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Multi-Objective Step Response Shaping via the Fractional-Order Proportional-Integral-Derivative Controller

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Abstract

A well-known problem in control system design and analysis is the shaping of the unit step reference response of a system to produce desired transient characteristics for various system references. The necessity of having fast, accurate, and stable control systems for a large number of practical applications has created the need for advanced control methods. In this regard, the development of fractional-order controllers has received considerable attention from the control community. Many papers and books on the topic of fractional-order systems have been published, which also include the usefulness of fractional calculus in the area of controllers. The fractional order proportional integral derivative controller is proven to be versatile, and its design can be obtained for any given target step response. A sufficiently large number of response characteristics, such as performance, phase margin, immunity to plant modeling, and robustness, can be adjusted by means of five tuning parameters. The control strategy of this paper focuses on developing a fractional order proportional integral derivative controller, which aims at overcoming the infeasibility of the controller to satisfy the conflicting goals of go-to speed and settling time in the traditional PID controller. The controller design has two main goals: one is to satisfy system stability, while the other is tuning the overshoot and the settling time. In this direction, the genetic algorithm is implemented. The results are presented through an illustrative example.

Keywords: "PI controller, overshoot, step response, stability, genetic algorithm."

1. Introduction

Fractional-order mathematics is a branch of applied mathematics focusing on fractional derivatives and integrals of various orders, extending the conventional calculus framework. A study of fractional order mathematics has been growing rapidly in different scientific and engineering fields. One of the main reasons behind the importance of fractional order mathematics is the historical background to this new area of mathematics. Nevertheless, fractional calculus gave way to the new discipline of modern theoretical physics by the end of the 20th century. The mathematical perspective of integer-order differential equations has advanced significantly, but their fractional-order derivatives and integrals are still in their early stages [1]. In today's world, there are several physical systems and processes that cannot be fully understood or described by classical calculus. A more general formulation called fractional calculus, or "Calculus of Non-Integer Order," was proposed to deal with systems whose properties are "memory dependent" or are of "hereditary nature." This approach takes inspiration from the Riemann, Grünwald-Letnikov, and Liouville definitions. By extending the power of traditional integrals and derivatives to non-integer values, many have explored the applicability of fractional order mathematics in various applications. It provides a local description of the classified energy distribution, degree of association, roughness spectrum, and so on in terms of time or frequency domain, which is more suitable for many physical processes [2]. Traditional calculus is designed to handle homogeneous, instantaneous processes with constant properties. There are many physical, mechanical, biological, electrical, chemical, air-water pollution controls, economic, and financial systems with different types of infinitely distributed or grouped media and material characteristics, operating continuously in relaxed states of nature. Such systems are solved using non-integer order calculus-like tools. It expands the scope of conventional calculus to describe many complex systems that are solved by undetermined integral coefficient linear, nonlinear, and fractional differential equations [3].

A control system is a system that measures the process states and provides corrective actions such that the process is carried out in a desired degree of stability, performance, and accuracy. The feedback mechanism has an instrumental role in several control strategies to determine the corrective actions or the manipulative inputs required by a process or output or system state

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objective. Classical control theory is perhaps the longest surviving control systems design paradigm, spanning three centuries. It was and indeed continues to be the cornerstone behind many control systems designs, many of which are still in operation today [4]. Since the start of control theory, simple (integer) order differential equations governed the standard of the time. They provide a minimal complexity system that is often used to simulate the output of real systems and act as a control mechanism in modern constructions. The primary argument for eliminating any other order comes mostly from technical limitations of the discipline and that additions to the normal linear and non-linear feedback, model moving components, can provide a better overall performance. The extension of control systems to fractional order is one way to insert these omitted components and provide enhanced performance and dynamics [5]. By considering a system in a fractional context, a number of advantages can be found. Improved accuracy of modeling mechanisms, simulation outputs, and the prediction of dynamic responses to a given control input is the first of these. It also opens the door for greater flexibility, since real physical systems constitute a mixture (or sum) of orders, and obscurities could be modeled in any simulations. The representation of a system in state-space gives a more detailed investigation into the makeup of a dynamic model, especially in one where the state contains an infinitesimal component. Fractional orders therefore present a more accurate reflection of the dynamic behavior, something integer controllers do not provide, giving a system with a fractional representation an edge in terms of capturing and reflecting its dynamic behavior [6]. One aspect that is shared within all feedback control systems, however, is the desire to analyze and ensure stability. For fractional closed-loop systems, stability does have its limitations, and it has seen work in more advanced domains, attacking stability through various methods. Each of these methods is a prime motivator for systems in industry, striving for a clearer, more detailed picture for their control dynamics, yielding controllers capable of improved performance from integer proportional-integral-derivative (PID) structures [7].

Stability analysis is undoubtedly the main part of control systems theory. Approximately 90% of engineering time in control engineering is occupied with the analysis of stability. It's one of the biggest research areas in engineering. But in the last few years, advances in the field of fractional differential equations have generated increasing interest in the study of various fractional order controllers [8]. Stability is the key aspect of fractional order control systems due to the involvement of the fractional derivative during the tuning of the fractional controller. There are many methods available to investigate the stability of fractional order control systems [9].

Step response analysis is a fundamental tool for understanding how linear time-invariant systems behave when they are subjected to a step input. The insights and conclusions drawn from the step response can subsequently be translated to any generic function of time through time-invariance. The purpose of step response analysis is to be able to understand the performance of a system over a long period of time; however, the impetus for the analysis comes from the transition that takes place from an initial to a steady-state operating condition due to an abrupt input change [10]. To aid in that understanding, a number of analytic and graphical tools are available. Other types of response analyses consider the immediate response of a system to a change in input or its time- or frequency-domain harmonic speed, respectively. In other words, step response analysis identifies the dynamic behavior of a system for all time instants, not only for small values of time [11]. In step response analysis, the system output behavior when introducing a step input to a system is studied. A step response is the system's output when the input switches from one constant level to another. The output of the system varies with time, and its behavior can be known from the following data: output values, the time at which the output changes, how long it takes for the system to reach stable output, the nature of the system's transient response, and whether the system output oscillates or not. A step input is a signal that starts at some initial value and jumps instantly to one of its final steady-state values. The behavior of the system is characterized by the time constant, which depends on the type of system [12]. A step response is generally concerned with, but not limited to, the following indices: Rise Time (Tr): the amount of time required for the response to rise from some initial pre-determined level to some final pre-determined level. Overshoot (OM): the greatest amount above unity that any overshoot in the response can achieve. Settling Time (Ts): the time required for the step response to settle within a particular error band for the remainder of the analysis. Steady-state error (SSE) is the difference between the desired value and the actual value when the time reaches infinity. In mathematical form, it is defined as the difference between the desired value and the real response as time approaches infinity [13].

In a wide range of practical engineering and technical systems, it is sometimes necessary to have a certain dynamic behavior in order to manage their actions. Here comes the basic aim of a control system, where the function of managing this behavior is done by a controller inside the system. By selecting several controller actions, one can define which features are its main goals that need to be managed by the system. In the open-loop case, where the system is isolated from the controller, the system isn't capable of managing and adjusting its behavior according to the input signal. However, if we attach a controller in the path of the system, the control action will start to regulate the system's behavior. However, controllers have different distinct structures and actions. Proportional (P), proportional-integral (PI), proportional-derivative (PD), and PID are all examples of the operating actions of the controllers, which represent the control actions of a proportional controller, an integral action, a derivative action, and a combination of all mentioned actions. Fractional or non-integer controllers are the natural evolution of classical PID controllers for managing today's complex control problems. The classical PID controller's integer order calculus has limited adaptability and flexibility vis-à-vis fractional order derivatives; hence, the fractional order PID (FOPID) controllers are able to provide improved performance. There are a number of significant differences between a classical PID and its fractional version in terms of operational requirements. The controller is a multi-input, multi-output system. It is generally too complex to be analytically described in a traditional form; hence, a direct tuning rule is not yet found. A few years ago, it was only the speculative theories that described the possible benefits of using fractional differentiation in industrial control theory and practice, but today it finds a big list [14, 15].

Controller tuning plays an important role in the design of many applications, such as chemical reactors, robot manipulators, and automotive systems. System uncertainties, nonlinearities, and dynamic changes that occur in many of these systems dictate the employment of precisely tuned controllers. These design applications virtually demand the use of feedback controllers to maintain the system characteristics so that it operates effectively. A well-tuned controller can improve performance by influencing both the setpoint tracking and transient responses. Genetic algorithms have recently received much attention for the tuning of controllers because they are capable of handling a non-differentiable scalar-valued function [16]. It is an especially efficient optimization method for searching the global optimum. Moreover, the genetic algorithm has faster computation times than other evolutionary strategies. In general, researchers have applied genetic algorithms and evolutionary strategies to the control of robotic manipulators, chemical processes, and aircraft guidance systems. The main purpose of this essay is to investigate the different methods and techniques that have been employed to achieve the optimal tuning of controllers using genetic algorithms in optimization. In the following sections, fuzzy logic, neural networks, a comparative introduction, and tuning methods will be explained before approaching the main concept of the genetic algorithm and controller tuning, followed by methodologies, experimental results, and conclusion. The need for exactly tuned controllers is described. Control strategies that benefit from exactly tuned controllers are discussed [17].

This paper aims to tune the fractional order FOPID controller to set the properties of the step response to researcher’s desire. For this purpose, the genetic algortihm (GA) is implemented. Here, second section briefly reminds the FOPID controller and the step response. Third section gives information about the GA and the case study is presented in section 4. The last section has the conclusions.

2. The Step Response and FOPID Controller

The step response of a system measures how it changes with time after receiving a unit step input. Understanding the step response has both theoretical and practical importance in the field of control engineering. A system's step response can provide valuable insight into its properties and is a great way to verify its behavior. For a physical system, a step input can manifest in various forms such as a sudden gust of wind, a person applying a force on an object, or a jet pilot inadvertently commanding a quick turn. Also referred to as the jump response, this behavior is primarily studied to gauge a system's stability, and quantitative analysis of the system's response is done concerning time [18]. Fig. 1 shows a sampe step response [19].

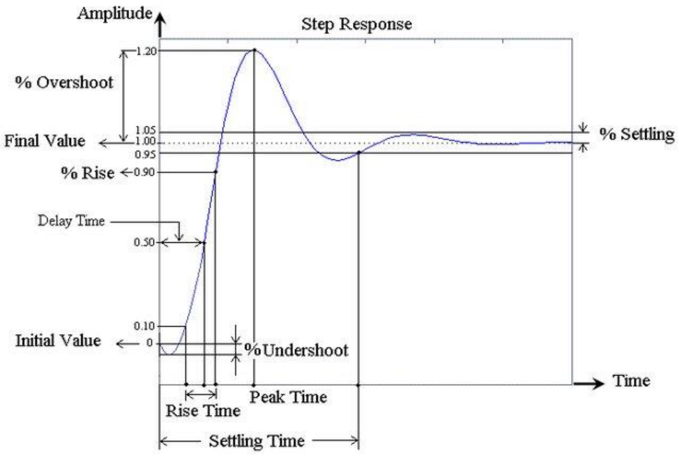

Fig. 1. An example step response.

The rise time of the system output is the time it takes for the response to go from 0% to 100% of its final value. The overshoot is the percentage by which the system output “overshoots” its final value. The settling time is the time it takes for the system response to reach and stay within a given percentage of its final value. Finally, the peak time is the time it takes for the output to reach the point of the first peak. The settling time, rise time, and overshoot are performance indicators that can be employed to analyze a number of different system performance characteristics. Each one of these parameters can be analyzed to draw performance inferences about a given dynamic system. By exploring the significance and interrelationship of these characteristics, one can better understand the stability and relative responsiveness of particular systems. For example, quick rise times and low overshoots correspond to systems that are both stable and fast. Moreover, changes in system parameters can affect the remaining parameters and the overall performance of the system. An increase in one parameter may be desirable, while in another the opposite may be true. For example, a rise time that is too long may cause an undesirable amount of overshoot [20].

Following is the transfer function of a FOPID controller.

$$C(s) = k_p + \frac{k_i}{s^{\lambda}} + k_d s^{\mu} \tag{1}$$

It would be useful to give information about how the fractional-order terms (the integral order λ and derivative order μ) influence the controller's flexibility in adjusting transient response parameters. The fractional-order terms, denoted by the integral order (λ) and the derivative order (μ), are crucial in endowing the FOPID controller with its unique flexibility and resilience. These parameters provide more precise modifications to the system's phase margin and gain crossover frequency, therefore enhancing stability margins relative to traditional PID controllers. The memory effect intrinsic to fractional calculus offers a distinct benefit in adjusting the system's response dynamics, leading to smoother transitions, less oscillations, and enhanced tracking performance. This improved tunability is especially beneficial in situations when competing performance goals, such as reducing overshoot while attaining a faster settling time, need to be satisfied. In contrast to integer-order controllers, which are limited by fixed-order calculus, fractional-order parameters provide a wider spectrum of response shaping, rendering the FOPID controller an effective instrument for tackling intricate control demands. We have provided examples and references to essential literature to elucidate these ideas, enabling readers to comprehend the theoretical foundations and practical ramifications of these terminology. We anticipate that this thorough elucidation adequately responds to the comment and enhances the overall comprehensiveness of the study.

3. The Genetic Algorithm

Genetic algorithms are powerful optimization methods that are frequently used to solve a wide variety of complex engineering optimization problems. The general flowchart of GA is given in Fig. 2 [22].

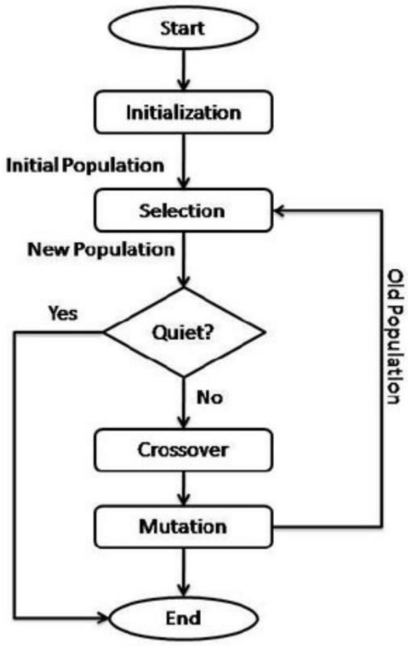

Fig. 2. The flowchart of the GA.

Since one of the aims of this text is to employ a GA to tune a PI controller for controlling a simple system, a solid foundation in genetic algorithms is required to know more about the tuning process. This text attempts to discuss the fundamentals of GAs and some of the various ways they can be used. A GA works with a population of chromosomes that represent the solutions of the variables being optimized at any given moment. Each chromosome is formed from a specific number of genes, where each gene is a decision variable within the optimization problem. These chromosomes evolve through a series of generations that become more and more optimized. When an optimization problem is first initialized, the population of chromosomes is usually generated randomly. Over time, these chromosomes go through a process whereby a new generation of solutions is created. Chromosomes evolve in order to get the best solutions. The major factors influencing this evolution process are the initial population, the fitness functions, and genetic operators [21]. Each chromosome is evaluated for its fitness with respect to the problem's objectives using a fitness function. High fitness values represent good solutions, and low values represent poor solutions. Ultimately, the GA is trying to evolve a population of chromosomes where the majority have high fitness values. A selection process based on the fitness of each chromosome, known as survivor selection, is essential to ensure the best individuals survive in each generation. This selection process mimics the principles of natural selection by allowing the most successful individuals to survive in the population and have the chance to produce offspring. Algorithm parameters, like population size, mutation rate, and crossover probability, are key components that critically affect how the genetic algorithm will work in solving the problem.

In GA, candidate solutions are represented as chromosomes, with the collection of all chromosomes forming a genetic pool. Each chromosome's fitness value indicates its suitability as a solution, affecting its likelihood of being selected for reproduction. Chromosomes with higher fitness values have a greater probability of survival, as they are more likely to contribute to the creation of new solutions. To generate new candidate solutions, GA applies genetic operations like crossover (recombination) and mutation. Crossover combines information from two parent chromosomes to create offspring, while mutation introduces small, random changes. These processes promote diversity within the pool, expanding the search space and enabling exploration of a broad range of possible solutions. GA's selection process prioritizes chromosomes with higher fitness values, ensuring that more promising candidates are retained. By iteratively repeating selection, crossover, and mutation, the population evolves, progressively converging toward an optimal or near-optimal solution. The algorithm concludes when certain termination criteria are met, such as reaching an adequate fitness level or a specified number of generations. Through this iterative, evolutionary approach, GA effectively searches complex solution landscapes, identifying highly optimal solutions.

Now, let us study the problem on an example.

4. The Study

Let us consider the following transfer function.

$$P(s) = \frac{K}{Ts^{\alpha} + 1} e^{-Ls} \tag{2}$$

The order of the numerator polynomial here is also a real number which yields to a fractional order plant. The parameters of the plant are, K=0.99932, T=1.0842, L=0.1922 and alpha=1.0132. The plant also has an internal delay which is represented by the parameter L. Initially, the overshoot of the step response is set to be 25%. In other words, the peak of the step response is tuned to be 1.25. At the same time, the steady state time is set to be 2.5 seconds. Besides, the most important property to be achieved is the stability. For these constraints, the following FOPID controller is calculated.

$$C_1(s) = -10.8481 + \frac{64.6632}{s^{0.73025}} + 2.0334 s^{0.57381} \tag{3}$$

With the FOPID controller above, the step response in Fig. 3 has been obtained.

The step response clearly shows that the stability is successfully achieved. Besides, the peak point of the step response is on 1.25 and the response reaches steady state at approximately 2.5 seconds. For comparison, the same objectives were considered, and a classical integer-order PID controller was re-tuned using the GA. The optimized controller is given in the following form.

$$C_2(s) = 1.3139 + \frac{4.1171}{s} + 0.34915 s \tag{4}$$

Step response obtained in this case is given in Fig. 4. This figure shows that the overshoot requirement is successfully met. However, the system showed a slower settling time in which the system reached the steady state in more than 2.5 seconds. Thus, it can be said that the fractional order controller showed better performance in satisfying time domain specifications. It was proven in the previous studies that the integral operator of the controller has significant effect on the steady state of the system. Since the integral operator of the fractional order controller has a fine-tuning ability because of the real order, the time domain response could be achieved in a more convenient way.

This time, no overshoot is wanted in the step response. Also, the rise time is desired to be 1 seconds and settling time is set to be 3 seconds. In this direction, the following FOPID controller is calculated.

$$C_3(s) = 8.0337 + \frac{35.9335}{s^{0.70419}} + 18.2109 s^{0.66562} \tag{5}$$

The step response obtained with the above controller is given in Fig. 5. It is clear in the figure that desired specifications have been successfully met.

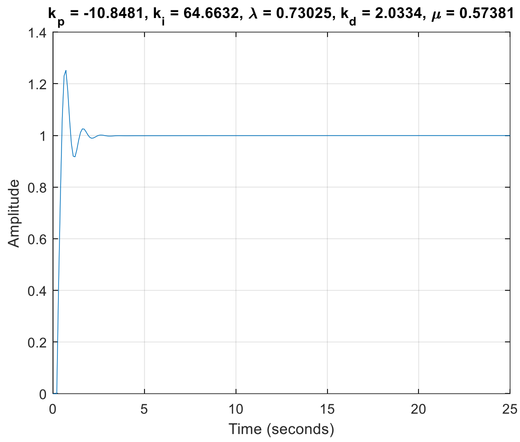

Fig. 3. Step response obtained with $C_1(s)$.

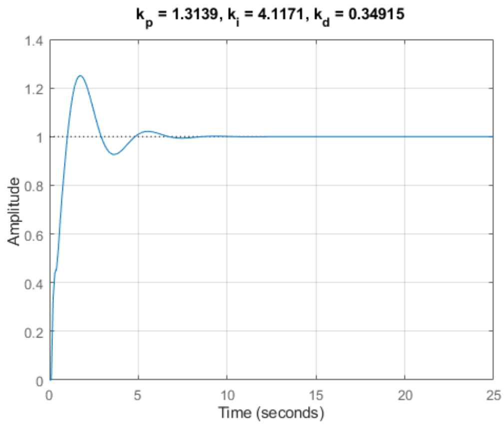

Fig. 4. Step response obtained with $C_2(s)$.

Again for the same specifications, following PID controller has been tuned with the GA.

$$C_4(s) = 4.0128 + \frac{3.3411}{s} + 0.44433s \tag{6}$$

The step response of the system controlled with $C_4(s)$ is given in Fig. 6. It is clearly seen when comparing Fig. 5 and Fig. 6 that the fractional order controller showed a smoother response in rise time although the desired specifications were largely met.

Finally, let us tune the overshoot to reach the point 1.1 having the peak time to be 1 second. It means that the step response will reach the peak point in 1 second. The settling time in this case is 5 seconds. FOPID controller obtained for this purpose is given below.

$$C_5(s) = 7.5493 + \frac{49.1058}{s^{1.3452}} + 2.5977s^{0.58411} \tag{7}$$

The step response is given in Fig. 7.

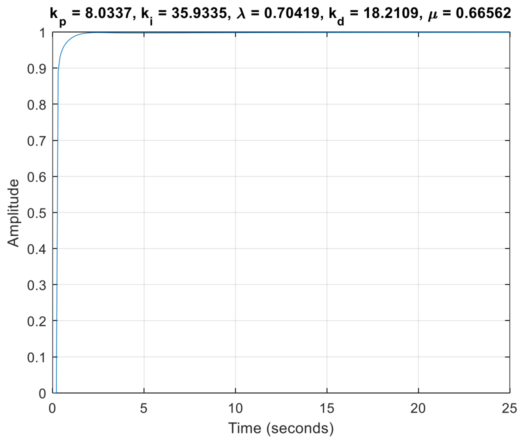

Fig. 5. Step response obtained with $C_3(s)$.

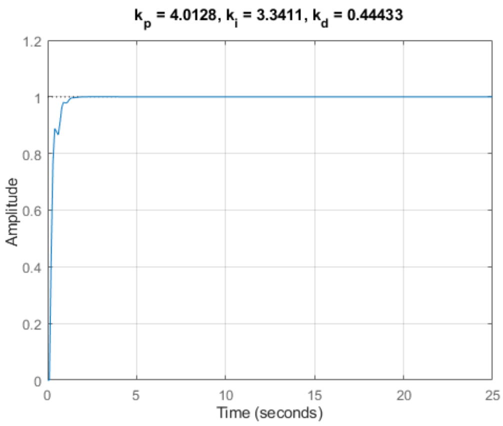

Fig. 6. Step response obtained with $C_4(s)$.

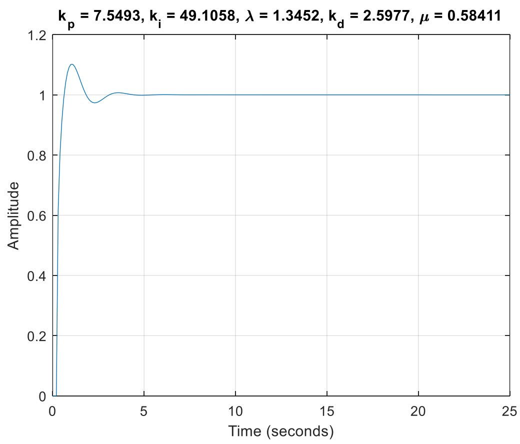

Fig. 7. Step response obtained with $C_5(s)$.

The figure demonstrates that the specified requirements are successfully met. Thus, the effectiveness of the method are shown in 3 different cases. Before proceeding to the next section, it would be better to provide more information on how the GA parameters were chosen. In the study, the population size of 50 was selected to optimize computing efficiency and genetic variety. A sufficiently large population guarantees that the method investigates an extensive solution space while minimizing computing expenses, which is essential for real-time or resource-limited applications. The mutation rate was established at 5%, a figure obtained from empirical research in optimization literature. This rate ensures adequate heterogeneity throughout the population, enabling the algorithm to prevent premature convergence to local optima while maintaining a steady advancement toward the global solution. The crossover probability, an essential element in recombination, was established at 80%, guaranteeing that most offspring acquire advantageous features from their progenitors. This elevated likelihood enhances convergence by using optimal solutions while preserving sufficient randomness to investigate new options. Tournament selection was utilized as the selection method, a well-established strategy known for promoting competition among chromosomes. This approach guarantees that the most fit individuals have a higher probability of reproduction, hence facilitating the exploitation of superior solutions and the exploration of the search space. The termination criteria were established to optimize computational efficiency and effectiveness. The method was programmed to conclude either upon achieving a specified fitness threshold or after 200 generations, a limit established to permit adequate iterations for convergence while preventing excessive computing burden.

5. Conclusions and Discussion

In recent years, the field of control system design and analysis has encountered a noteworthy issue, particularly in relation to adjusting a system's response when faced with a unit step reference. This adjustment aims to achieve specific transient characteristics for various system references, taking into account the diverse demands of practical applications that require fast, precise, and stable control systems. Consequently, there has been increasing interest within the control community towards the development of advanced control methods, specifically fractional-order controllers. Numerous scholarly works, including papers and books, have contributed significantly to the literature on fractional-order systems, as they emphasize the value of fractional calculus in controller applications. Among the different types of fractional-order controllers, the fractional-order proportional-integral-derivative (FOPID) controller has proven its adaptability by successfully achieving desired step responses. This achievement is made possible through the adjustment of five tuning parameters, which collectively influence a wide range of response characteristics such as performance, phase margin, immunity to plant modeling, and robustness. The focus of this paper is to delve into the development of a FOPID controller, which aims to overcome the limitations of traditional PID controllers when it comes to meeting both rapid response and settling time requirements. The primary objectives of this controller design are to ensure the stability of the system, while concurrently fine-tuning overshoot and settling time. This study illustrates that including fractional orders in controller design provides notable benefits compared to traditional integer-order controllers, especially in modulating the transient response. Fractional orders provide more degrees of freedom via the integral order (λ) and derivative order (μ), enabling more accurate adjustment of system dynamics. Fractional-order controllers provide smoother rising times, less overshoot, and expedited settling periods relative to integer-order controllers, even when both are tuned under analogous conditions. The enhancement is apparent in the step response plots, where the fractional-order controller consistently meets rigorous time-domain criteria with more efficacy. The fine-tuning capabilities of fractional operators, due to their non-integer flexibility, enables the system to more effectively balance conflicting objectives, such as reducing overshoot while maintaining settling time. Conversely, conventional PID controllers are restricted by fixed-order calculus, which hinders their flexibility and frequently leads to inferior performance, particularly in complex or nonlinear systems. The study's results demonstrate that fractional controllers improve stability margins and deliver enhanced performance in achieving multi-objective requirements, rendering them a formidable option for advanced control applications. To accomplish this, the researchers employ the use of a genetic algorithm, which proves to be effective in identifying the optimal tuning parameters. Throughout the paper, detailed examples are provided to demonstrate the exceptional effectiveness of the proposed FOPID controller in meeting the targeted performance criteria. With the study in this paper a FOPID controller has been designed using the genetic algorithm approach. The five parameters of the controller are tuned to satisfy multi-objectives in the step response of the system. The step response includes properties like rise time, overshoot, peak time, settling time and steady state. The method is told to be a multi-objective approach in that moe than one of these properties are tried to be satisfied simultaneously. As the result, the step response could be shaped towards system requirements. The effectiveness of the method has been shown on an illustrative example including different cases. This study aims to serve as an enlightening reference for researchers exploring controller tuning.

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