik kontrolcüler.

1. INTRODUCTION

In the realm of control systems engineering, the proportional-integral-derivative (PID) controller stands as a cornerstone, offering a versatile and widely employed method for regulating dynamical systems. The efficacy of PID control hinges significantly upon the appropriate tuning of its parameters to suit the dynamics of the system under consideration. Traditional methods for PID tuning often involve manual adjustment or simplistic heuristics, which may not always yield optimal performance, especially in complex or nonlinear systems. In recent years, the advent of metaheuristic optimization algorithms has revolutionized the field of control system design, offering powerful tools for automated parameter tuning and optimization. Among these algorithms,

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Swarm-Based Optimization such as Cuckoo Optimization Algorithm and other evolutionary techniques have garnered considerable attention for their ability to efficiently navigate complex search spaces and converge towards optimal solutions. The seminal work by Sheel and Gupta [1] introduced new techniques for PID controller tuning specifically tailored for DC motors, laying the groundwork for subsequent research in this domain. Following this, researchers such as Güdemen and Furat [2] have explored the application of PID parameter tuning methods to diverse systems, evaluating their performance comprehensively. Moreover, the integration of metaheuristic algorithms into PID tuning processes has demonstrated remarkable success across various domains. For instance, Barbosa and Jesus [3] elucidated the optimization of control systems using the Cuckoo Search algorithm, showcasing its effectiveness in achieving superior control performance. Similarly, Verma et al. [4] and Singh et al. [5] employed Cuckoo Search for PID controller design in buck-boost converters and pressure plants, respectively, demonstrating its versatility and applicability. Furthermore, the exploration of hybrid optimization approaches, such as the integration of Particle Swarm Optimization with Grey Wolf Optimizer, as illustrated by Koçaslan et al. [6] , showcases the ongoing efforts to enhance the efficiency and robustness of PID tuning methodologies. In parallel, studies by Gniadek and Brock [7][8][9] delve into the analysis of input shaping techniques and their interaction with PID controllers, providing valuable insights into the design and implementation of control systems for complex dynamic processes. Amidst this landscape of research, the Cuckoo Optimization Algorithm (COA) proposed by Rajabioun [10] has emerged as a prominent tool for optimization tasks, offering an elegant and efficient approach to solving complex engineering problems.

This study examines the effectiveness of classical tuning methods, including Ziegler-Nichols Step Response (ZN-SR), Chien-Hrones-Reswick Set-Point Response (CHR-SPR), and Load Disturbance Rejection (CHR-LDR), as well as the Wang-Juang-Chan (WJC) and Cohen-Coon (CC) methods, in comparison to the Cuckoo Optimization Algorithm (COA), a well-known optimization technique. This evaluation is conducted based on the Integral of Absolute Error (IAE) and Integral of Squared Error (ISE) criteria, using a brushed DC motor with unknown parameters. One challenge with optimization methods is the reliance on choice of PID parameter ranges by designers, potentially leading to undesired overshoot due to high proportional gain aimed at minimizing the cost function. To address this, a cascaded approach combining COA with Input Shaping (IS) is proposed to mitigate overshoot and enhance overall system performance. The hybrid controller aims to capitalize on the strengths of different techniques while minimizing their drawbacks, ultimately striving for improved system response metrics such as IAE, ISE, and Integral of Time-weighted Absolute Error (ITAE) with reduced overshoot. This research underscores the importance of leveraging modern optimization techniques to optimize PID controllers for dynamical systems. By integrating advanced algorithms like COA and open-loop control strategies such as input shaping, the objective is to achieve optimal control performance while addressing undesirable system behaviors like overshoot. Through these efforts, this study contributes to the ongoing pursuit of efficient control solutions in engineering and automation domains.

In subsequent sections, the introduction presents the Cuckoo Optimization Algorithm (COA) and input shaping techniques. The methodology details how COA optimizes PID controller parameters, incorporating input shaping, system transfer function, and a block diagram. Results compare COA with classical tuning methods (CHR, ZN, CC, WJC), showing COA's faster response. Notably, ZN has less overshoot. Integrating input shaping into COA reduces overshoot for a fast response. The conclusion analyzes the cascade structure's superior system response, discusses future research, and considers performance enhancements.

1.1.Cuckoo Optimization Algorithm

The Cuckoo Optimization Algorithm (COA) draws inspiration from the behavior of cuckoo birds in their natural habitat. The unique lifestyle and characteristics of these birds, particularly in egg laying and breeding, serve as the fundamental motivation for the development of this novel evolutionary optimization algorithm. Similar to other evolutionary methods, COA begins with an initial population. The cuckoo population consists of two types: mature cuckoos and eggs. The primary objective of COA is to survive and thrive within the cuckoo population. During the process of survival competition, some cuckoos or their eggs perish. The surviving cuckoo populations migrate to more favorable environments, where they reproduce and lay eggs. The ultimate goal is for the survival efforts of the cuckoos to converge to a state where only one cuckoo population remains, all with the same level of profitability. The application of the proposed algorithm to various benchmark functions and real-world problems has demonstrated its capability to effectively tackle challenging optimization problems [10]. The flowchart of the COA is illustrated in Figure 1.

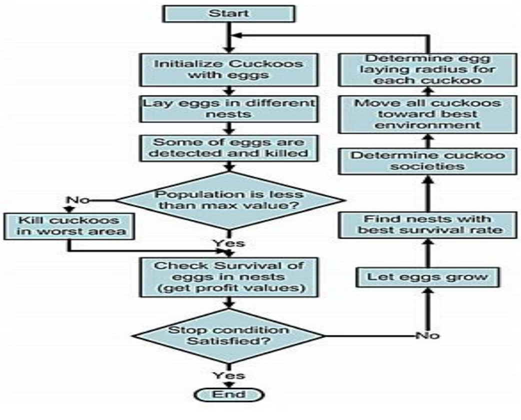

Figure 1. Cuckoo search algorithm [10]

1.2.Input Shaping (IS)

The fundamental concept of the input shaping method revolves around convoluting the baseline command with a sequence of Dirac impulses. These impulses are strategically applied at specific moments in time and with predetermined amplitudes. It is crucial that the responses of these impulses are in antiphase to effectively counteract each other and diminish oscillations [8]. The main idea of input shaping is summarized in Figure 2-3. Unshaped input and shaper impulses are convoluted so that the shaped input is handled, which are illustrated in Figure 2 (a-b-c), respectively.

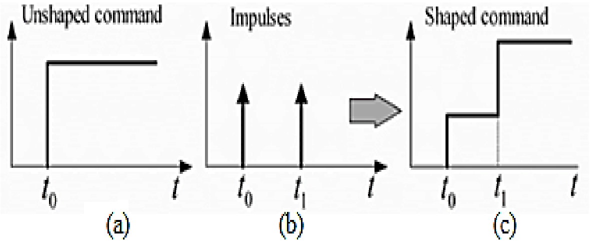

Figure 2. a) Unshaped input, **b)** Shaper impulses, **c)** Shaped input

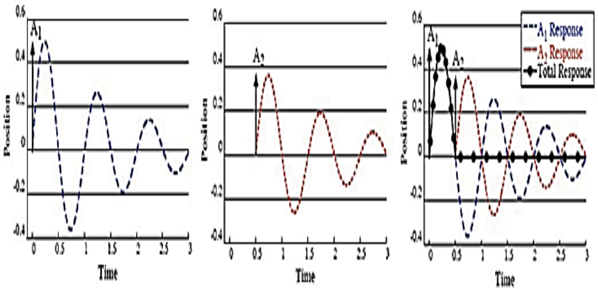

Figure 3. Total response with input shaping

2. METHODOLOGY

The COA is utilized to calculate the gains K_p, K_i, K_d of the PID controller in pre-described parameter space in order to keep the cost function minimum. According to the PID parameters chosen by COA, the characteristic equation of the system is handled. The characteristic equation of the closed-loop system is the main criterion for shaper parameters. The overall block diagram of the hybrid optimized PID controller with shaper is illustrated in Figure 4.

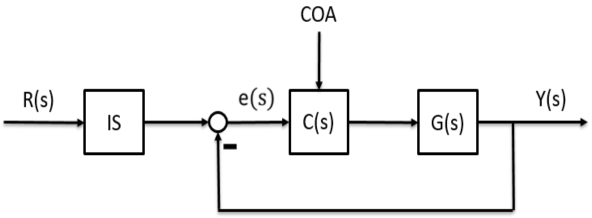

Figure 4. Block diagram of optimized cascade controller

A proper transfer function and PID controller are formulated as follows:

$$G(s) = \frac{N(s)}{D(s)} = \frac{a_0 + a_1 s + \cdots + a_{n-1}s^{n-1} + a_n s^n}{b_0 + b_1 s + \cdots + a_{n-1}s^{n-1} + b_n s^n} \qquad (1)$$

$$C(s) = K_p + \frac{K_i}{s} + \frac{K_d s}{1 + Ts} \qquad (2)$$

where K_p, K_i, K_d are PID gains respectively. T is a small value when pure differentiation is required because of high frequency noises. Otherwise, it is set to zero. The characteristic equation of the plant with controller becomes:

$$\delta(s, K_p, K_i, K_d) = sD(s) + (K_i + K_d s^2)N(s) + K_p sN(s) \qquad (3)$$

or with $\widehat{D(s)} = D(s)(1 + sT)$

$$\delta(s, K_p, K_i, K_d) = s\widehat{D(s)} + (K_i + K_d s^2)N(s) + K_p sN(s) \qquad (4)$$

The 'habitat' vector for PID controller as follow:

$$habitat = [k_p, k_i, k_d] \qquad (5)$$

Equation 6 represents the profit function to be maximized. For the utilization of COA in a cost minimization problem, the following profit function can be easily maximized:

$$profit = f_p(habitat) = f_p(k_p, k_i, k_d) \qquad (6)$$

$$profit = -cost(habitat) = -f_c(k_p, k_i, k_d) = -\left(\int |e| \int |e|^2 \int |te|\right) \qquad (7)$$

COA is initiated by creating a candidate habitat matrix of size N_{pop}xN_{var}. Subsequently, randomly generated eggs are allocated to each habitat. The number of eggs laid by each cuckoo bird in nature is typically between 5 and 20. These values are expressed as lower and upper limits in different iterations. In nature, real cuckoo birds lay their eggs at distances ranging from their actual habitats to the farthest distance. This maximum distance is referred to as the "Laying Radius (LR)," and it is expressed as follows:

$$LR = \alpha \, x \, \frac{number\ of\ current\ cuckoo's\ eggs}{total\ number\ of\ eggs} \, x \, (k_{p,i,d}^{max} - k_{p,i,d}^{min} \quad (8)$$

Here, α represents a constant, $k_{p,i,d}^{max}$ and $k_{p,i,d}^{min}$ denote the upper and lower limits for PID parameters in the optimization problem. Each cuckoo only flies λ% of all distance toward goal habitat and also has a deviation of φ radians. These two parameters, and φ, help cuckoos search much more positions in all environments. For each cuckoo, and φ are defined as follows:

$$\lambda \sim (0,1), \varphi \sim (-\omega, \omega) \quad (9)$$

means that it is a random number (uniformly distributed) between 0 and 1. ω is a parameter that constrains the deviation from goal habitat. An ω of $\frac{\pi}{6}$ (rad) experimentally seems to be enough for good convergence of the cuckoo population to global maximum profit according to the author [10]. When all cuckoos immigrated toward the goal point and new habitats were specified, each mature cuckoo is given some eggs. Then considering the number of eggs dedicated to each bird, a LR is calculated for each cuckoo. Afterward, the new egg laying process restarted [10]. The shaper formula is:

$$[A_i \; t_i\,] = \left[\frac{1}{1+K_i} \quad \frac{K_i}{1+K_i} \quad 0 \; 0.5T_{d_i}\right] \quad (10)$$

Where

$$K_i = exp\,\left(\frac{-\zeta_i \pi}{\sqrt{1-{\zeta_i}^2}}\right) \quad (11)$$

where A_i is the amplitude of the shaper and t_i is the specific time for the impulse to be applied to the system. ζ_i and T_{d_i} are the damping ratio and oscillation period respectively. Complex poles lead to overshoot in control problems. To mitigate overshoot caused by complex pole pairs, multiple shapers can be connected in series [8]. Each complex pole pair requires one input shaper. By analyzing the characteristic equation in Equation 3, the damping ratio and oscillation period due to complex pole pair are determined to design the shaper for the selected resonant frequency.

2.1.Brushed DC Motor Model

The System Identification Toolbox in Matlab provides an experimental approach to construct the open-loop system of a plant. This involves recording the speed of a motor in rpm based on the applied voltage. The measured input-output data is then loaded into the System Identification App in Matlab to facilitate the handling of the transfer function of the DC motor. This transfer function can be validated using another dataset. Additionally, the degree of the system needs to be estimated to create a more realistic model. By applying various levels of voltage from 0 V to 12 V to the motor terminal, the rotor spins at different speeds in rpm. Based on the recorded input-output datasets, the transfer function of the 99:1 Pololu brushed DC motor with encoder is determined as follow:

$$G(s) = \frac{1487}{s^2 + 22.79s + 169.2} \quad (12)$$

3.RESULTS

The system responses of the controller, as per the tuning methods mentioned, were depicted in Figure 5. Among all the tuning methods based on the open-loop step response of the system, the ZN-SR method exhibited the superior system response in terms of overshoot and settling time. Both the CHR-SPR methods, with no overshoot and 20% overshoot, demonstrated a similar amount of overshoot, while the WJC method showed more overshoot than the CHR-SPR 20% overshoot method, albeit with a shorter settling time. It is evident that the CC and CHR-LDR methods yielded comparable responses with higher oscillation and overshoot compared to the ZN-SR, CHR-SPR, and WJC methods.

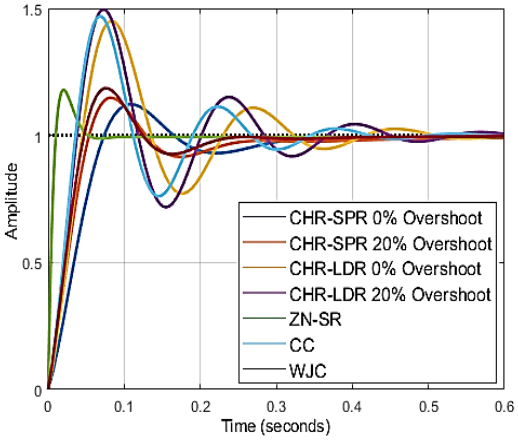

Figure 5. Step response of *ad hoc* tuning methods

Figure 6 illustrates the step responses of COA w.r.t. IAE, ISE and sum of IAE and ISE. This illustration proves that all the system responses with Cuckoo optimization are 4 times faster than ZN-SR, but the controllers designed with criterion has a little bit more overshoot than that of ZN-SR, shown in Figure 6. In addition, only the IAE criterion's response is almost the same with the sum of IAE and ISE. The comparison of the controllers based on tuning methods and Cuckoo optimization in terms of IAE, ISE and ITAE was tabulated in Table 1 where the best performance was achieved ZN-SR method as expected from the step response in comparison to other *ad hoc* tuning methods, CHR-SPR, CHR-LDR, CC and WJC respectively. WJC and CHR-SPR with 20% overshoot performed better response after ZN-SR

Table 1. Comparison of tuning methods and COA without shaper

Method	**IAE**	**ISE**	**ITAE**	**Overshoot (%)**	**GM (db)**	**PM (deg)**
CHR SPR 0%	0.0333	0.0577	0.0038	12.3	∞	54.3
CHR SPR 20%	0.0264	0.0491	0.0041	14.8	∞	52.5
CHR LDR 0%	0.0386	0.0830	0.0088	45.2	∞	27.3
CHR LDR 20%	0.0385	0.0840	0.0092	49.5	∞	23.9
ZN	**0.0144**	**0.0361**	**0.0060**	17.9	∞	70.3
CC	0.0326	0.0699	0.0062	47.1	∞	26.7
WJC	0.0249	0.0439	0.0020	18.6	∞	50
COA (IAE)	**0.0024**	**0.0097**	**0.0142**	28.9	∞	51
COA (ISE)	**0.0026**	**0.0043**	**0.0008**	21.2	∞	62.7
COA (IAE+ISE)	**0.0026**	**0.0042**	**0.0142**	20.9	∞	63

method, with similar values. The former is 2 times better than the latter in ITAE while both are very similar in other criterions. The optimization method, COA, dramatically has better response in all criterions because it is almost 10 times lower for all cost functions chosen in comparison to classical methods. Overall performance of COA compared to best performer ZN-SR is satisfactory except for overshoot.

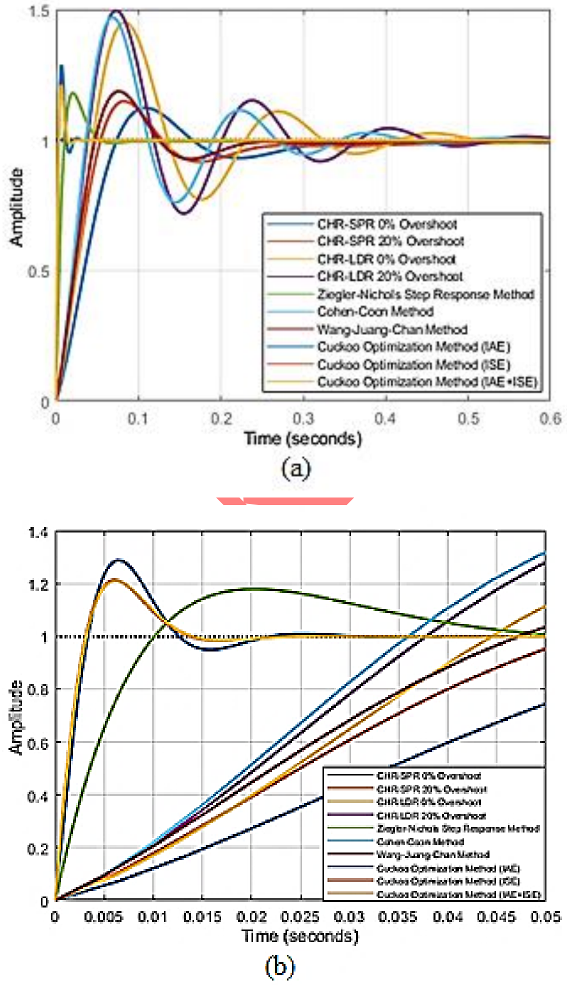

Figure 6. (a) Step response of tuning methods and COA in 0.6 secs and (b) 0.05 secs

3.1.Nominal Sensitivity Peaks and Stability Margins

Stability margin and robustness of a system are important in addition to its stability. While classical control methods are a result of experimental studies, as indicated in the Figure 7 below, it is evident that they are particularly close to the desired peak range in terms of sensitivity peaks, especially at low frequencies. Conversely, the sensitivity peak of the controller designed with the Cuckoo Optimization Algorithm (COA) is far from the desired range in all methods except for the COA w.r.t. IAE method. In the IAE method, it can be observed that it approaches the desired range at higher frequencies compared to classical methods, but it never reaches the desired range. In this aspect, classical controllers are more robust compared to the COA method. In the provided Table 1, while an infinite gain margin is obtained for all controller types, the phase margin for COAs according to ISE and IAE plus ISE are the highest after Ziegler-Nichols (ZN).

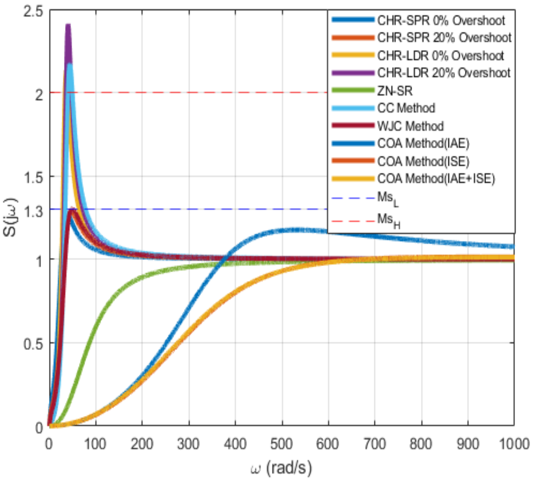

Figure 7. Sensitivity peaks of tuning methods and COA

3.2.Optimized PID with Input Shaping

In order to review the effect of the input shaper in overall performance and minimize the overshoot, a basic input shaper was integrated to the system. The effect of the shaper was shown in Figure 8. It is clear that the shaper is able to reduce the overshoot and damping in COA. In overall, shaper is capable of reducing the undesired overshoot in COA so that better total response is achieved in comparison to ZN-SR. The systems' performance with shaper according to IAE, ISE and ITAE was tabulated in Table 2.

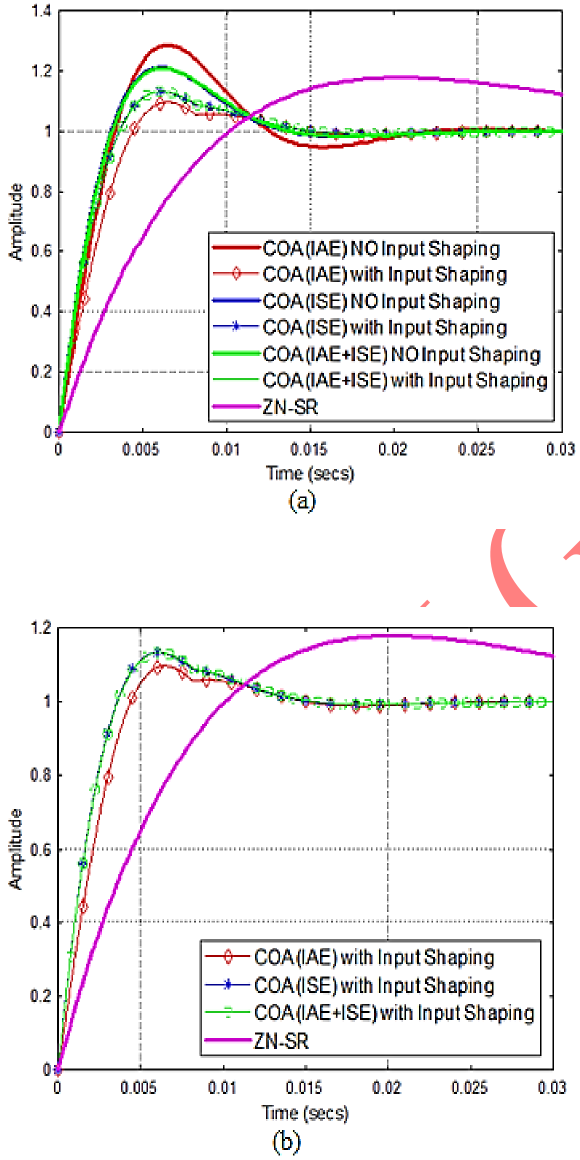

Figure 8. (a) Effect of input shaping in COA, (b) ZN-SR and COA with input shaping step response

Table 2. Effect of input shaper in COA

Method	**IAE**	**ISE**	**ITAE**
CHR SPR 0%	0.0333	0.0577	0.0038
CHR SPR 20%	0.0264	0.0491	0.0041
CHR LDR 0%	0.0386	0.0830	0.0088
CHR LDR 20%	0.0385	0.0840	0.0092
ZN	**0.0144**	**0.0361**	**0.0060**
CC	0.0326	0.0699	0.0062
WJC	0.0249	0.0439	0.0020
COA (IAE)	0.0024	0.0097	0.0142
COA (ISE)	0.0026	0.0043	0.0008
COA (ITAE)	0.0026	0.0042	0.0142
COA + IS (IAE)	0.0018	0.0087	0.0142
COA + IS (ISE)	**0.0022**	**0.0041**	**0.0009**
COA + IS (IAE+ISE)	**0.0018**	**0.0037**	**0.0006**

4.CONCLUSION

Classical tuning methods CHR-SPR, CHR-LDR, ZN-SR, CC and WJC were compared with COA, one of the popular optimization method in design of PID controller, in terms of step response parameters such as overshoot and settling time as well as IAE, ISE and ITAE. Although the CHR-SPR with 0% overshoot and CHR-LDR with 0% overshoot guarantees the zero overshoot in theory, there is unexpected overshoot because CHR method was designed to achieve the best performance for the First Order Plus Dead Time (FOPDT) plants. It was reviewed that the popular classical tuning methods still achieve the tracking and disturbance rejection, with more robustness as expected, but the controller tuned by these methods may not fullfill the desired performance by the designer especially in case of faster-response requirement.

The research focuses on enhancing the performance of the Cuckoo Optimization Algorithm (COA) by incorporating input shaping to reduce undesired overshoot while maintaining COA's advantages in time response and steady-state error. Results from Table 2 indicate that COA without input shaping outperforms ad hoc methods, showing the smallest settling time and less overshoot compared to CHR-LDR and CC. Although Input Shaping slightly decreases overshoot in COA-optimized PID controllers, the proposed cascaded controller with input shaping achieves the smallest overshoot and settling time. In summary, the study designs a cascaded PID controller optimized by COA with input shaping, demonstrating superior performance for a Pololu DC motor with encoder in Matlab based on IAE, ISE and ITAE criteria.

In future works, classical tuning methods with shaper could be compared to current optimization methods with shaper and these cascaded controllers would be implemented in a real microcontroller such as Texas Instrument C2000 F28379d. Moreover, the robustness of the proposed hybrid controller would be increased by robust input shapers. Another study would be loop shaping with the help of a classical controller with low gain in high frequency and optimized controller with high gain in low frequency.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS’ CONTRIBUTIONS

Büşra YALÇINER DURUKAN: Performed the experiments and analyse the results.

Halit Murat DURUKAN: Performed the experiments and analyse the results.

İlyas ÇANKAYA: Supervision, reviewing and editing of the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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