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Design of an Adaptive Controller for Magnetic Levitation System Based on Bacteria

Foraging Optimization Algorithm

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Master Thesis

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نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة شئون البحث العلمي والدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ رمزي جاسر حسن الغمري لنيل درجة الماجستير في كلية الهندسة قسم الهندسة الكهربائية - أنظمة التحكم وموضوعها:

تصميم متحكم تكيفي للتحكم في جهاز التعليق المغناطيسي استناداً إلى الأمثلية المتحققة من الخوارزمية للبكتيريا في طريقة بحثها عن الطعام

Design of an Adaptive Controller for Magnetic Levitation System Based Bacteria Foraging Optimization Algorithm

وبعد المناقشة العلنية التي تمت اليوم الثلاثاء 06 ذو الحجة 1435هـ، الموافق 2014/09/30م الساعة الواحدة ظهراً بمبنى طبية، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

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واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله والتوفيق،،،

مساعد نائب الرئيس للبحث العلمي والدراسات العليا

.....
أ.د. فؤاد علي العاجز



DEDICATION

I dedicate this thesis to my father and my mother in recognition of their endless help; support and encouragement also dedicate this work to my beloved wife, I will not forget my brothers and sisters.

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ABSTRACT

Design of controllers for non-linear systems in industry is very complex and difficult task. Because of importance, researchers have been doing their best efforts for finding the best controller for these systems to achieve their demands. Many approaches have been developed in this way to help in control of such systems such as; optimal control, robust control, fuzzy control, and adaptive control. One approach, which has shown promise for solving nonlinear control problems, is Adaptive Control (AC) based on Optimization Techniques especially adaptive PID and Model Reference Adaptive Control (MRAC) based on Bacterial Foraging Optimization Algorithm (BFOA) to optimize the controller parameters.

In this thesis a magnetic levitation system is considered as a case study for nonlinear systems. The adaptive controller is designed to keep a magnetic object suspended in the air counteracting the weight of the object. Two educational models will be used in this thesis that is 730 and CE152. We will design two controllers; adaptive PID controller and MRAC based BFOA to control of this system using Matlab/Simulink software. The results will be compared with that coming from using Fuzzy Logic (FL) based Genetic Algorithm (GA), Feedback Linearization (FBL), Deadbeat, and H_2 Controller.

ملخص الرسالة

تعتبر مهمة التحكم في الأنظمة غير الخطية من أصعب وأكثر المهام تعقيدا، ولأن عملية التحكم في هذه الأنظمة مهم جدا، بذل العلماء المجهود الكبير ولازالوا في ايجاد أفضل الطرق وأكثرها فاعلية للتحكم في هذه الأنظمة وكذلك تحقق المطلوب منها. الكثير من هذه الطرق تم تطويرها منها المتحكم المثالي والمتحكم المتين والمتحكم المبهم وكذلك المتحكم التكيفي. من هذه الطرق التي تعد بحل مثل هذه الأنظمة غير الخطية بشكل فعال هي استخدام المتحكم التكيفي مع طرق تحقيق الأفضلية أو الخوارزميات وبشكل خاص استخدام المتحكم التكيفي PID و المتحكم التكيفي المعتمد على نموذج مرجعي مع طريقة تحقيق الأفضلية التي تعتمد على كيفية حصول البكتيريا الموجودة في الأمعاء على الطعام.

في هذه الأطروحة سوف نقوم باستخدام نظام التعليق المغناطيسي كموضوع دراسة للأنظمة غير الخطية. المتحكم التكيفي سوف يستخدم في حفظ الكرة معلقة في الهواء ضد قوة الجاذبية الأرضية في هذا النظام. سوف يتم استخدام نموذجين لنظام التعليق المغناطيسي في هذه الأطروحة 730 و CE152 . كذلك سوف يتم تصميم المتحكم في هذا النظام باستخدام نوعين من المتحكم التكيفي PID و MRAC وذلك باستخدام برنامج Matlab/Simulink بالاعتماد على خوارزمية البكتيريا . سوف يتم مقارنة نتائج استخدام هذا المتحكم مع استخدام المتحكم المثالي H_2 و المتحكم المبهم المعتمد على الخوارزمية الجينية وكذلك مع المتحكم Feedback Linearization (FBL) و Deadbeat .

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ABBREVIATIONS

BFOA	Bacteria Foraging Optimization Algorithm
PSO	Particle Swarm Optimization
MRAC	Model Reference Adaptive Control
PID	Proportional, Integral, and Derivative
GT	Genetic Algorithm
FBL	Feedback Linearization
AC	Adaptive Control
FL	Fuzzy Logic
Maglev	Magnetic Levitation

CHAPTER 1

INTRODUCTION

1.1. Overview

Control systems are one of the most important science issues, and no one can deny that contribution in development and advancement of modern civilization and technology. Control systems are found in many types of applications in industry, such as power systems, computer control, space technology, robotics, weapon systems and many others [1]. Due to the development of civilization and progress, systems become more complex and traditional controllers do not become efficient, so different types of controller appeared to meet this progress.

1.12 Classical and Modern Control

Control systems can be classified into two types' classical control and modern control. Each one has its advantages over the applications.

1.12.1 Classical Control

The scope of classical control is limited to single-input and single-output (SISO) system design and its methods are based on frequency response measurement deal with linear systems. The linear system is described by a transfer function model. The most common controllers designed using classical control theories are PID controllers (over 90 percent of applications are using this controller).

1.2.2Modern Control

On the other hand, modern control deals with state space and its methods are based on time response measurement. The systems under this type of control cover multi-input and multi-output (MIMO) systems and deal with nonlinear systems such as our case study which is magnetic levitation system. Adaptive control and robust control are examples of modern control.

1.3 Linear and Nonlinear Systems

The systems can be classified into two types: linear and nonlinear systems. In our life, most of systems are nonlinear.

1.3.1 Linear Systems

The linear system is a mathematical model of a system based on the use of linear operations. It exhibits features and properties that are much simpler than, nonlinear systems. Linear systems satisfy the properties of superposition and homogeneity [1]. Linear systems find important applications in automatic control theory, signal processing, and telecommunications.

1.3.2 Nonlinear Systems

A nonlinear system is a system where the superposition (Super position means that if $y_1(t)$ is the response of input $x_1(t)$ and $y_2(t)$ is the response of $x_2(t)$. Then the net response for two inputs is the sum of the responses for two inputs) and homogeneity (homogeneity means if an input scaled by a certain factor produces an output scaled by that same factor) do not apply [1]. Thus, an approximation is used to deal with these systems by converting them to linear systems via linearization; however, this method is used only over specific ranges.

1.4 Adaptive Control

An adaptive control system is a branch of modern control that can deal with nonlinear systems and gives the desired performance. It measures a certain performance index (IP) of the control system using the inputs, the states, the outputs and the known disturbances [2]. The adaptation mechanism modifies the parameters of the adjustable controller and/or generates an auxiliary control in order to maintain the performance index of the control system close to a set of given ones.

1.5 Optimization

The heuristic optimization techniques such as Bacteria Foraging Optimization Algorithm (BFOA), simulated annealing, tabu search, particle swarm, etc. are proposed as a solution to many complex optimization problems that were previously difficult or impossible to solve. These tools make the systems very robust, and insensitive to noisy and/or missing data.

1.6 Motivation

Magnetic Levitation System is one of the most nonlinear complex systems. As it is known, it has many applications in our life such as high speed trains. In these systems, the traditional controllers such as PID controllers will not meet our performance conditions. So this motivated to design an adaptive controller with Bacteria Foraging Optimization Algorithm (BFOA) to control the maglev system and makes the levitation object as stable as possible and meet our demands in performance criteria.

1.7 Statement of Problem

This research proposes a new approach for controlling the position of magnetic levitation systems. The adaptive control methodology does adaptation quickly to make changing in the environment or the model and also self-adjusts its parameters. The bacteria forging optimization is a very powerful technique that can be utilized to compute the adaptation gains. The magnetic levitation system is used as a case study for the nonlinear complex systems of magnetic levitation. This system is unstable and is difficult to control using classical control methods. So in this status, a modern controller that can deal with nonlinear systems which is Model Reference Adaptive Controller (MRAC) and an optimization technique for choosing the controller parameters, Bacteria Foraging Optimization Algorithm (BFOA), are utilized to improve the time of response and the stability margins for this system.

1.8 Thesis Objective

This thesis aimed to achieve six main points:

1. Design of a Model Reference Adaptive Controller (MRAC) for controlling the ball position of the magnetic levitation system.
2. Implement the Bacteria Foraging Optimization Algorithm (BFOA) using Matlab Code.
3. Perform a comparison between BFOA and PSO on a specific plant to show the effectiveness of BFOA technique.
4. Design of the Model Reference Adaptive Controller (MRAC) for controlling the ball position of the magnetic levitation system based on the Bacteria

Foraging Optimization Algorithm (BFOA) to choose the controller adaptation gains.

5. Design of the Proportional, Integral and Derivative (PID) controller for controlling the ball position of the magnetic levitation system based on the Bacteria Foraging Optimization Algorithm (BFOA) to choose the controller parameters.
6. Perform a comparison study between our results and the results of using other controllers based on Genetic Algorithm and Particle Swarm Optimization (PSO).

1.9 Thesis Contributions

This thesis presents a design of Model Reference Adaptive Controller (MRAC) for the magnetic levitation system to make it stable over all the operation time. The main contribution is utilizing the power of the Bacteria Foraging Optimization Algorithm (BFOA) for obtaining the parameters and adaptation gains of the PID controller and MRAC respectively using MatLab/Simulink to achieve the desired performance.

1.10 Literature Review

In 2012, Xiu-Chun Zhao, Guo-Kai Xu, Tao Zhang, and Ping-Shu Ge, [10], proposed a model reference adaptive controller which had simpler structure, fewer adjustable parameters, easier operation and accurate tracking capability even in the presence of external disturbances and uncertainties. The controller was applied into the perforated mill automatic speed control system and simulation results illustrated the practicality and effectiveness. However, there was no specific technique in this paper for choosing the adaptation gain for the MRAC which will be found in our thesis during BFOA.

In 2011, Abu Elreesh, [1] discussed the Magnetic Levitation (Maglev) model as an example of a nonlinear system and used the design of fuzzy logic controller for this model to prove that the fuzzy controller can work properly with nonlinear systems. Genetic Algorithm (GA) was used in this thesis as an optimization method that optimized the membership, output gain, and inputs gain of the fuzzy controller. The

result of fuzzy controller with GA optimization compared with H2 controller which is one of optimal control techniques, and proved that fuzzy controller with GA optimization gave better performance over H2 controller. Also in this thesis, fuzzy controller was implemented using FPGA chip. The design used a high-level programming language, HDL, for implementing the fuzzy logic controller using the Xfuzzy CAD tools to implement the fuzzy logic controller into HDL code. However, in our thesis, we will use BFOA instead of genetic algorithm and adaptive control instead of fuzzy control.

In 2011, Elamassie, [6] proposed a ripple-free deadbeat control for nonlinear systems in discrete time. The proposed method combined two ripple-free deadbeat control laws. The new controller guaranteed robustness and handles multi-rate systems. Multi-rate digital control was used when processing time was greater than controller updating time; thus, processing time was decreased by increasing at least one of the following: state feedback sampling time; output feedback sampling time, input sampling time, and/or decreasing controller updating rate for some processes; therefore, the sampling time was not unique for the whole system. The new controller was applied to magnetic ball levitation CE152 as a case study for nonlinear systems. However, our thesis will use another technique (Adaptive control with BFOA) and show the output response for square wave.

In 2010, E. Salim Ali and S. M. Abd-Elazim, [11] proposed BFOA based Load Frequency Control (LFC) for the suppression of oscillations in power system. A two area non-reheat thermal system was considered to be equipped with PID controllers. BFOA was employed to search for optimal controllers parameters to minimize certain performance index. The performance of the proposed controllers was evaluated with the performance of the conventional integral (I) controller in order to demonstrate the superior efficiency of the proposed BFOA in tuning PID controllers. By comparison with the conventional technique, the effectiveness of the anticipated scheme was confirmed. However, we will use adaptive control instead of classical PID control with BFOA for nonlinear system and get better results than using classical PID controller.

In 2007, Dong Hwa Kim, Ajith Abraham and Jae Hoon Cho, [12] proposed a hybrid approach involving genetic algorithms (GA) and bacterial foraging (BF) algorithms for function optimization problems. They first illustrated the proposed method using four test functions and the performance of the algorithm was studied with an emphasis on mutation, crossover, variation of step sizes, chemotactic steps, and the lifetime of the bacteria. The proposed algorithm was then used to tune a PID controller of an automatic voltage regulator (AVR). Simulation results clearly illustrated that the proposed approach was very efficient and could easily be extended for other global optimization problems. However, this research also used optimization technique with classical PID controller rather than using modern adaptive control.

1.11 Thesis Organization

This thesis is organized as follows: Chapter 2 deals with adaptive control and its two types (direct and indirect adaptive controller) and focuses on Model Reference Adaptive Control (MRAC). In addition it deals with the nonlinear magnetic levitation system and its mathematical model. Chapter 3 concentrates on the heuristic optimization technique which is Bacteria Foraging Optimization and its four processes, namely chemotaxis, swarming, reproduction, and elimination dispersal, also it exhibits the extraction of its algorithm. Chapter 4 shows the simulation and results for the magnetic levitation system with adaptive controller before and after applying BFOA. Chapter 5 concludes this thesis and presents the future work.

CHAPTER 2

ADAPTIVE CONTROL SYSTEM AND NONLINEAR MAGNETIC LEVITATION SYSTEM

2.2.1 Model Reference Adaptive Control (MRAC)

The general idea behind Model Reference Adaptive Control (MRAC, also known as an MRAS or Model Reference Adaptive System) is to create a closed loop controller with parameters that can be updated to change the response of the system. In this type, the adaptation mechanism directly adapt the controller parameter which will control the given plant system to make tracking to the reference model which has a desired performance. The error coming from the difference between the output of the plant and the output of the reference model is act as input to the adaptation mechanism.

The MRAC structure consists of four main parts: the plant, the controller, the reference model and the adjustment mechanism as shown in figure 2.2.

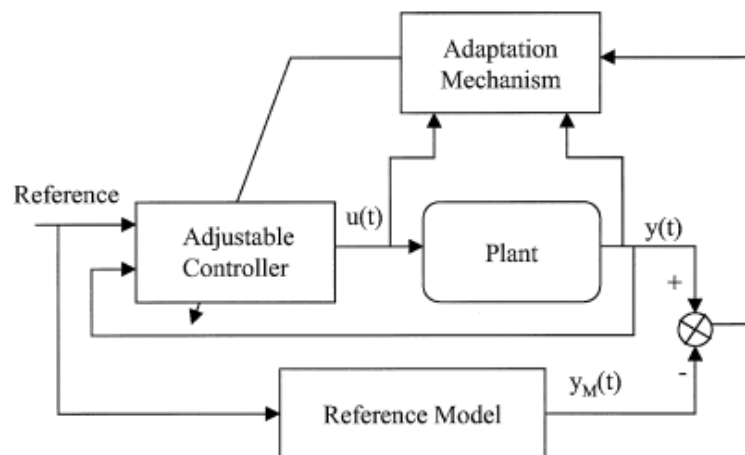


Figure (2.2): Model reference adaptive control system (Direct Adaptive Control)

2.2.2 MIT Rule

This rule is developed in Massachusetts Institute of technology and is used to apply the MRAC approach to any practical system [4]. MIT rule is an important technique of adaptive control. It can be included into a general scheme of circuit with MRAC structure. This research will cover the design using the MIT rule. When designing an MRAC using the MIT rule, the designer chooses: the reference model, the controller structure and the tuning gains for the adjustment mechanism. In this rule, we can begin by defining the tracking error, e . which is:

$$e = y_{plant} - y_{model} \quad (2.1)$$

From this error, a cost function of θ can be formed. θ is the parameter that will be adapted. The choice of this cost function will determine how the parameters are updated based on the optimization technique. A cost function will be defined as:

$$J(\theta) = \frac{1}{2}e^2(\theta) \quad (2.2)$$

To find the updated of the parameter; θ , we need to form an equation for the change in θ . If the goal is to minimize this cost related to the error, it is sensible to move in the direction of the negative gradient of J . This change in J is assumed to be proportional to the change in θ . Thus, the derivative of θ is equal to the negative change in J . The result for the cost function chosen above is:

$$\frac{d\theta}{dt} = -\gamma \frac{\delta J}{\delta \theta} = -\gamma e \frac{\delta e}{\delta \theta} \quad (2.3)$$

Where γ is the adaptation gain. This relationship between the change in θ and the cost function is known as the MIT rule [5]. This equation is called sensitivity derivative. This term is the partial derivative of the error with respect to θ . This determines how the parameter θ will be updated. The choice above results in all of the sensitivity derivatives must be multiplied by the error. We can also write the cost function as follows:

$$J(\theta) = |e(\theta)| \quad (2.4)$$

$$\frac{d\theta}{dt} = -\gamma \frac{\delta e}{\delta \theta} \text{sign}(e) \quad (2.5)$$

$$\text{Where } \text{sign}(e) = \begin{cases} 1, & e > 0 \\ 0, & e = 0 \\ -1, & e < 0 \end{cases}$$

2.3 Indirect Adaptive Control

Indirect methods are based on estimated parameters that calculated the required controller parameters. In this method, adaptation of the parameters of the controllers is done in two steps: (1) estimation of the process parameters and (2) computation of the controller parameters based on the current process estimated parameters. We can

also name it self-tuning method. As shown below, the block diagram of this method controller is consisting of plant model estimator, controller design, plant, and adjustable controller.

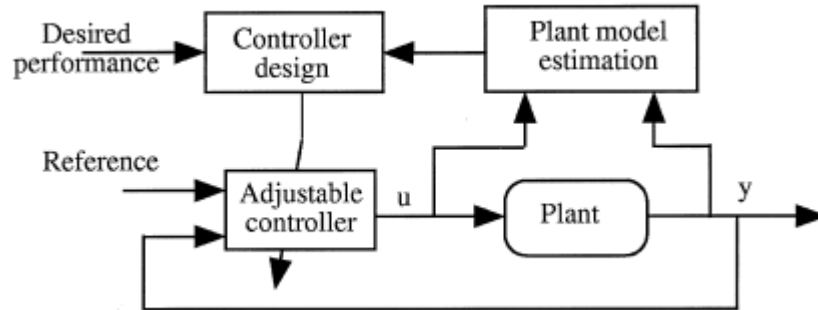


Figure (2.3): Indirect adaptive controls (self-tuning control)

2.5 Adaptive PID Controller

PID Control (proportional-integral-derivative) is the widest type of automatic control used in industry. A PID controller corrects the error between the output and the desired input or sets point by calculating and gives an output of correction that will adjust the plant output. A PID controller has the general form:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de}{dt} \quad (2.6)$$

Where K_p is proportional gain, K_i is the integral gain, and K_d is the derivative gain. A PID controller form in S domain is:

$$G_c(s) = k_p + k_d s + \frac{k_i}{s} \quad (2.7)$$

These three parameters can be tuned based on optimization technique such as bacteria foraging algorithm to reach to the desired performance depending on the requirements of the system. The block diagram and the effects of increasing a parameter independently for the PID controller are shown below:

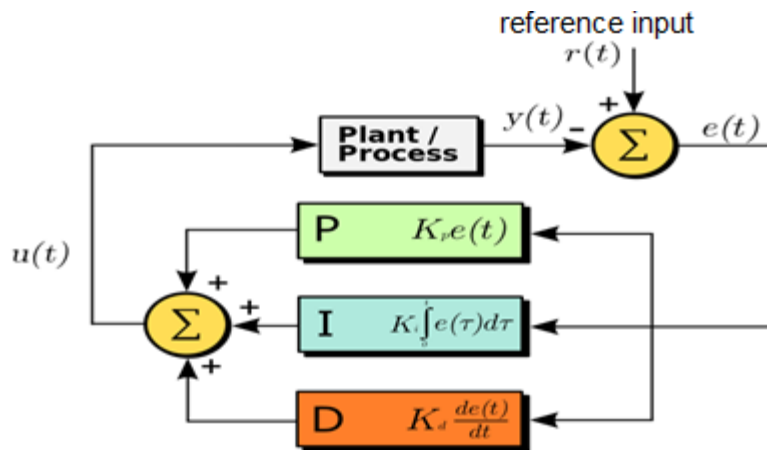


Figure (2.4): Block diagram of PID Controller

Table 2.1 Effects of <i>increasing</i> a parameter independently					
Parameter	Rise time	Overshoot	Settling time	Steady-state error	Stability
K_p	Decrease	Increase	Small change	Decrease	Degrade
K_i	Decrease	Increase	Increase	Eliminate	Degrade
K_d	Decrease	Decrease	Decrease	No effect in theory	Improve if K_d small

2.5 Magnetic Levitation System

Magnetic levitation is one of the most complex, nonlinear, and unstable system. Maglev system has so many applications in use in the field of control engineering such as high-speed Magnetic Levitation trains, and frictionless bearings. Because of this, many researches have been done on this system using different methods such as classical PID control, fuzzy logic control, optimal control, feedback linearization, sliding mode and adaptive control. They did their researches on the maglev models such as Maglev model 730 [5] and CE152 model [6].

Magnetic levitation is the process of levitating an object by exploiting magnetic fields. In other words, it is overcoming the gravitational force on an object by applying a counteracting magnetic field [5].

2.5.1 Maglev System model 730

The magnetic levitation system model 730, as shown in figure 2.5, consists of a disk whose position can be controlled by a top and a bottom coil. Depending on which coil is used, this system can be either open loop stable (using the bottom coil) or unstable (using the top coil) [5]. Disk position is measured by laser sensors. The coil voltage is limited between $[0, 3]$ V.



Figure (2.5): Magnetic Levitation Model 730

The levitation system according to force balance analysis in vertical plane is:

$$my = F_u - mg - c\dot{y} \quad (2.8)$$

Where m is the mass of the levitation magnet, y is the distance of levitated magnet, and F_u is the magnetic force term that is modeled as having the following form:

$$F_u = u/(a+b)^4 \quad (2.9)$$

Where a , b and c are constants which may be determined by numerical modelling methods [5]. The 2nd order transfer function model [5] is defined such as;

$$G(s) = \frac{s + 1}{s^2 + s + 1} = \frac{Y(s)}{U(s)} \quad (2.10)$$

2.5.2 Maglev System model CE152

The CE 152 magnetic levitation model is one of the ranges of educational scale models offered by Humusoft Company for teaching system dynamics and control engineering principles [6]. The model belongs to the range of teaching systems directly controllable by a PC computer in real time. The CE 152 Magnetic Levitation Model is one dimensional strongly unstable system designed for studying system

dynamics and experimenting with number of different control algorithms based on classical and control theory. Figure 2.6 shows CE 152 model and its components.

The system consists of a coil levitating steel ball in magnetic field. Position of the steel ball is sensed by an inductive linear position sensor connected to A/D convertor. The coil is driven by a power amplifier connected to D/A convertor. The basic control task is to control the position of the ball freely levitating in the magnetic field of the coil [7].



Figure (2.6): CE152 Magnetic Levitation Model

The magnetic levitation system model CE 152 is characterized by the third order differential equation [6] as shown in equation (2.11):

$$m_k \ddot{x} = \frac{i^2 k_c}{(x-x_0)^2} - m_k g - k_{fv} \dot{x} \quad (2.11)$$

Where m_k is the ball mass, i is the current, K_c is coil constant, x_0 is coil bias, g is gravity acceleration constant, and K_{fv} is viscose friction. After making linearization and substitute the values mentioned in reference [6], we get the third order transfer function as shown in equation (2.12):

$$G_p(s) = \frac{1.83e9}{s^3 + 5.349e4 s^2 + 1.432e5 s + 8.464e8} = \frac{N(s)}{D(s)} \quad (2.12)$$

CHAPTER 3

BACTERIA FORAGING
OPTIMIZATION
ALGORITHM

3.1 Overview

Many of species depend in its survival on their fitness (the law of evolution that supports those species who have better food searching ability and either eliminates or reshapes those with poor search ability). Bacteria Foraging Optimization method is based on the natural selection which tends to eliminate the animals with poor foraging strategies and favour those having successful foraging strategies [2]. The notion of this new algorithm is that a group foraging strategy of a swarm of *E.coli* bacteria can be applied on multi-optimal function optimization. If we understand and model the foraging behavior of the E.coli, we can use its application in any nonlinear optimization problem.

The foraging strategy of Escherichia coli bacteria present in human can be described by four processes, namely chemotaxis, swarming, reproduction, and elimination and dispersal.

3.1.1 Chemotaxis

The movement of *E.coli* bacteria during its search for food can be defined in two ways: swimming and tumbling. It can swim for a period of time in the same direction or it may tumble (moving in random directions), and alternate between these two modes of operation for the entire lifetime. Figure (3.1) shows the swim and tumble of bacteria.

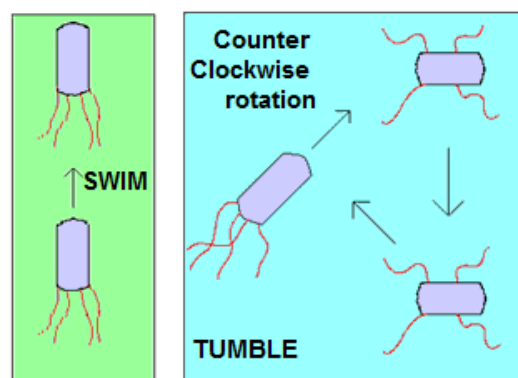


Figure (3.1): Swim and tumble of a bacterium

3.1.2 Swarming

The swarming in *E.coli* means that the bacteria collected into groups moves as concentric patterns with high bacterial density for food searching. When the

bacterium reaches the richest food location in the search period, it should try to attract other bacteria so that together they converge on the desired location.

3.1.3 Reproduction

In the reproduction stage, the best set of bacteria is divided into two groups: the least healthy bacteria eventually dies while each of the healthier bacteria asexually splits into two bacteria, which are then placed in the same location. This keeps the population of bacteria constant in the evolution process.

3.1.4 Elimination and Dispersal

During the evolution process, sudden events may occur such as rising of the temperature in the local environment which may kill a group of bacteria and/or disperse them to a new environment. Elimination and dispersal are parts of the population level and occur based on a probability ratio. In our applications, this phenomenon helps us reducing the behaviour of stagnation often seen in such parallel search algorithms. To simulate this phenomenon in BFOA, some bacteria are liquidated at random with a very small probability while the new replacements are randomly initialized over the search space [5].

3.2 BFO Algorithm

The following figure illustrated the flow chart of the BFO algorithm:

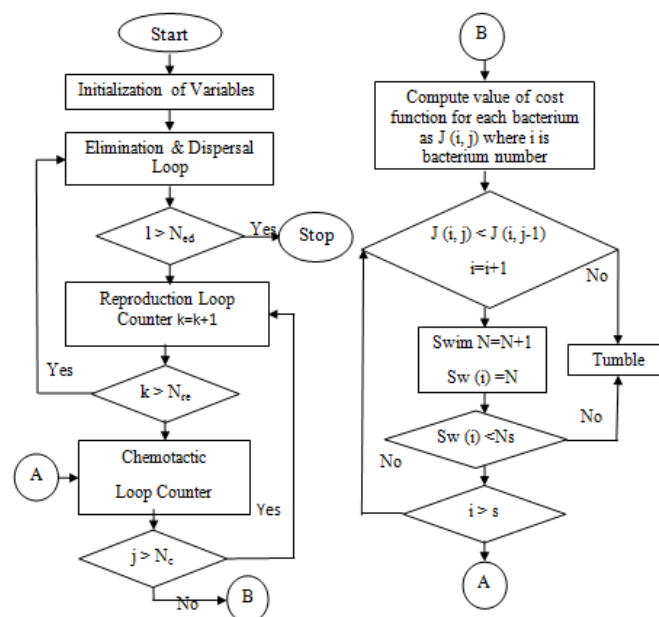


Figure (3.2): Flowchart of the Bacterial Foraging Algorithm [8]

The algorithm is listed as a pseudo code below with its steps detailed as follow:

Pseudo Code of the BFO Algorithm [9]:

Parameters:

[Step 1] Initialize parameters $p, S, N_c, N_s, N_{re}, N_{ed}, P_{ed}, C(i)(i=1,2,\dots,S), \theta_i$.

- p : Dimension of the search space,
- S : Total number of bacteria in the population,
- N_c : The number of chemotactic steps,
- N_s : The swimming length.
- N_{re} : The number of reproduction steps,
- N_{ed} : The number of elimination-dispersal events,
- P_{ed} : Elimination-dispersal probability,
- $C(i)$: The size of the step taken in the random direction specified by the tumble.

[Step 2] Elimination-dispersal loop: $l = l+1$

[Step 3] Reproduction loop: $k = k+1$

[Step 4] Chemotaxis loop: $j = j+1$

- a) For $i = 1, 2, \dots, S$ take a chemotactic step for bacterium i as follows:
Compute the fitness function $J(i, j, k, l)$.
- b) Let, $J(i, j, k, l) = J(i, j, k, l) + J_{cc}(\theta_i(j, k, l), P(j, k, l))$ (i.e. add on the cell-to cell attractant-repellant profile to simulate the swarming behavior).
- c) Let $J_{last} = J(i, j, k, l)$ to save this value since we may find a better cost via a run.
- d) Tumble: generate a random vector $\Delta(i) \in R^p$ with each element $\Delta_m(i)$, $m = 1, 2, \dots, p$, a random number on $[-1, 1]$.
- e) Move: Let

$$\theta^i(j+1, k, l) = \theta^i(j, k, l) + C(i) \frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \quad (3.1)$$

This results in a step of size $C(i)$ in the direction of the tumble for bacterium i .

- f) Compute $J(i, j+1, k, l)$ and let

$$J(i, j+1, k, l) = J(i, j, k, l) + J_{cc}(\theta_i(j+1, k, l), P(j+1, k, l)) \quad (3.2)$$

- g) Swim

- Initialize $m=0$ (counter for swim length).
- While $m < N_s$ (if have not climbed down too long). Let $m=m+1$.
 - If $J(i, j+1, k, l) < J_{last}$ (if doing better), let $J_{last} = J(i, j+1, k, l)$ and let

$$\theta^i(j+1, k, l) = \theta^i(j, k, l) + C(i) \frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}$$

- Use this $\theta^i(j+1, j, k)$ and eq. (3.2) to compute the new $J(i, j+1, k, l)$

- Else, let $m = N_s$. This is the end of the while statement.
- Go to the next bacterium ($i+1$) if $i^1 \neq S$ and return the loop.

[Step 5] If $j < N_c$, go to step 4. In this case continue chemotaxis since the life of the bacteria is not over.

[Step 6] Reproduction:

For the given k and l , and for each $i = 1, 2, \dots, S$, let J_{health}^i be the health of the bacterium i (a measure of how many nutrients it got over its lifetime and how successful it was at avoiding noxious substances) as mentioned in equation (3.3).

$$J_{health}^i = \sum_{j=1}^{N_c+1} J(i, j, k, l) \quad (3.3)$$

- a) Sort bacteria and chemotactic parameters $C(i)$ in order of ascending cost J_{health} (higher cost means lower health).
- b) The S_r bacteria with the highest $health J$ values die and the remaining S_r bacteria with the best values split (this process is performed by the copies that are made which placed at the same location as their parent).

[Step 7] If $k < N_{re}$, go to step 3. In this case, we have not reached the number of specified reproduction steps, so we start the next generation of the chemotactic loop.

[Step 8]

- a) Elimination-dispersal: For $i = 1, 2, \dots, S$ with probability P_{ed} , eliminate and disperse each bacterium (this keeps the number of bacteria in the population constant). To do this, if a bacterium is eliminated, simply disperse another one to a random location on the optimization domain.
- b) If $l < N_{ed}$, then go to step 2; otherwise end.

3.3 Minimization of A simple Function Using BFOA

In this section, we will use the BFO Algorithm to minimize a simple exponential function cost function as in equation (3.4). This example is presented only to show the power and the effectiveness of this algorithm. The cost function J consists of two parameters θ_1 and θ_2 and these two parameters will be used to minimize the proposed function using BFOA.

$$J(\theta_1, \theta_2) = a * e^{(b*(\theta_1-c)^2+(\theta_2-d)^2)} \quad (3.4)$$

Where a, b, c and d are variable numbers.

In BFOA code, we will use:

- ☒ p=2 Dimension of the search space
- ☒ S=50 the number of bacteria in the population
- ☒ $N_c = 100$ Number of chemotactic steps per bacteria lifetime

- ☒ $N_s=4$ Limits the length of a swim when it is on a gradient
- ☒ $N_{re} = 4$ The number of reproduction steps
- ☒ $N_{ed} = 2$ The number of elimination-dispersal events (N_{re} reproduction steps in between each event)
- ☒ $P_{ed} = 0.25$ The probability that each bacterium will be eliminated/dispersed
- ☒ Flag =2.

Figure (3.3) shows the nutrient concentration during the search process for the bacteria. The valleys represent the food concentrations which are needed for the bacteria; in contrast the peaks represent the noxious concentration which must be avoided. Figure (3.4) shows the movement of the bacteria towards the nutrient concentration. The blue circles represent the nutrient locations while the red circles represent the noxious locations.

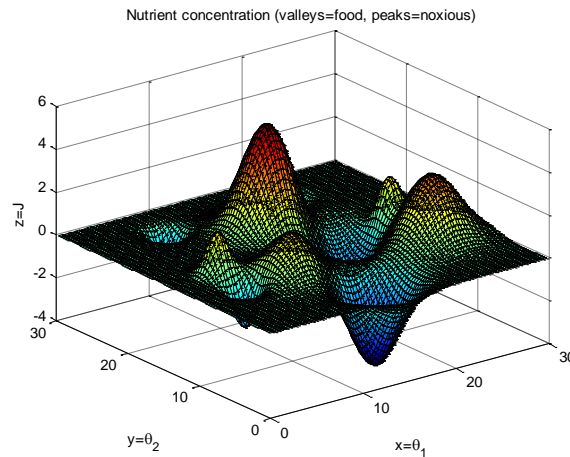


Figure (3.3): Nutrient Concentration (Valleys and Peaks) for the cost function J

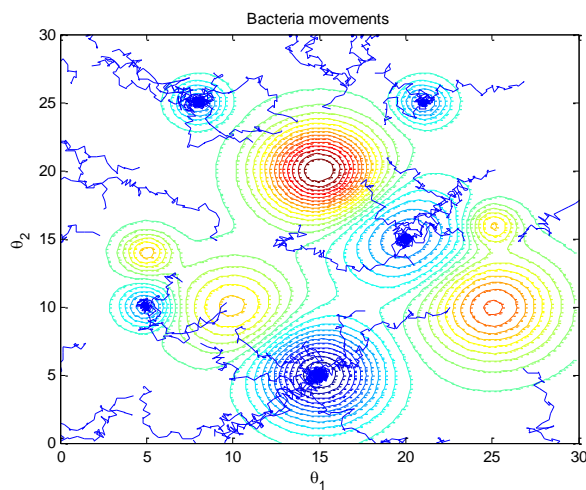


Figure (3.4): Bacteria Movement towards the nutrient concentration

3.4 Comparison study between BFOA, PSO and Matlab Tuner

To show the power and effectiveness of BFOA over Particle Swarm Optimization (PSO) and Matlab Tuner, we will make a comparison study using the following general transfer function which is used for applying different methodology:

$$G(s) = \frac{5}{s^4+3s^3+7s^2+5s} \quad (3.5)$$

BFOA, PSO and Matlab Tuner are applied to a PID controller to tune the controller parameters K_p, K_d and K_i for a plant and actuator system as shown in figure (3.5).

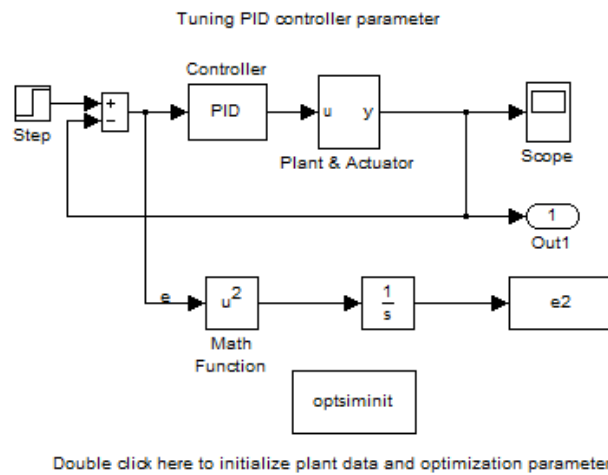


Figure (3.5): Tuning of PID parameters using optimization methods

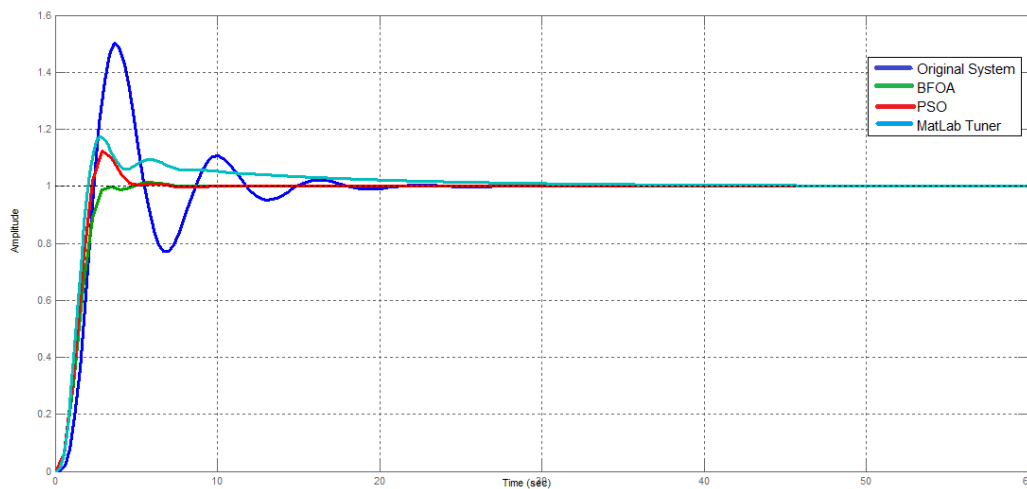


Figure (3.6): Step response for the plant system with PID controller before and after applying optimization methods

Figure (3.6) shows the output for the original plant and the output of the plant after applying PID controller based on BFOA, PSO, and Matlab tuner. As noticed in this figure, the behavior of the response after using BFOA is better and close to the reference input than the others during the known performance specifications such that: it has the best overshoot 2% when compared to others, the settling time is approximately 10 s, rising time is 1.5 s, and the steady state error is zero. Table 3.1 shows a comparison of performance results of the PID controller in terms of settling time, overshoot, rising time, and steady state error for all methods.

Table (3.1): Performance of the PID controller over BFOA, PSO, and Matlab Tuner

Property	Original system	After applying BFOA	After applying PSO	After applying Matlab Tuner
Overshoot (%)	50	2	12	17
Settling Time (s)	31	10	9.6	47
Rising Time (s)	4	1.5	1.5	1
Steady State Error (%)	2	0	0	4

We can conclude that using of BFOA to tune the PID parameters is the best technique.

CHAPTER 4

SIMULATION AND RESULTS

4.1 Overview

In this chapter, we are going to generate the output response of the magnetic levitation system models 730 and CE152 so that it conforms to the desired performance. In order to do that, we will design the Model Reference Adaptive Controller (MRAC) for these two models before and after applying Bacteria Foraging Optimization Algorithm (BFOA) and designing the adaptive PID controller based on BFOA for the same models.

4.2 Steps for Designing MRAC

First of all, we will include in our design the PID controller so the design becomes MRAPIDC to kill the oscillations as possible. Steps for designing the MRAC are coming as follows:

1. Define the adaptation error ε as in equation (4.1):

$$\varepsilon = y_p(t) - y_m(t) \quad (4.1)$$

Where y_p is the output of the plant while y_m is the output of the reference model.

2. Define the cost function J which will be minimized according to the adaptation error ε as in equation (4.2):

$$J = \frac{1}{2} \varepsilon^2(t) \quad (4.2)$$

3. Define the MIT rule which is the time rate of change of θ that is proportional to the negative gradient of the cost function (J) as:

$$\frac{d\theta}{dt} = -\gamma \frac{dJ}{d\theta} = -\gamma \varepsilon \frac{d\varepsilon}{d\theta} \quad (4.3)$$

4. For our design, we will choose the second order transfer function as a reference model that is:

$$G_m(s) = \frac{b_{m1}s + b_{m0}}{s^2 + a_{m1}s + a_{m0}} \quad (4.4)$$

5. Define the tracking error e for the system as:

$$e = r - y_p \quad (4.5)$$

Where r is the reference input for the system. So:

$$\frac{de}{dt} = - \frac{dy_p}{dt} \quad (4.6)$$

6. Define the control law for the system according to PID controller as:

$$u(t) = K_p e(t) + K_i \int e(t) dt - K_d \frac{dy_p}{dt} \quad (4.7)$$

The Laplace transform for the control law is:

$$U = K_p E + \frac{K_i}{s} E - s K_d y_p \quad (4.8)$$

Where K_p is proportional gain, K_i is integral gain, and K_d is derivative gain. So the adjustment parameters θ_1, θ_2 and θ_3 equal K_p, K_i and K_d respectively.

7. After applying this control law to the system, the closed loop transfer function is:

$$Y_p = \frac{G_p s (G_p K_p r + \frac{G_p K_i r}{s})}{(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} \quad (4.9)$$

Solving for y_p in terms of r and substituting in equation (4.1), the adaptation error becomes:

$$\varepsilon = \frac{(G_p K_p s + G_p K_i) r}{(s(1 + G_p K_p) + G_p K_i + s^2 G_p K_d)} - Y_m \quad (4.10)$$

8. Make extraction of the adaptation error ε regarding to the MIT rule for getting the adjustment parameters K_p, K_i and K_d as follows:

$$\frac{d\varepsilon}{dK_p, K_i, K_d} = \frac{dY_p}{dK_p, K_i, K_d} \quad (4.11)$$

We can rewrite ε as follows:

$$\varepsilon = \frac{G_p K_p r + \frac{G_p K_i r}{s}}{1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s} \quad (4.12)$$

$$\varepsilon = (G_p K_p r + \frac{G_p K_i r}{s})(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)^{-1} \quad (4.13)$$

☒ **Applying MIT rule to obtain K_p :**

$$\frac{d\varepsilon}{dK_p} = \frac{G_p r}{(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} - \frac{G_p (G_p K_p r + \frac{G_p K_i r}{s})}{(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)^2} \quad (4.14)$$

We can substitute equation (4.9) in equation (4.14), we get:

$$\frac{d\varepsilon}{dK_p} = \frac{G_p r}{(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} - \frac{G_p Y_p}{(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} \quad (4.15)$$

After making some arrangement, we got:

$$\frac{d\varepsilon}{dK_p} = \frac{G_p E}{(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} \quad (4.16)$$

The same procedure will be done for the other two parameters K_i and K_d .

☒ **Applying MIT rule to obtain K_i :**

$$\frac{d\varepsilon}{dK_i} = \frac{\frac{G_p r}{s}}{(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} - \frac{\frac{G_p}{s} (G_p K_p r + \frac{G_p K_i r}{s})}{(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)^2} \quad (4.17)$$

We can substitute equation (4.9) in equation (4.17), we get:

$$\frac{d\varepsilon}{dK_i} = \frac{\frac{G_p r}{s}}{(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} - \frac{\frac{G_p Y_p}{s}}{(1 + G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} \quad (4.18)$$

After making some arrangement, we got:

$$\frac{d\varepsilon}{dK_i} = \frac{\frac{G_p E}{s}}{(1+G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} \quad (4.19)$$

☒ **Applying MIT rule to obtain K_d :**

$$\frac{d\varepsilon}{dK_d} = - \frac{G_p s (G_p K_p r + \frac{G_p K_i r}{s})}{(1+G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)^2} \quad (4.20)$$

We can substitute equation (4.9) in equation (4.20), we get:

$$\frac{d\varepsilon}{dK_d} = - \frac{G_p s Y_p}{(1+G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} \quad (4.21)$$

9. Because of the exact formulas cannot be used, so we need valid approximations such that parameters are closed to ideal value as follows:
Denominator of plant \approx Denominator model reference.

$$\text{den} \left(\frac{G_p}{(1+G_p K_p + \frac{G_p K_i}{s} + G_p K_d s)} \right) = s^2 + a_{m1}s + a_{m0} \quad (4.22)$$

10. Applying MIT gradient rules for determining the adjustment parameters $\theta_1, \theta_2, \theta_3$. Regarding to equation (4.3), the adjustment parameters are:

$$\bullet \frac{d\theta_1}{dt} = \frac{dK_p}{dt} = -\gamma \varepsilon \frac{d\varepsilon}{dK_p} = \left(-\frac{\gamma_p}{s} \right) \varepsilon \left(\frac{s}{a_0 s^2 + a_{m1}s + a_{m2}} \right) e \quad (4.23)$$

$$\bullet \frac{d\theta_2}{dt} = \frac{dK_i}{dt} = -\gamma \varepsilon \frac{d\varepsilon}{dK_i} = \left(-\frac{\gamma_i}{s} \right) \varepsilon \left(\frac{1}{a_0 s^2 + a_{m1}s + a_{m2}} \right) e \quad (4.24)$$

$$\bullet \frac{d\theta_3}{dt} = \frac{dK_d}{dt} = -\gamma \varepsilon \frac{d\varepsilon}{dK_d} = \left(\frac{\gamma_d}{s} \right) \varepsilon \left(\frac{s^2}{a_0 s^2 + a_{m1}s + a_{m2}} \right) Y_p \quad (4.25)$$

4.3 Design of MRAC for Maglev System

Based on the previous steps for designing the MRAC, the design for the Model Reference Adaptive Control for a nonlinear Magnetic Levitation System will be as follows:

4.3.1 Design of MRAC for Maglev Model 730

In this section, the Maglev system model 730 will be used. To design the MRAC for this model, we need the transfer function for the system and the transfer function for the reference model which the output from the plant will be track. The transfer function for the reference model must be chosen based on the needed desired specifications (the overshoot, settling time, rising time, and steady state error).

We will use the same transfer function as in equation (2.10) according to [5] after making linearization

The specifications of the reference model that are mentioned in [5] are:

- Overshoot = 22%
- Settling Time = 0.07s
- Rising Time = 0.02s
- Steady State Error = 0%

So the transfer function for the reference model becomes:

$$G_m(s) = \frac{100s + 10000}{s^2 + 140s + 10000} \quad (4.26)$$

❖ The adjustment parameters for the system will be:

$$\bullet \frac{d\theta_1}{dt} = \frac{dK_p}{dt} = -\gamma \varepsilon \frac{d\varepsilon}{dK_p} = \left(-\frac{\gamma_p}{s}\right) \varepsilon \left(\frac{100s}{s^2+140s+10000}\right) e \quad (4.27)$$

$$\bullet \frac{d\theta_2}{dt} = \frac{dK_i}{dt} = -\gamma \varepsilon \frac{d\varepsilon}{dK_i} = \left(-\frac{\gamma_i}{s}\right) \varepsilon \left(\frac{10000}{s^2+140s+10000}\right) e \quad (4.28)$$

$$\bullet \frac{d\theta_3}{dt} = \frac{dK_d}{dt} = -\gamma \varepsilon \frac{d\varepsilon}{dK_d} = \left(\frac{\gamma_d}{s}\right) \varepsilon \left(\frac{s^2}{s^2+140s+10000}\right) Y_p \quad (4.29)$$

As we said before that there is no method used in MIT rule for getting the adaptation gains. What we know only that the adaptation gains must be small enough to get good tracking for the response of the reference model, so in this section, we got the values of the adaptation gains by experiment; first trying small numbers and make some changes up to get the desired response. The adaptation gains used in this system are:

$$\gamma_p = -0.001, \quad \gamma_i = -0.008, \quad \gamma_d = 0.008.$$

Figure (4.1) shows the structure of MRAC for the magnetic levitation system model 730. In figure (4.2), we see the square response for the system based MRAC which make a good tracking for the output of the reference model and as the time progress the two graphs become close together so meet the performance specifications. In addition; figure (4.3) presents the adaptation error which ensures the effectiveness of MRAC when it is close to zero with continued of the adaptation time, but at small instant of time there is a value of error because there is a value of the output of reference model and no value for the output of the plant depending on the quickness difference between the two outputs; the reference model and the plant.

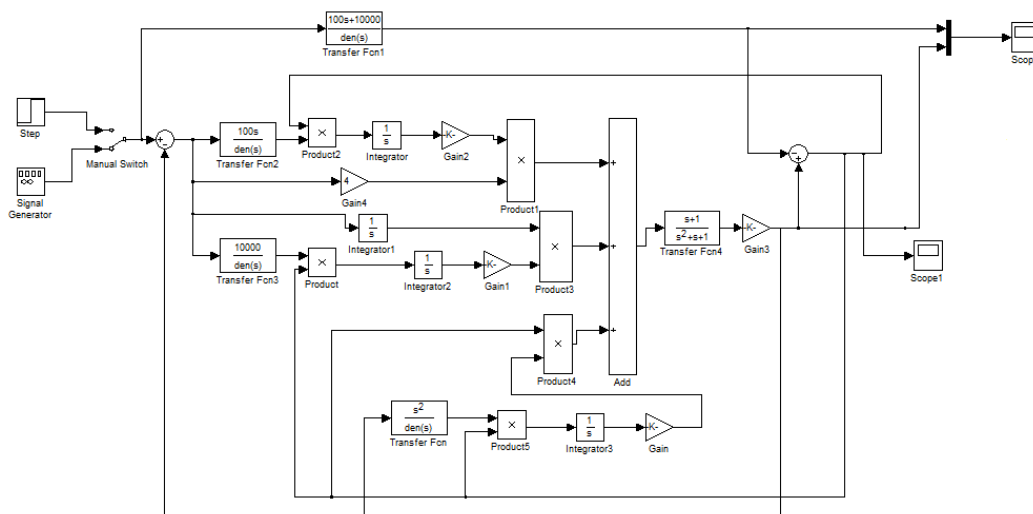


Figure (4.1): Simulink Diagram for Maglev 730 System used MRAC

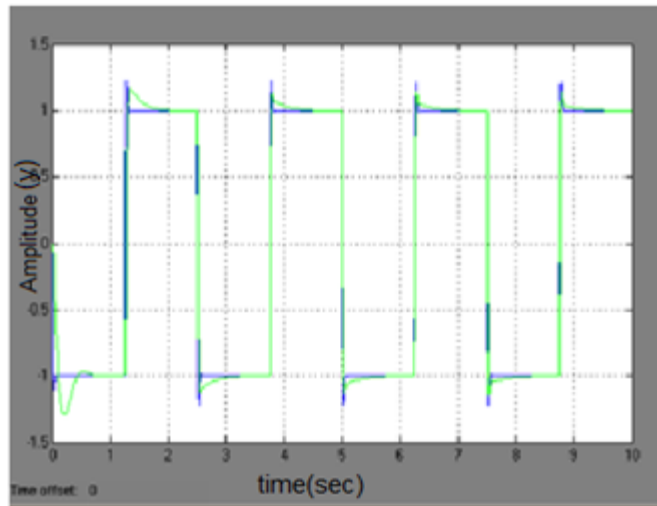


Figure (4.2): Square response for the Maglev 730 used MRAC (plant output "green", reference output "blue")

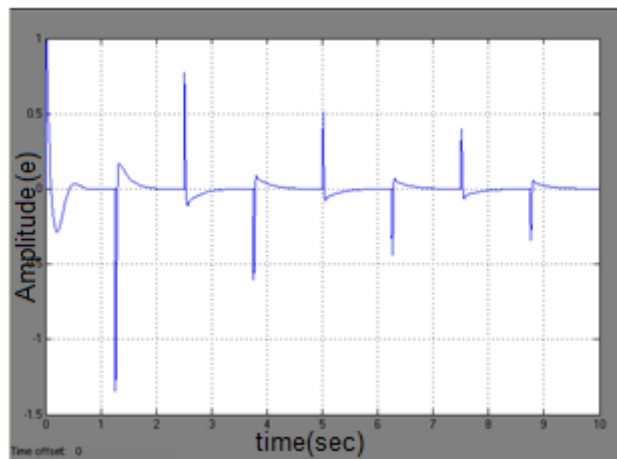


Figure (4.3): The adaptation error for the Maglev 730 used MRAC

4.3.2 Design of MRAC for Maglev Model CE152

The principle scheme for the magnetic levitation system CE152 is shown in the figure below.

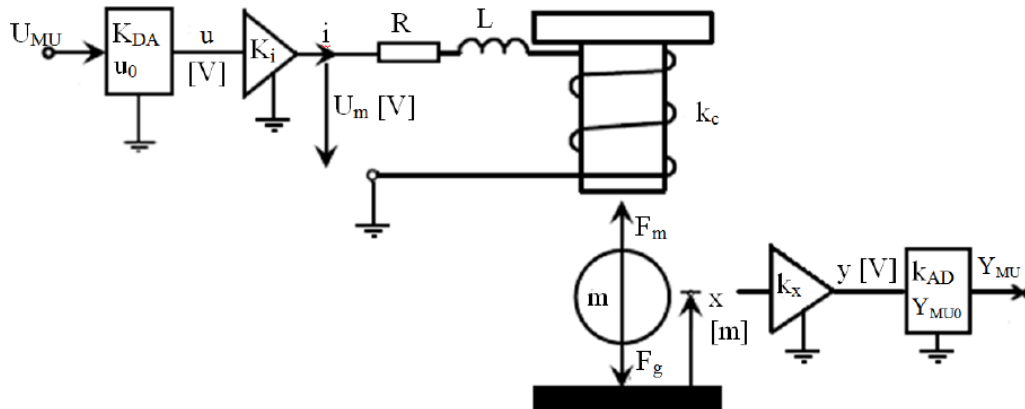


Figure (4.4): The principle scheme of the magnetic levitation system CE152

The model shown in Figure (4.4) consists of the following blocks [1]:

1. D/A converter.
2. Power amplifier.
3. Ball & coil subsystem.
4. Position sensor.
5. A/D converter.

We will use the third order transfer function for the system after making linearization and substitution for the values of the parameters as in [6] is in equation (2.12):

The second order transfer function will be chosen to be a reference model according to the following performance specifications that are mentioned in [6]:

- Overshoot = 5%
- Settling Time = 0.01s
- Rising Time = 0.01s
- Steady State Error = 0%

So the transfer function for the reference model becomes:

$$G_m(s) = \frac{2.313e5}{s^2 + 663.8s + 2.313e5} \quad (4.30)$$

❖ The adjustment parameters for the system will be:

$$\bullet \frac{d\theta_1}{dt} = \frac{dK_p}{dt} = -\gamma \varepsilon \frac{d\varepsilon}{dK_p} = \left(-\frac{\gamma_p}{s}\right) \varepsilon \left(\frac{2.313e5s}{s^2+663.8s+2.313e5}\right) e \quad (4.31)$$

$$\bullet \frac{d\theta_2}{dt} = \frac{dK_i}{dt} = -\gamma \varepsilon \frac{d\varepsilon}{dK_i} = \left(-\frac{\gamma_i}{s}\right) \varepsilon \left(\frac{2.313e5}{s^2+663.8s+2.313e5}\right) e \quad (4.32)$$

$$\bullet \frac{d\theta_3}{dt} = \frac{dK_d}{dt} = -\gamma \varepsilon \frac{d\varepsilon}{dK_d} = \left(\frac{\gamma_d}{s}\right) \varepsilon \left(\frac{2.313e5s^2}{s^2+663.8s+2.313e5}\right) Y_p \quad (4.33)$$

As in the previous section, the same way used to get the adaptation gains that used in this system that are:

- $\gamma_p = -e-6$.
- $\gamma_i = -8e-7$.
- $\gamma_d = 0.01$.

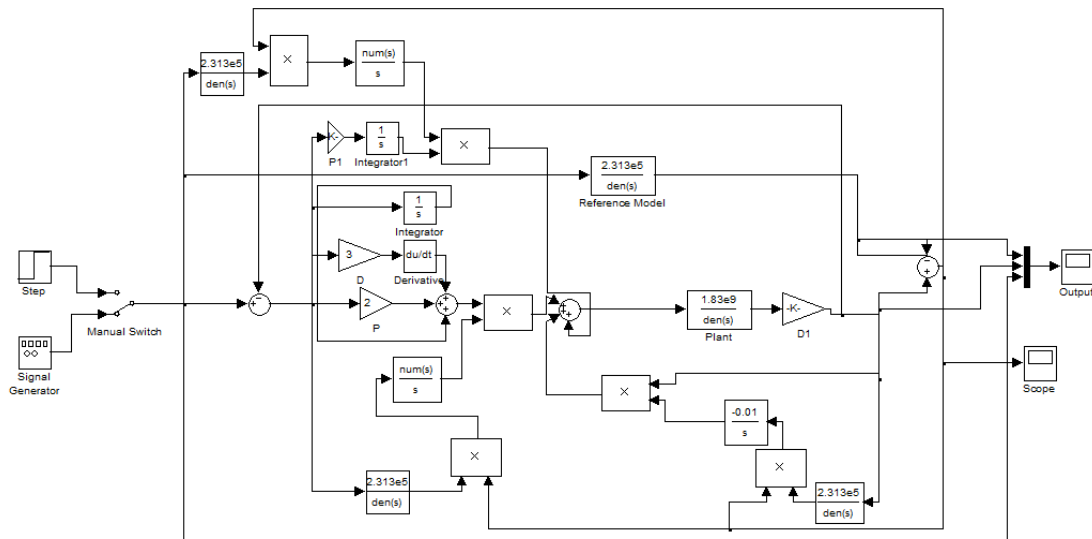


Figure (4.5): Simulink Diagram for Maglev CE152 used MRAC

Figure (4.5) shows the Simulink Diagram for Maglev CE152 System using MRAC technique. It is clearly shown in figure (4.6) that the square signal response for the system makes a good tracking and close to the output of the reference model. In the output of the plant, there is an oscillation rounding the peak by 0.4% tolerance; in addition, there is an enhancement in rising time.

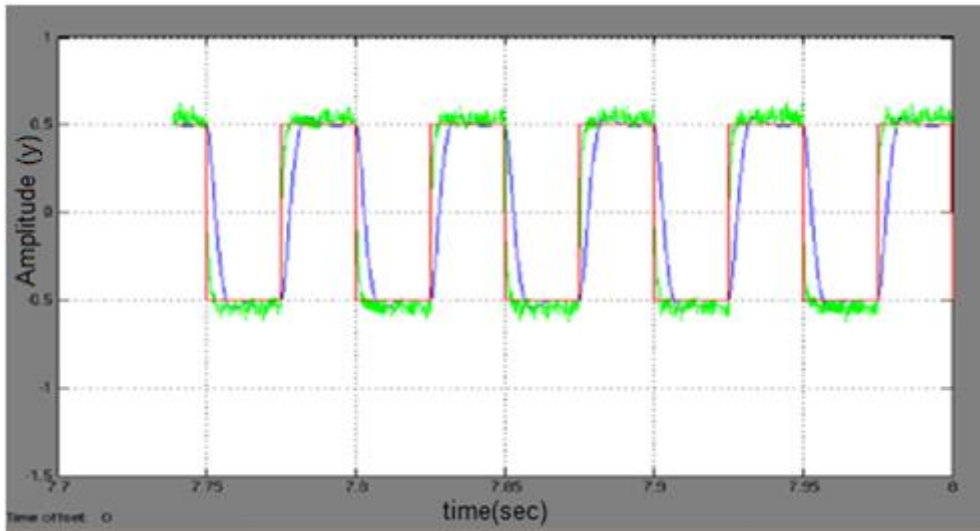


Figure (4.6): Square response for the Maglev CE152 used MRAC (plant output "green", reference output "blue", reference input "red")

Figure (4.7) shows the behavior of the error (the difference between the output of the plant system and the output of the reference model) during the adaptation process, and it clearly shows that it approaches to zero but there is oscillation around the zero because of the oscillation around the peak in the previous figure.

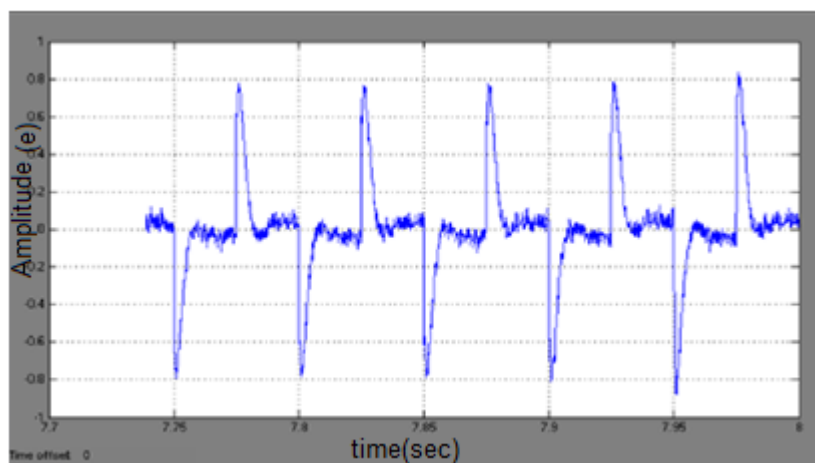


Figure (4.7): The adaptation error for the Maglev CE152 used MRAC

4.4 Design of MRAC Based BFOA

In this section, we will talk about how we can use the optimization methods with adaptive control especially Bacteria Foraging Optimization Algorithm (BFOA) with Model Reference Adaptive Controller (MRAC).

As it is known that the adaptation gain γ used in MRAC must be small enough according to MIT Rule. So in this section we will use the BFO Algorithm to choose the optimal values for the adaptation gains.

In BFOA, there are three codes; the first one is the main code, the second one is the cost function which will be optimized and the last one is the back cell to cell attraction function which study the behavior of each bacterium with respect to other bacteria.

4.4.1 Design of MRAC for Maglev Model 730 Based BFOA

In this system, the following specifications will be used for BFOA:

Table (4.1): Specifications for BFOA with Maglev 730 used in MRAC

Number of Bacteria, S	10
Dimension of The Search Space, P	3
Number of Chemotactic Steps, N_c	4
Limits The Length of A swim, N_s	4
Number of Reproduction Steps, N_{re}	4
The Probability of Eliminated/Dispersed, P_{re}	0.25

In this example, the Simulink diagram for the maglev system with MRAC as shown in figure (4.8) is connected to the BFOA codes through an optisimini button for making an optimizing of the adaptation gains.

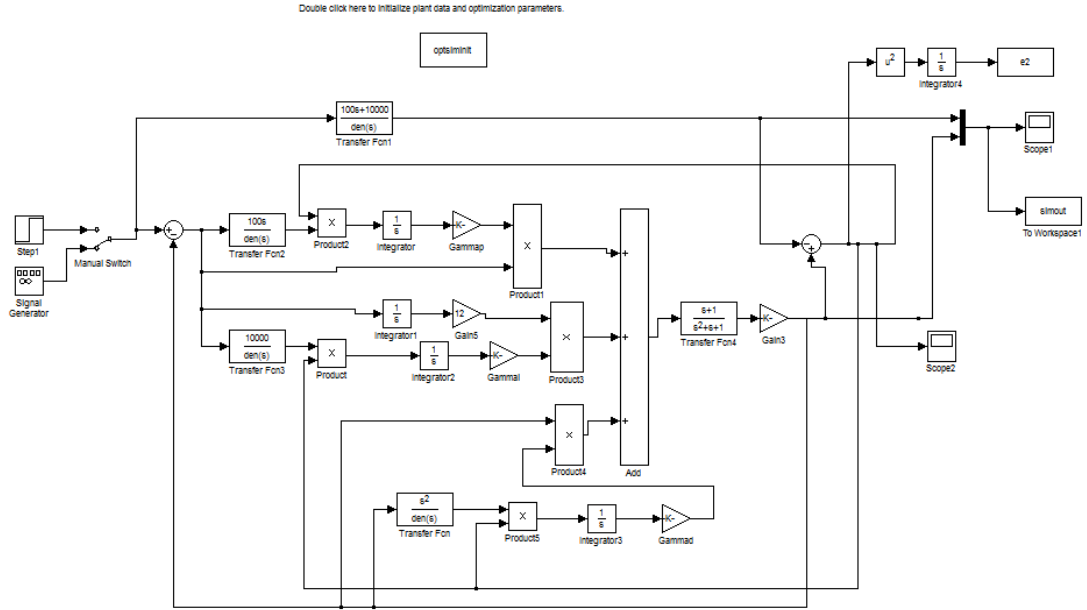


Figure (4.8): Simulink Diagram for Maglev 730 used MRAC Based BFOA

After tuning the optimal values for the adaptation gains using BFOA, the adaptation gains become as follows:

- $\gamma_p = -0.0074$.
- $\gamma_i = -0.7812$.
- $\gamma_d = 0.1028$.

The results come in figures (4.9) and (4.10). From figure (4.9), it is seen that the square response of the plant is better than the response in figure (4.2). The overshoot initiates big in the plant output 60% and reduced to approach approximately 5%. Also the settling time ($T.S.$) is approximately 0.2s. In addition, the improvement presented in the adaptation error ε as shown in figure (4.10) where it goes to zero more quickly than it in figure (4.3).

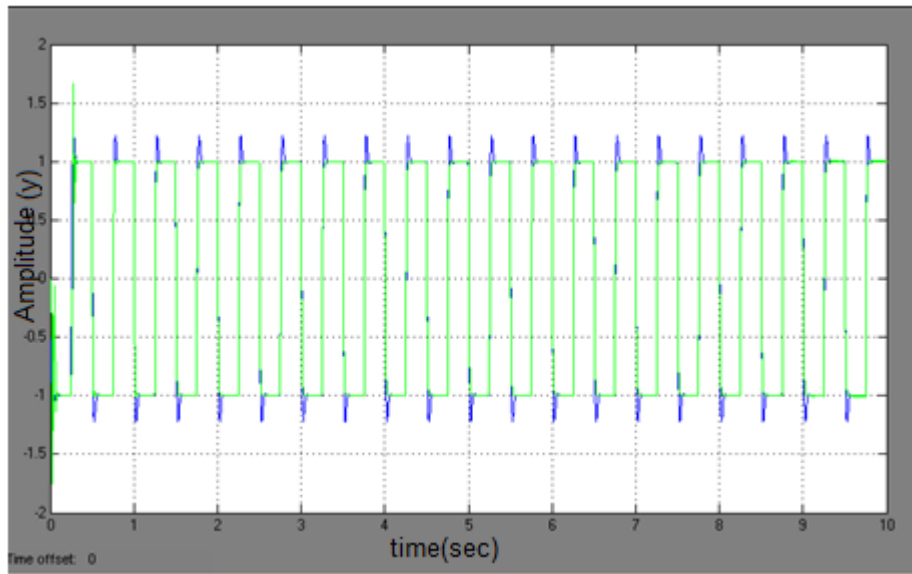


Figure (4.9): Square Response for the Maglev 730 used MRAC Based BFOA (plant output "green", reference output "blue")

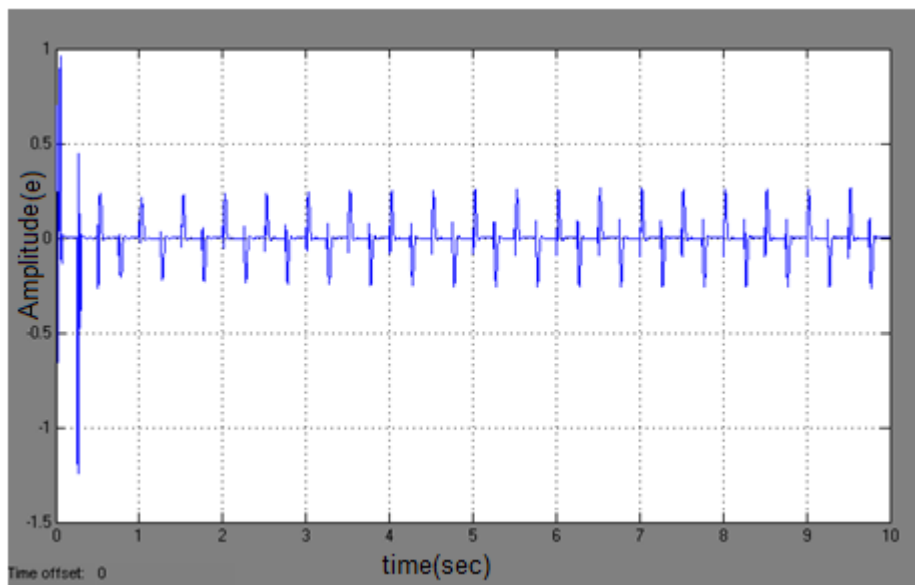


Figure (4.10): The adaptation error for the Maglev 730 with MRAC BFOA

4.4.2 Design of MRAC for Maglev Model CE152 Based BFOA

In this third order system, as before, we will use the following specifications for BFOA as below:

Table (4.2): Specifications for BFOA with Maglev CE152 used in MRAC

Number of Bacteria, S	10
Dimension of The Search Space, P	3
Number of Chemotactic Steps, N_c	10
Limits The Length of A swim, N_s	4
Number of Reproduction Steps, N_{re}	4
The Probability of Eliminated/Dispersed, P_{re}	0.25

The Simulink diagram for the maglev system CE152 with MRAC is shown in figure (4.11). The Simulink diagram is connected to the BFOA codes for making an optimizing for the adaptation gains.

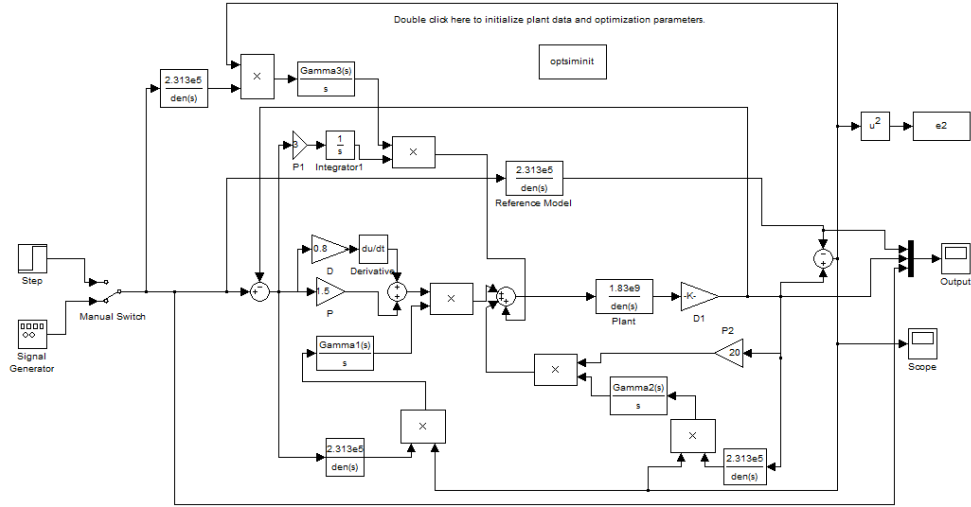


Figure (4.11): Simulink Diagram for Maglev CE152 used MRAC Based BFOA

After the tuning, the adaptation gains become as follows:

- $\gamma_p = -3.3951e-007$, $\gamma_d = -0.007$, $\gamma_i = -6.8481e-006$.

The results come in figures (4.12) and (4.13). From figure (4.12), it is noticed that the square response is better when compared with that in figure (4.6) where the oscillation about the peak value is narrower and present good tracking for the reference model output. In addition, the improvement presented also in the adaptation

error ε as shown in figure (4.13) where the oscillation about zero is also narrower than it in figure (4.7). But the problem still exist which is the oscillation.

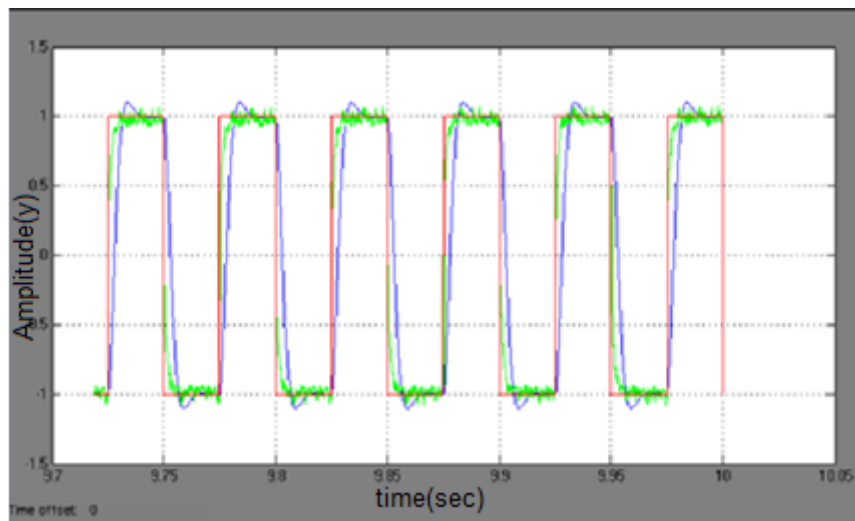


Figure (4.12): Square Response for the Maglev CE152 used MRAC Based BFOA (plant output "green", reference output "blue", input signal "red")

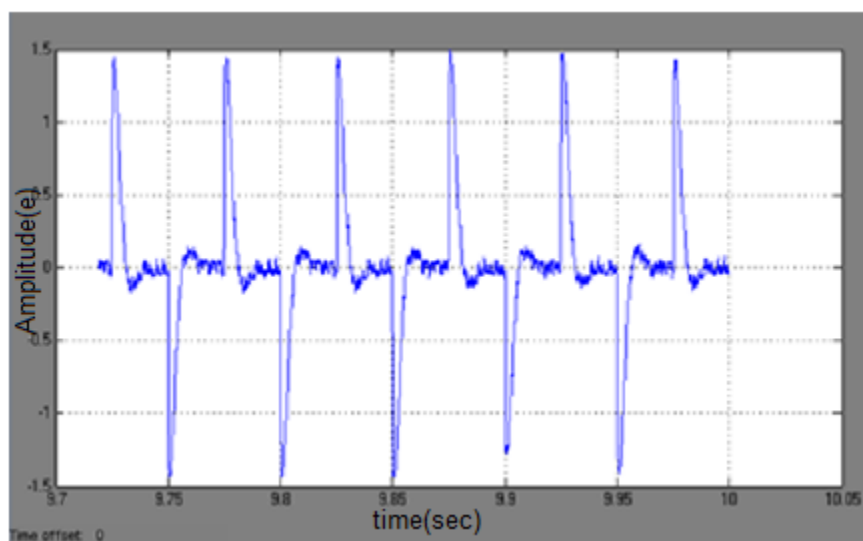


Figure (4.13): The adaptation error for the Maglev CE152 with MRAC BFOA

We can overcome the oscillation problem by omitting the higher order from the denominator of the auxiliary transfer functions which are used in MRAC as filters.

After make this treatment, the denominator becomes:

$$663.8s + 2.313e5 \quad (4.34)$$

The results that were shown in figures (4.14) and (4.15) confirm this approximation that there is no oscillation around the peak value.

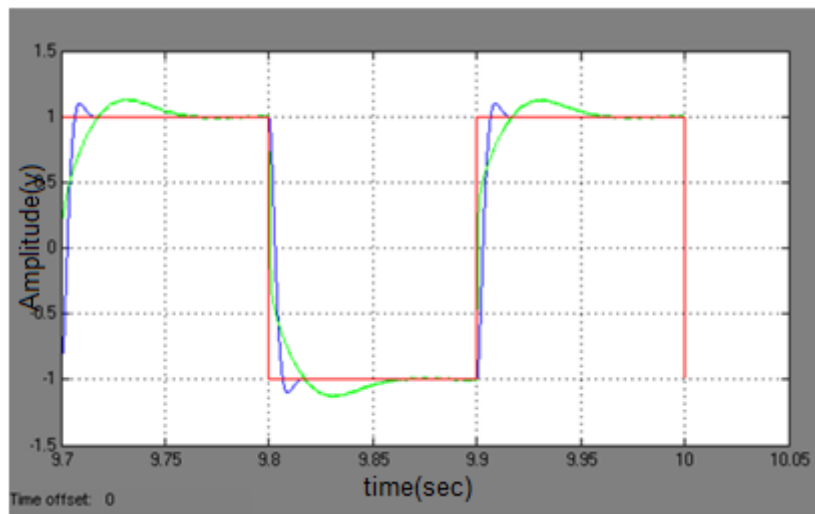


Figure (4.14): Square Response for the Maglev CE152 used MRAC Based BFOA after approximation (plant output "green", reference output "blue", input signal "red")

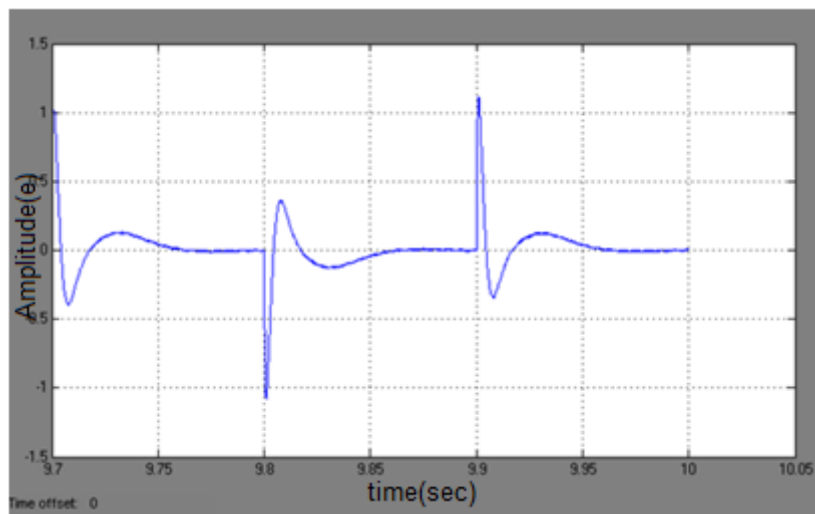


Figure (4.15): The adaptation error for the Maglev CE152 with MRAC BFOA after approximation

4.5 Design of PID Controller for Maglev System Based BFOA

As mentioned before, the PID controller is the widest controller used in industry, so there was considerable interest by researchers to find a way for tuning its parameters (K_p, K_i, K_d). In this section, Bacteria Foraging Optimization Algorithm is used to confirm the idea of using the optimization techniques with Adaptive Control. We will use it to make tuning the PID parameters to control the nonlinear system

(Maglev System). The step signal will be used as an input signal. We will use the same Simulink diagram which is shown in figure (3.5).

4.5.1 Design of PID Controller for Maglev Model 730 Based BFOA

Referring to the Simulink diagram in figure (3.5), the transfer function that will be used for the Maglev system is presented in equation (2.10). The limits for the input to the plant system are -5 and 5 volts. The Optsiminit button is the interconnection between the Simulink diagram and the BFOA Matlab code. The cost function which will be minimized is:

$$J = \frac{1}{2} e^2 \quad (4.35)$$

Where e is the tracking error that is:

$$e = r - y \quad (4.36)$$

Where r is the reference input and y is the plant output.

We will use the same specifications for the BFO Algorithm that are used in table (4.2) for optimizing process

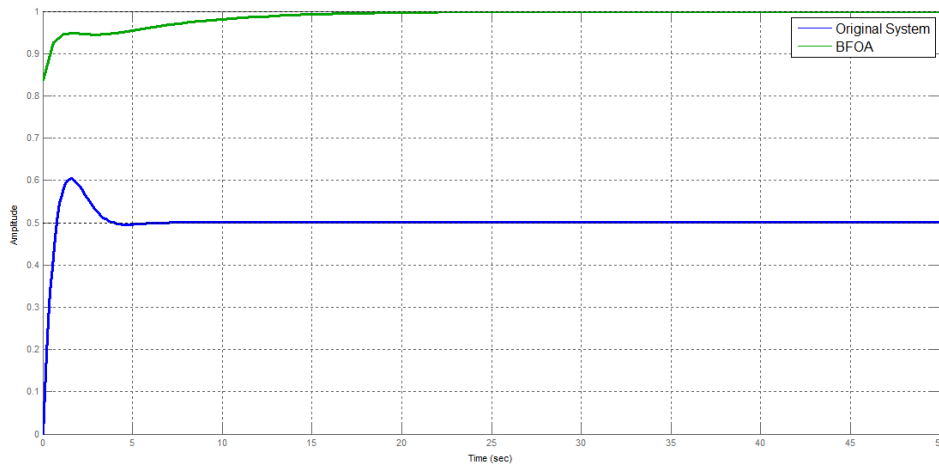


Figure (4.16): PID step response of Maglev 730 with and without BFOA

The values of the PID parameters that are generated when using BFOA as a tuner technique for the previous example are:

- $K_p = 9.8731$ $K_i = 1.8030$ $K_d = 5.1500$

From the previous figure, we noticed that BFO Algorithm is capable of making the output of the Maglev system to be adequate with the desired specifications that is no overshoot (approximately zero) and the steady state error is approximately zero.

4.5.2 Design of PID Controller for Maglev CE152 Based BFOA

At the same way, in this section, we will control of the third order Maglev system CE152 referred to equation (2.12) by a PID controller based BFO Algorithm. The same limits and the same cost function in the previous section will be used. The specifications for the BFO Algorithm that are used in the optimizing process are the same as in table (4.1).

The values of the PID parameters that are generated when using BFOA as a tuner technique for the previous example are:

- $K_p = 10.0461$ $K_i = 8.9064$ $K_d = 2.9447$

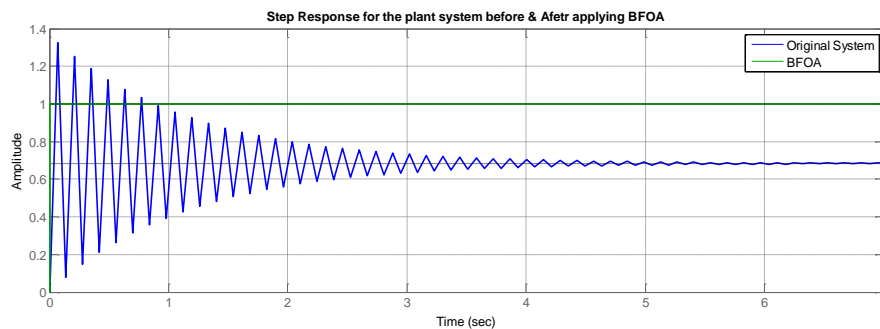


Figure (4.17): PID step response of Maglev CE152 with and without BFOA

From figure (4.17), we can confirm the effectiveness of BFO Algorithm for tuning the PID parameters and meeting the desired specifications that are no overshoot, small settling time, small rising time, and the steady state error is approximately zero.

4.6 Comparison Study

Comparison Study method is considered as one of the best scientific methods used by researchers to demonstrate the strength and effectiveness of their methodology. In this section, we will make a comparison study between our method

(Adaptive Control based BFOA), Fuzzy logic control based Genetic Algorithm (GT), H_2 controller, and Ripple Free Dead Beat.

4.6.1 Comparison between Adaptive Control, Feedback Linearization (FBL), Deadbeat control, and H_2 controller

In this subsection, the comparison will be done between Adaptive PID Controller based BFOA, Feedback Linearization, Deadbeat with FBL and H_2 controller after applying these types on Maglev System. From [6] as shown in figures (4.18, 19, and 20) when compared with figure (4.17), the comparison is listed below in table (4.3), figures (4.18), (4.19) and (4.20).

Table (4.3): Comparison between AC based BFOA, FBL, deadbeat with FBL, and H_2 controller

Property	FBL [6]	Adaptive PID based BFOA	Deadbeat with FBL [6]	H_2 controller [6]
O.S. (%)	0	0	10	40
t_s (s)	0.35	0.001	0.17	0.25
t_r (s)	0.2	0.001	0.01	0.02
S.S.E. (%)	0	0	0	0

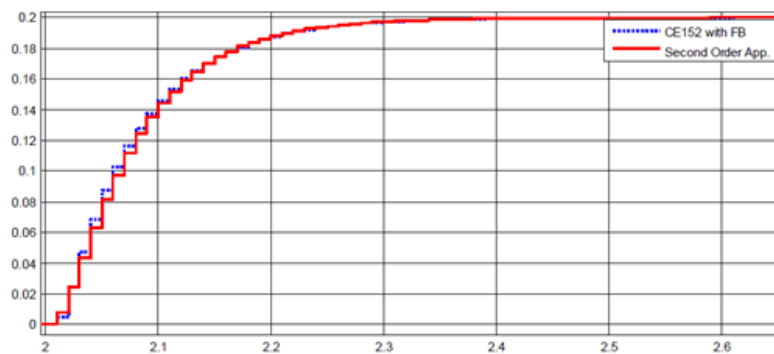


Figure (4.18): Step response of CE152 with third FBL and approximated model [6]

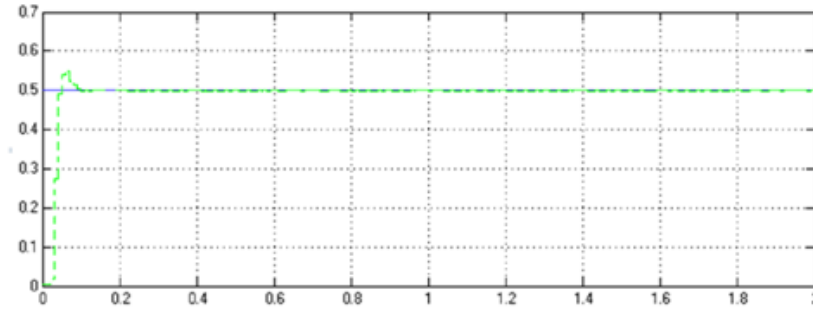


Figure (4.19): Step response of deadbeat controller with FBL for CE152 [6]

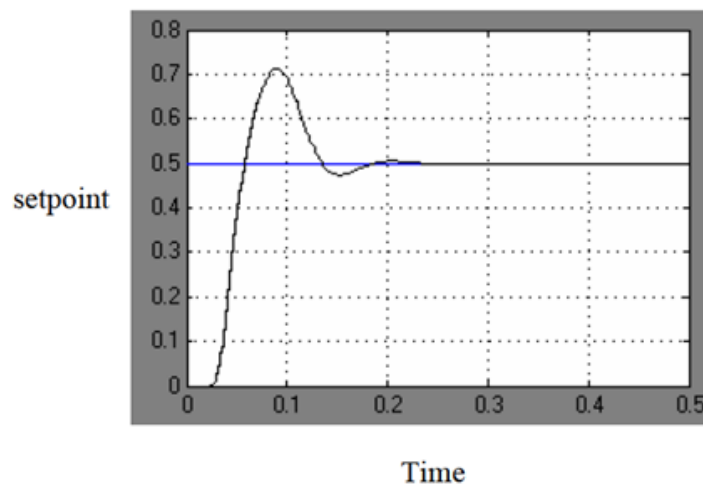


Figure (4.20): Step response with H_2 controller for CE152 [6]

From table (4.5), we can notice that adaptive PID controller based BFOA out done the other methods in terms of overshoot, settling time, and rising time. It gives better results than the nearest one which is deadbeat with FBL that is almost zero in all of these specifications. The other two techniques which are FBL and H_2 controller presented the worst performance. So in dealing with nonlinear magnetic levitation system, the adaptive PID controller based BFOA confirms its strength over the other techniques.

4.6.2 Comparison between Adaptive Control, Fuzzy Logic, and Fuzzy Logic Based GA Control

In this subsection, the comparison will be done between MRAC based BFOA, Fuzzy Logic, and Fuzzy Logic based GA after applying these types on Maglev

System. From [1] as shown in figures (4.21) and (4.22) and when compared with figure (4.14), the comparison is shown below in table (4.4), figures (4.21) and (4.22).

Table (4.4): Comparison between MRAC based BFOA, Fuzzy Logic, and Fuzzy Logic based GA

Property	MRAC based BFOA	Fuzzy Logic [1]	Fuzzy logic based GA [1]
O.S. (%)	15	17	20
t_s (s)	0.08	0.2	0.1
t_r (s)	0.01	0.2	0.1
S.S.E. (%)	0	0	0

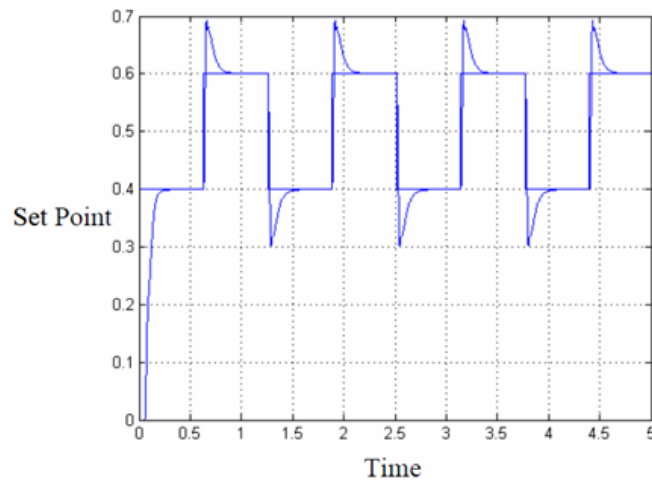


Figure (4.21): Square output with fuzzy logic for CE152 [1]

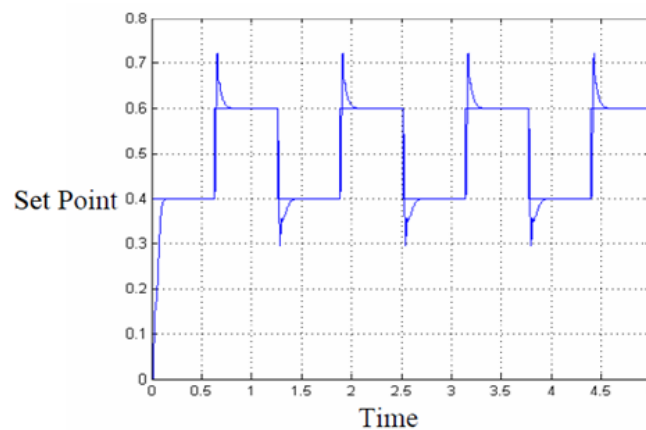


Figure (4.22): Square output with fuzzy logic based GA for CE152 [1]

The square signal is applied on the input of the magnetic levitation system after applying the three controllers in table (4.6) separately and the results are shown in table (4.6). We can notice that MRAC based BFOA outperforms the other controllers in terms of overshoot, settling time, and rising time. As seen that the overshoot using MRAC based BFOA is 15% while the *O.S.* in the other two methods, Fuzzy Logic and Fuzzy logic based GA, are 17% and 20% respectively. Also the settling time and rising time are better when using our method than the others. So using of MRAC with BFOA confirms its effectiveness over the other techniques.

4.7 Summary

We can summarize our results as follows:

- Adaptive controller is a good controller in dealing with nonlinear systems.
- BFOA is a very efficient heuristic optimization technique that gives precise results during choosing of optimal values.
- Making a combination between adaptive controller and optimization methods (BFOA) is very efficient as seen using adaptive PID and MRAC based on BFOA.
- Our method outperforms all the other methods such as fuzzy logic, FBL, deadbeat, and H_2 controller in terms of step and square responses.

CHAPTER 5

CONCLUSION AND

FUTUER WORK

Because of the development and progress happened in recent times in industry and other fields, most systems becomes difficult and more complex (nonlinear). So it's important to control of these systems by sufficient controllers (intelligent Controllers) such as adaptive controller, fuzzy controller, and others.

In this thesis, a magnetic levitation system was used as a case study and example of nonlinear systems. Two models of magnetic levitation system were used 730 and CE152. Adaptive Control such as adaptive PID controller and Model Reference Adaptive Controller (MRAC) based on Bacteria Foraging Optimization Algorithm (BFOA) was designed to control this nonlinear system. Matlab/Simulink software was used in simulation. A comparison study between our results and others such as Fuzzy Logic Control based Genetic Algorithm (GA), H_2 Controller, Feedback Linearization, and Deadbeat Controller was done and our technique showed excellent results especially in overshoot 0% and 15% in two comparisons and approximately 0.08 and 0.01 in settling time and rising time respectively, in contrast the other methods presented low performance on overshoot and settling time as shown in tables (4.5) and (4.6), so we can conclude that our methods showed its strength and effectiveness and outperforms the others.

Future work may include the use of other optimization methods with Adaptive Control such as PSO or GA, and using indirect adaptive control with BFOA. Moreover, this work can be extended to real time on Maglev system or using practical model such as small Magnetic Levitation Train.

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