DEVELOPMENT OF THREE DEGREE OF FREEDOM CONTROLLER FOR SHELL AND TUBE HEAT EXCHANGER USING NON-DOMINATED SORTING GENETIC ALGORITHM II

BY

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DECLARATION

I, declare that this research work **"Development of Three Degree of Freedom Controller for Shell and Tube Heat Exchanger using Non-Dominated Sorting Genetic Algorithm II**"has been carried out by me in the Department of Computer Engineering, Ahmadu Bello University, Zaria as part of the requirements for the award of the degree of Master of Science (M.Sc) in Control Engineering. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other institution.

HUDU KATAGUM MAGAJI _____ _____

(Student) **Signature** **Date**

CERTIFICATION

This dissertation titled ‘‘DEVELOPMENT OF THREE DEGREE OF FREEDOM CONTROLLER FOR SHELL AND TUBE HEAT EXCHANGER USING NON-DOMINATED SORTING GENETIC ALGORITHM II’’ by Hudu Katagum MAGAJI meets the regulations governing the award of the degree of Master of Science (M.Sc) in Control Engineering of the Ahmadu Bello University, Zaria and is approved for its’ contribution to knowledge and literary presentation.

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DEDICATION

This research work is dedicated to my wife Mrs Stella Hudu-Magaji.

ACKNOWLEDGMENT

In the name of ALLAH the most compassionate and the most merciful.Praise be to ALLAH, the cherisher and sustainer of the worlds.May His blessings and salutations be upon the noble prophet, Muhammad (PBUH). I thank Almighty Allah for giving me the grace to do this research, particularly with the challenges of having my family in Lagos, office in Abuja, and school in Zaria, without whom it would not have been possible.

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ABSTRACT

This thesis presents the development of a Three Degree of Freedom (3DoF) based outlet fluid temperature controller for Shell and Tube Heat Exchanger (STHX). Shell and Tube Heat Exchangers are classes of heat exchangers being used in industries for heat transfer between fluids. Tracking a setpoint by the STHX is usually a challenging problem, especially when subjected to noise and disturbance. Addressing this challenge, an existing STHX experimental data was employed to develop a three degree of freedom Proportional Integral Derivative (PID) controller. The parameters of the controller were optimized using the Non-Dominated Sorting Genetic Algorithm II (NSGA) while subjecting the system to noise. A Multi-objective Optimization Problem (MOP) of setpoint tracking, disturbance rejection, and noise suppression was formulated using Integral Absolute Error (IAE), Integral of Squared Error (ISE), and Integral of Time-weighted Absolute Error (ITAE) as cost function. Simulations were performed using MATLAB/SIMULINK R2018a. From the obtained results, the percentage overshoot under IAE using 3DoF controller, were slightly higher than that of 2DoF controller in setpoint tracking, the trend was reversed under the ISE criterion. The research found that the flow and temperature disturbance responses were optimally reduced to the range of 90% to 99% in all three criterions as compared to 2DoF controller which was in the range of 25% to 78%. The results also proved great suppression of noise with the developed 3DoF controller.

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LIST OF ABBREVIATIONS

Acronym	Definition
ART	Analytical Robotic Tuning
CHR	Chien-Hrones Reswick
DoF	Degree of Freedom
FDR	Flow Disturbance Response
GA	Genetic Algorithm
HEX	Heat Exchanger
IAE	Integral Absolute Error
IMC	Internal Model Control
ISE	Internal Square Error
ITAE	Integral Time-Weighted Absolute Error
L-R	From Left to Right
MOP	Multi-Objective Problem
NSGA	Non-Dominated Sort Genetic Algorithm
PID	Proportional-Integral-Derivative Controller
SOP	Single Objective Problem
SPR	Set Point Response
STHX	Shell and Tube Heat Exchanger
TDR	Temperature Disturbance Response
TLBO	Teaching Leaning Based Optimization
ZN	Ziegler Nichole

CHAPTER ONE

INTRODUCTION

1.1 Background

Heat exchanger being an indispensable unit in chemical processes is mostly used to transfer heat energy from a fluid of higher temperature to a cooler fluid (Padhee *et al.*, 2011). There are various kinds of heat exchangers available in the process industry such as, plate heat, plate fin, pillow plate heat exchangers, but the most frequently usedis Shell and Tube type Heat Exchanger (STHX) system. The popularity is due to its efficiency and less complexity (Duran *et al.*, 2009). The STHXs are mostly used to control fluid having varying temperatures and pressures. Typically, it consists of some special designed pipes in a cylindrical shaped shell in which a set of fluid is allowed to flow through the tubes, and while the other fluid is directed to flow between the tubes and the shell (Sodja & Zupanˇ, 2009). In the operation of STHX, fluid from a storage tank which is to gain heat flows through the tube while the fluid from a steam tank which is to loss heat flows in between the tube and the shell. The main purpose of a heat exchanger (HEx) unit is to ensure that the temperature of an outlet fluid is maintained at a specific value.This is normally achieved by implementing a control law that will regulate the exit temperature of the fluid in the presence of varying operating conditions such as noise and disturbances (Berto & Jr, 2000). Heat Exchangers are extensively used in areas such as petroleum refining, petrochemical processing and food industries as well as nuclear reaction systems, aircraft and space vehicles (Dhakad *et al.*, 2013).

Since the purpose of heat exchanger is mainly to transfer heat energy from the hot fluid in the shell to the fluid in the tube. Therefore, maintaining a specific temperature of the outlet fluid

irrespective of disturbances requires the use of controllers(Araki & Taguchi, 2003). Designing controllers for Heat Exchangers have been an area of interest to researchers over time due to its nonlinear dynamics and time delay, which poses challenges in regulating the outlet fluid temperature in the presence of a disturbance(Suthar & Gadit, 2017b). Different controllers ranging from classical PID, PID with feedforward as well as internalmodelbasedcontrollers have been implemented and studied with their merits and demerits in terms of transient behavior and computational complexity (Padhee *et al.*, 2011). In this research, a controller, with three degrees of freedom, capable of achieving a desired setpoint tracking and disturbance rejection has been developed. In the developed method, the number of system variables to be controlled will form the degree of freedom. Degree of freedom in control system can be said to be the number of controlled variables in the system (Suthar & Gadit, 2017b). The structure of One Degree of Freedom (1DoF) control has a drawback of its inability to optimize two objectives i.e. ensuring setpoint tracking and disturbance rejection concurrently. For this reason, controlling two system objectives at the same time leads to 2DoF control system structure (Araki & Taguchi, 2003;Suthar & Gadit, 2017b). In a typical 2DoF control, the disturbance rejection and the command input response characteristics can be determined separately. However, there exist a trade-off relationship between noise suppression and disturbance rejection characteristic. Hence, there is a need to design a 3DoF control scheme for determining setpoint tracking, disturbance rejection and noise suppression independently (Suzumura & Fujimoto 2015).

Researchers have used different tuning algorithms such as Ziegler Nichols (ZN), Choen-Coon, Chien-Hrones-Reswick (CHR) for optimizing control parameters. However, these tuning algorithmsdoes not give an improved results in many high frequency applications where optimal performances are required (Gupta *et al.*, 2017). Optimizing the tuning parameters using

evolutionary algorithm based on cost function had been adopted by various researchers in many successful applications. One of such is the application of genetic algorithm (GA) in optimizing parameters of a 2DoF controller for STHX system (Suthar & Gadit, 2017b).To further achieve an enhanced setpoint tracking, disturbance rejection and noise suppression necessitated the need for a 3DoF controller using a multi-objective optimization algorithm Non-Dominated Sorting Genetic Algorithm (NSGA) in this research.

This research designed and developed a 3DoF controller using NSGA-II for Shell and Tube Heat Exchanger.

1.2 Significance of Research

Deviation in setpoint temperature of outlet fluid in heat exchangers due to disturbances and noise had led to lost of materials.The developed design is able tominimizesetpointdeviation, enhance disturbance rejection,and noise suppression simultaneously thereby minimizing material losses, and enhancing efficiency.

1.3 Statement of Problem

Over the years, researchers have developed different controllers for regulating the outlet fluid temperature of Shell and Tube Heat Exchanger. Most designs have successfully achieved setpoint tracking and disturbance rejection while neglecting process noise(Suthar & Gadit, 2017a). From the controlled process, there exists a tradeoff between setpoint tracking, disturbance rejection and noise suppression (Suzumura & Fujimoto 2015). The control problem here is to design a controller that will regulate the temperature of outlet fluid of STHX in the presence of external disturbances and process noise. The existing 2DoF controllers has not been able to address the problem of process and measurement noise(Suthar & Gadit, 2017b; Suzumura

& Fujimoto, 2015). Hence, this research designed and developed a 3DoF controller scheme to effectively achieve setpoint tracking, disturbance rejection and noise suppression using NSGA II in tuning the parameters of the controllers.

1.4 Aim and Objectives

The aim of this research is to develop a 3 degree of freedom controller for STHX using NSGA II in tuning the parameters of the controllers.

The objectives of this research are as follows:

1. To implement a multi-objective optimization of two-degree of freedom Controller using NSGA II for STHX, adopted from the work of Suthar & Gadit, (2017a).
2. To develop a multi-objective optimization of 3DoF controller for regulating outlet fluid temperature of Shell and Tube Heat Exchanger using NSGA II and subjecting the system to noise.
3. To compare the performance of the 2DoF controller and 3DoF controller using overshoot, rise time and settling time.

1.5 Methodology

The steps adopted in achieving this work are:

1 Designa 2DoF multi-objective optimization controller for STHX using NSGA-II base on the work of Suthar & Gadit,(2017a)

   a. Adopting the standard transfer function of a heat exchanger and model of the 2DoF controller for optimization problem.

   b. Formulation of the multi-objective optimization problem for the STHX

c. Conversion of the multi-objective to single objective optimization problem of a 2DoF controller for dominate-solution

d. Formulation of multi-objective optimization problem considering vector of three objective functions for non-dominated solution using NSGA II

e. Implementation and simulation for

   i. Determining dominate solution

   ii. Determining non-dominated set

   iii. Obtaining the pareto optimal set

2 Design of a 3DoF multi-objective optimization controller for STHX using NSGA-II subjected to noise.

a. Adopting the standard transfer function of a heat exchanger.

b. Modeling of the 3DoF controller for optimization problem.

c. Formulation of the multi-objective optimization problem for the STHX.

d. Conversion of the multi-objective to single objective optimization problem of a 3DoF controller for dominate-solution.

e. Formulation of multi-objective optimization problem considering vector of four objective functions for non-dominated solution using NSGA II.

f. Implementation and simulation for:

   i. Determining dominate solution

   ii. Determining non-dominate solution

iii. Obtaining the parato optimal set

3 Performance comparison of objective 1 and 2 in terms of overshoot, rise time and settling time.

1.6 Dissertation Organization

The literature review and the relevant fundamental concepts of the research are presented in Chapter Two. Materials and methodology adopted in this research are presented in Chapter Three, while the analysis, performance and results are discussed in Chapter Four. Finally, Conclusions and recommendations are presented in Chapter Five. At the end, Appendices and References are provided.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The literature review consists of review of basic concepts as it relates to the research topic and review of the trend of previous works that are also related to the research with a view to understanding the fundamental concepts of the research area.

2.2 Review of Fundamental Concepts

Here, the fundamental concepts of heat exchangers, controllers and Algorithms are discussed.

2.2.1 Heat Exchanger (HEx)

Heat exchangers are systems or unit widely used in various process industries such as petrochemical industries, food processing industries among others mainly for the transfer of heat energy from one solid surface or fluid to another fluid (Suthar & Gadit, 2017b).The main function of a HEx unit is mainly to maintain a desired setpoint temperature of an outlet fluid in the presence of obvious disturbances such as deviation in input fluid flow rate and deviation in input fluid temperature (Dhakad *et al.,* 2013). Though as part of process industries, heat exchangers are one of the main units for the transfer of thermal energy, they are yet very much indispensable unit (Sarabeevi & Laila, 2016). Heat exchangers are mostly used in chemical processes, heating and power generation, manufacturing, and medical applications(Padhee *et al.,* 2011). There are varieties of HEx available for use in industries, but commonly used, is the Shell and Tube Heat Exchanger (Suthar & Gadit, 2017a).

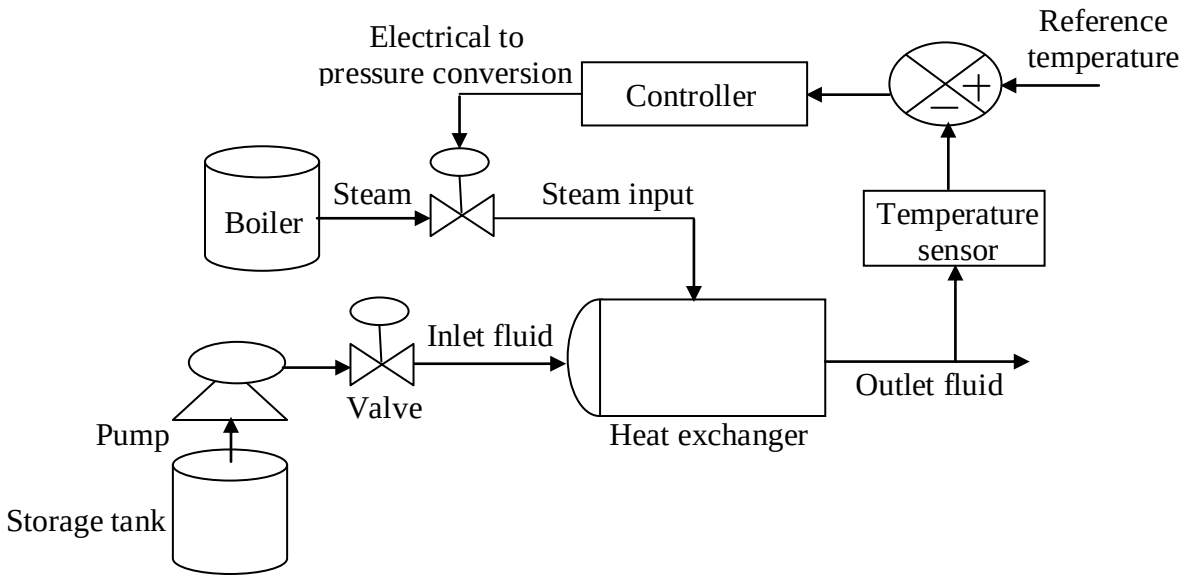


Figure 2.1: Book Diagram of the Physical Model of STHX

Figure 2.1 shows the block diagram of the physical model of STHX in which the process of heat exchanging system is modeled as First Order Plus Time Delay (FOPDT) system.

The process variable (temperature of outlet fluid) that is measured is compared with the set point temperature and error difference between the two is estimated. This error is fed as input to controller which then generates electrical control signal that is in turn, converted into pressure signal through a current-to-pressure electro-pneumatic transducer. The valve actuator adjusts the position of the valve in proportion to control signal whose input is the output of the pressure signal. The flow of the steam depends on this valve positioning. While the temperature sensor senses the temperature of outlet fluid that is compared with the reference. Consequently, two disturbances are present which are: (a) Flow variation of input fluid. (b) Temperature variation of input fluid, with the following assumptions.

a. An equivalent inflow and out flow rate of fluid (kg/sec) is considered in order to have constant fluid level in HEx system.

b. Heat exchanger system's insulating wall does not store any heat.

Heat exchanger plant model's transfer function of the various components in response to the steam flow, process fluid flow and disturbances is adopted from the work of Suthar and Gadit, (2017a) as follows:

Actuator:

$$A(s) = \frac{0.1}{3s+1} \tag{2.1}$$

Plant:

$$P(s) = \frac{50e^{-2s}}{30s+1} \tag{2.2}$$

Sensor:

$$H(s) = \frac{1}{10s+1} \tag{2.3}$$

Flow disturbance:

$$P_{Fd}(s) = \frac{3}{30s+1} \tag{2.4}$$

Temperature disturbance

$$P_{Td}(s) = \frac{1}{3s+1} \tag{2.5}$$

Figure (2.2) summaries the block diagram of the heat exchanger with controller and disturbances.

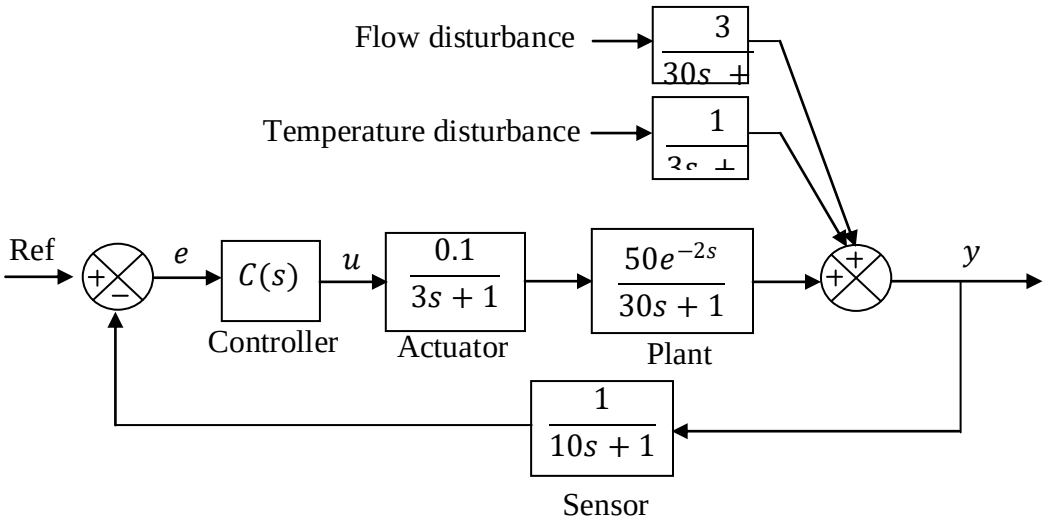


Figure 2. 1: Description of Heat Exchanger Model with Controller and Disturbance

2.2.2 Shelland Tube Heat Exchanger

The Shell and Tube Heat Exchanger (STHX) is made of bundles of pipesor tubes enclosed within a cylindrical shaped shell, this allows fluid (which is to gain temperature) to flow through the tubes while the other fluid (which is losing temperature) is allowed to flows in between the tubes and the shell (Padhee *et al.,* 2011) as shown in Figure 2.1.STHXs are the commonly used heat exchangers due to the fact that it is used for a wide range of varying temperature and pressure, they also have a better and larger ratio of heat energy transfer in terms of surface area than other types of HEx. Figure 2.3 shows STHX control scheme. The STHXs can be manufacture in different sizes and configuration, these facilitate its periodic maintenance making it flexible and gives the designers wide range of choice on ranges of temperature and pressure desired (Padhee *et al.*, 2011).

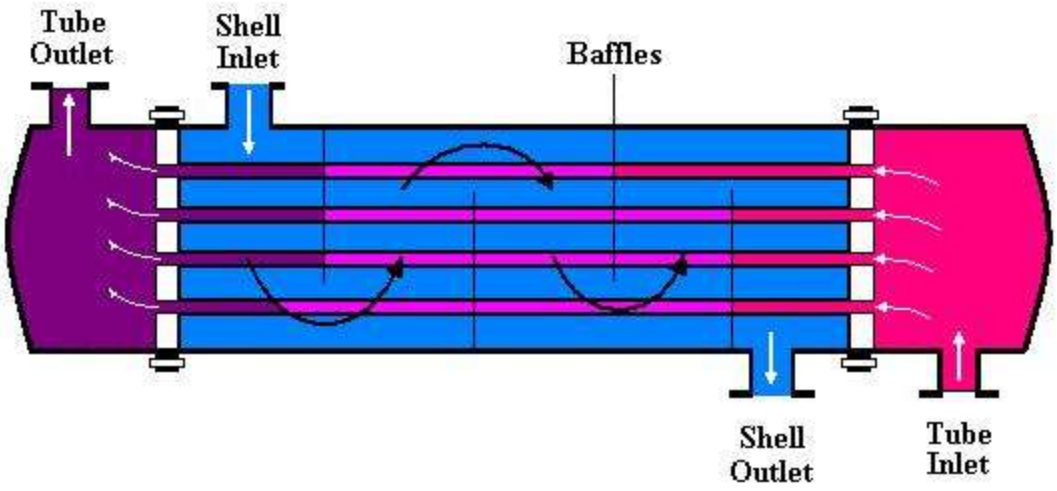


Figure 2. 3: Shell and Tube Heat Exchanger Control Scheme (Padhee et al., 2011)

The heat exchanger model will be adopted from the work of Suthar & Gadit(2017a). Two assumptions will be applied in the heat exchanger system representation as applied in Dhakad *et al.*,(2013).

1. Same inlet and outlet fluid flow rate (kg/sec). This is to have a constant fluid level in the system i.e. heat exchanger.
2. The insulation wall of the system does not store any heat. Justify why these two assumptions will not significantly negate this research.

The steam flow response of the heat exchanger has the following parameters:

PHYSICAL QUANTITY	VALUE
Steam flow gain	50 ℃ / (kg/Sec)
Time constant	30 Sec
Process fluid gain	3℃ / (kg/sec)
Process temperature gain	1℃ /(kg/sec)
Capacity of control valve	1.6 kg/sec of steam
Control valve (time constant)	3 sec
Sensor range	50 ℃ to 150 ℃
Sensor time constant	10Sec
Gain of the valve	0.133
Gain of 1 to P converter	0.75
Critical gain	KC

The transfer function model of a heat exchanger including temperature and flow disturbances is shown in Figure 2.4 as adopted from Suthar & Gadit, (2017a).

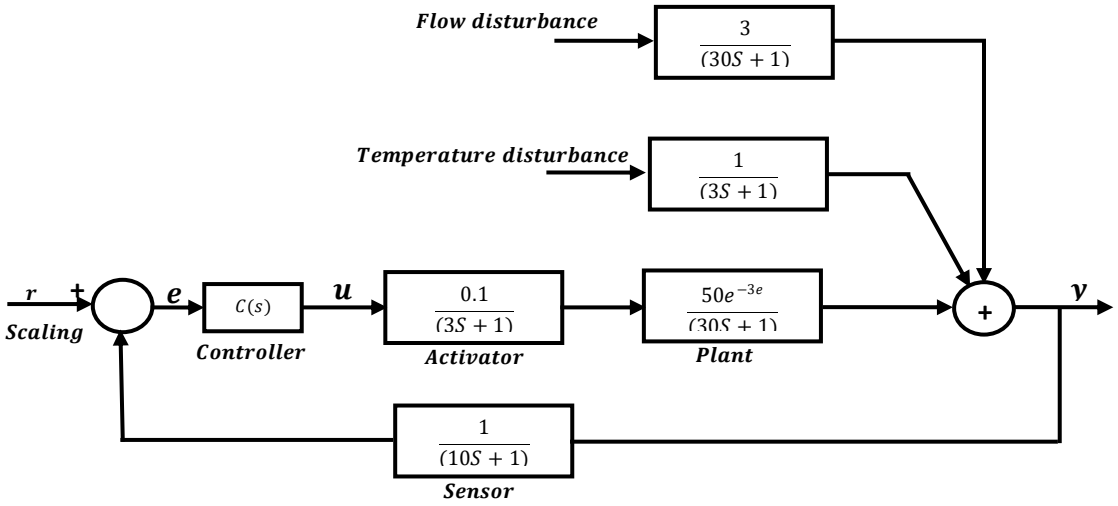


Figure 2. 4: Heat Exchanger Transfer Function Model (Suthar & Gadit, 2017a).

The ultimate purpose of using a heat exchanger is to keep the outlet fluid temperature at the desired set point and improves disturbance rejection. These two aspects of set point and disturbance rejection conflict with each other and therefore cannot be fulfilled by the 1DoF Proportional Integral Derivative (PID) controller. Hence, the need for a Two Degree of Freedom (2DoF) PID (Suthar & Gadit, 2017b).

2.2.3 Two Degree of Freedom PID Controller

The Degree of Freedom (DoF) of a control system could be defined as the number of closed-loop transfer function that can independently be adjusted (Araki & Taguchi, 2003). In using 1DoF PID controllers to control more than one objective functions, causes some difficulties such that while trying to obtain disturbance response, setpoint response will oscillate while trying to obtain setpoint response, it leads to deviation in disturbance response (Deshmukh & Kadu, 2017). To solve the stated challenges, a 2DoF PID controller is used, this imply that when two objectives which are mainly disturbance rejection and set point tracking and are required, a 2DoF PID controller is preferred. Here, the 2DoF controller is applied to control setpoint tracking and disturbance rejection simultaneously. The 2DoF controller consists of two controllers a feed-forward controller and a feedback controller for set point tracking and disturbance rejection respectively. The 2DoF controller is designed with two inputs, one as the reference input while the other from the feedback path. The output is the difference between the two signals. Figure 3.2 shows a block diagram of a conventional 2DoF PID controller with details in section 3.3 Tuning of PID controllers involves utilization of an optimization method, most classical optimization methods require further fine tuning and a longer time before the right parameter is obtained. Hence, the need for a Genetic Algorithm for optimizing tuning of the parameters.

2.2.4 Two Degree of Freedom Controller Model

Figure 3.3 shows the 2DoF control system adopted fromSuthar & Gadit, (2017a), which consist of serial compensator $C(s)$, feed forward compensator $C_f(s)$, disturbance transfer function $P_d(s)$, and the plant transfer function $P(s)$. The closed-loop transfer functions $T_{ry2}(s)$(from 'r' to 'y') and $T_{rd2}(s)$(from 'd' to 'y ') are shown in Equations (3.1) and (3.2). The subscript "2" denotes the use of 2DoF controller. The feed forward compensator controls the set point tracking while the feedback compensator is used for disturbance rejection as presented in Figure 2.5.

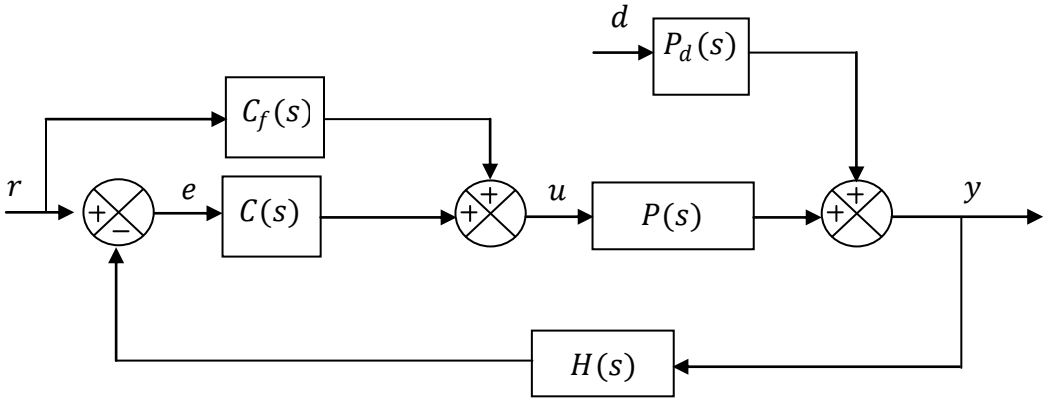


Figure 2. 5: Configuration of 2DoF Control System

$$T_{ry2}(s) = \frac{y}{r} = \frac{P(s)[C(s)+C_f(s)]}{1+P(s)*C(s)*H(s)} \quad (2.6)$$

$$T_{ry2}(s) = \frac{y}{r} = \frac{P_d(s)}{1+P(s)*C(s)*H(s)} \quad (2.7)$$

Where $C(s)$ and $C_f(s)$ are

$$C(s) = K_p + \frac{K_p}{T_i s} + K_p * T_D * D(s) \quad (2.8)$$

$$C_f(s) = -K_p[\alpha + \beta * T_D * D(s)] \quad (2.9)$$

$$D(s) = \frac{s}{\tau * s + 1} \quad (2.10)$$

And $\tau = \frac{T_D}{\sigma}$ (2.11)

The parameters for the optimization are K_p, proportional gain, T_i, integral time constant and T_D, derivative time constant for the serial controller; α and β as 2DoF controller parameters for the feed forward controller. One major drawback to this configuration is that, measurement noise is coupled to the disturbance in the system which leads to a trade-off between the two. In the proposed 3DoF controller configuration, there is a clear separation between the process noise, measurement noise and the disturbances in the system.

2.2.5 Three Degree of Freedom Controller Model

The 3DoF control system is modeled in such a way that the plant transfer function $P(s)$ is divided into two sub functions $P_1(s)$ and $P_2(s)$(Suzumura & Fujimoto, 2015). This makes it easy to identify any process noise ϵ_1 in the system as well as the measurement noise ϵ_2 as depicted in Figure 3.4. The system consist of three compensators $C_1(s)$, $C_2(s)$ and $C_3(s)$ with distinct respective functions. The set point tracking response, the disturbance response and that of the measurement noise, $P_n(s) * \epsilon$ are presented in Equations (2.12) to (2.14).

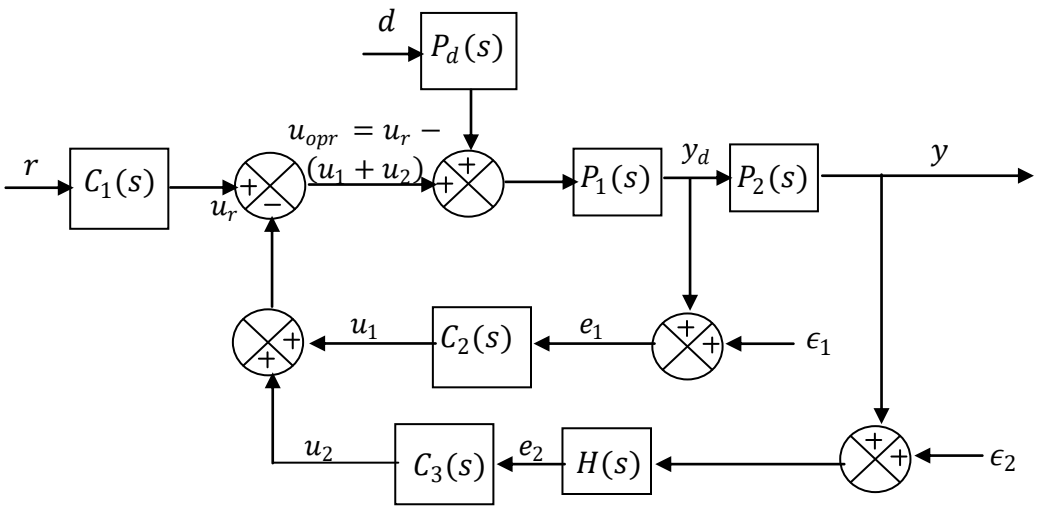


Figure 3. 2: Configuration for 3DoF control system

$$T_{yr}(s) = \frac{y}{r} = \frac{P_1(s)P_2(s)C_1(s)}{1 + P_1(s)C_2(s) + P_1(s)P_2(s)C_3(s)H(s)} \quad (3.12)$$

$$T_{yd}(s) = \frac{y}{d} = \frac{P_d(s)P_1(s)P_2(s)}{1 + P_1(s)C_2(s) + P_1(s)P_2(s)C_3(s)H(s)} \quad (3.13)$$

$$T_{y\epsilon}(s) = \frac{y}{\epsilon} = \frac{-P_n(s)P_1(s)P_2(s)C_3(s)H(s)}{1 + P_1(s)C_2(s) + P_1(s)P_2(s)C_3(s)H(s)} \quad (3.14)$$

The transfer functions for the three controllers are:

$$C_1(s) = K_p\left[\frac{\eta}{T_i * s} + T_D * D(s)\right] \quad (3.15)$$

$$C_2(s) = K_p + \frac{K_p}{T_i s} + K_p * T_D * D(s) \quad (3.16)$$

$$C_3(s) = \frac{\zeta}{K_p * H(s)} \quad (3.17)$$

The set point tracking response is dependent on the three controllers$C_1(s)$, $C_2(s)$ and $C_3(s)$ with $C_1(s)$ serving as filter to the input signal. The $C_2(s)$ is essentially a PID controller that cut across all responses but more visible in the disturbance rejection characteristics while $C_3(s)$ is another filter whose primary function is prominent in noise suppression at the output of the system. In this model, the parameters η and ζ can be adjusted independently even after the $C_2(s)$ parameters are set to fine-tune the set point tracking and noise suppression property.

It can easily be verified by final value theorem that the disturbance and noise responses tend to zero at steady state shown as in equations (3.18) and (3.19) respectively.

$$y_{dss} = \lim_{s\to 0} s.\frac{P_d(s)P_1(s)P_2(s)}{1 + P_1(s)C_2(s) + P_1(s)P_2(s)C_3(s)H(s)}.\frac{1}{s} = 0 \qquad (3.18)$$

$$y_{nss} = \lim_{s\to 0} s.\frac{-P_n(s)P_1(s)P_2(s)C_3(s)H(s)}{1 + P_1(s)C_2(s) + P_1(s)P_2(s)C_3(s)H(s)}.\frac{1}{s} = 0 \qquad (3.19)$$

2.2.6 Genetic Algorithm

Genetic Algorithm (GA) was first proposed by a researcher named J. Holland in the early 1970s.It is an Evolutionary Algorithm (EA) in the same group with other algorithms such as Genetic Programming, Evolution Strategies and Evolutionary Programming (Brownlee, 2011). GA is a population-based global optimization technique. The production of offspring for next generation, the algorithm mimics a natural selection process where fittest individuals (chromosomes) are picked for the purpose of reproduction. The process of GA begins with fittest individuals being selected from the population. The offspring produced by these individuals possess an inherit genes of their parents which eventually makes up next generation. When parents present an improved or a much better fitness values, it results in the offspring having a better and higher tendency for surviving. This process is kept evolving and eventually a

generation consisting of fittest Individuals will be found (Mallawaarachchi, 2017). In general, GA involves some major processes which include initial population, fitness function, selection, crossover, and mutation as well as Stopping criteriaas shown in Figure2.3

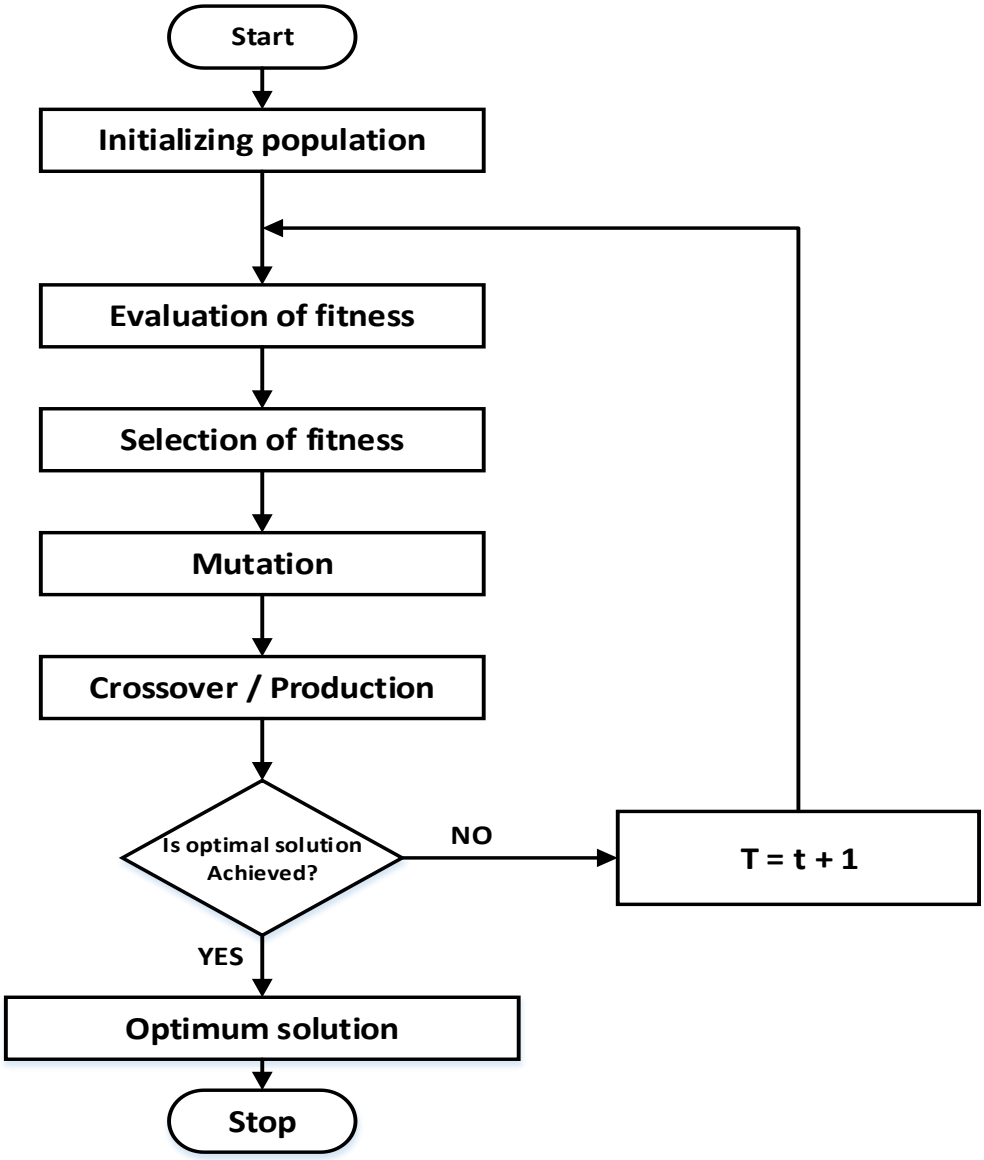


Figure 2. 1: Flowchart of a Genetic Algorithm (Gupta et al., (2017)

Genetic algorithm involves the following steps:

i. **Initial Population**: As shown in Figure 2.4, GA process starts with population which is a set of individuals. Each individual in the population is a possible solution to the problem being solved. Those individuals are characterized by parameters called genes. The genes are combined to form a chromosome.

ii. **Fitness function**: Each chromosome's objective function value is to be computed so as to obtain an optimal value. The chromosome's fitness value of each generation would be evaluated using a performance objective.

iii. **Selection**: the aim of these selection process is to select the fittest individuals so that they can transfer their genes to members of next generation. The selection of individuals for reproduction is done on fitness score, hence those individuals having the highest fitness value have a better opportunity of being selected for reproduction (Mallawaarachchi, 2017).

iv. **Crossover:** This is an important phase in GA when parents of a generation are to be mated, a crossover point is chosen at random from the genes. Exchanging of genes among the parents leads to the creation of the offspring.

v. **Mutation:** Mutation is said to mainly be a random process which involves the replacement of a gene with another producing a gene with new genetic structure. Here, application of mutation is done randomly which modifies elements in the chromosomes. Mutation is mostly to give an assurance that the probability of search is not zero. This process also provide a safety net to regain the improved genetic material which could have been lost during the action of selection and crossover (Chen, n.d.)

vi. **Stopping Criteria**: Genetic Algorithm terminates when it converges, that is, when offspring produced are not significantly different from the previous generation. At this point, a set of solutions are said to have been provided by the algorithm.

Since tuning the 2DoF PID parameters of the STHX is in the form of multiple objective problems, a multi-objective optimization algorithm form of GA called Non-dominated sorting Genetic Algorithm (NSGA) is being proposed for this research.

2.2.4.1 Non-dominated sorting genetic algorithm(NSGA)

TheNSGA is a multiple-objective optimization algorithm of GA. The NSGA has two versions, the classical version and the extended version developed by Deb *et al.*, (2002) to address three critical issues of lack of elitism, complexity and need for parameter sharing for fitness sharing. This version are called Non-Dominated Sorting Genetic Algorithm II (NSGA II)(Brownlee, 2011).

The NSGA II has three main features which includes:

i) Non-dominated sorting: Here, sorting is done according to the level of non-domination.

ii) Elitism: Keeps all non-dominated solutions that improve fast convergence properties.

iii) Crowding Distance: Ensuring diversity and spread of solution.

These features have been incorporated in the flowchartshowedin Figure 3.5

A composite function (functional) consisting of separate objective functions for the set point tracking, flow disturbance rejection, temperature disturbance rejection and noise are formulated. The chosen criterions for evaluating these objective functions are Integral of Absolute Error (IAE), Integral of Squared Error (ISE) and Integral of Time-weighted Absolute Error (ITAE) for the purpose of validation. These criterions are defined as follows:

1. Integral of absolute value of error

$$IAE = \int_0^\infty |e(t)|dt \tag{3.20}$$

2. Integral of error squared

$$ISE = \int_0^\infty |e(t)|^2 \, dt \tag{3.21}$$

3. Integral of Time-weighted Absolute Error

$$ITAE = \int_0^\infty [t * e(t)]dt \tag{3.22}$$

We looked at the formation of the functional for each of the criterions designed for the two controllers' configurations.

2.3 Review of Similar Works

This section present review of works related to this research which includes previous works on STHX and 2DoF controllers. Some related research works and their drawbacks are discussed below;

Dhakad *et al.*, (2013) did a comparative study of two methods of controlling the outlet fluid temperature of a heat exchanger. First, an internal model based PID controller was developed,

and secondly it was replaced with a Fuzzy Logic Controller (FLC) all for the purpose of controlling an outlet fluid temperature of an STHX. From the result, FLC demonstrated an improvement in overshoot and settling time when compared with conventional PID. Though the system showed a better accuracy and faster response, selection of membership function is done by trial and error and solely depend on the designer's experience which makes it complicated.

Khalili Dizaji, (2015) developed a PID feed-forward efficient controller for the control of the outlet fluid temperature of STHX usingZiegler-Nichols (ZN) closed-loop regulation method to regulate the PID controlling parameters was adopted. Though, the designed controller was able to achieve the desiredsetpoint and enhance flow disturbance rejection at the least possible time, the use of ZN led to aggressive gain causing large overshoot and oscillatory response.

Singh & Goel, (2015)proposed the use of a PID controller for regulating the outlet fluid temperature of the STHX. The focus of the work was on the tuning parameters of PID. The work compared the use of a Genetic Algorithm (GA) with (ZN) in tuning the PID parameters. From the result, GA provided an improved performance in terms of rise time, settling time, and overshoot. The system can better be improved to suppress process noise by extending it to a three degree of freedom control system.

Sarabeevi & Laila, (2016)developed and evaluated three different kinds of controllers for controlling the outlet fluid temperature of STHX. The three controllers include Internal Model ontroller (IMC) combined with disturbance rejection function, IMC based PID and IMC-PID with feed-forward controllers. From the analysis of the results, disturbance was successfully suppressed but it could not overcome the limitation of time delay it also showed poor setpoint tracking due to the combination of disturbance rejection function. IMC-PID based controller had improvement in setpoint tracking and the effect of time delay was reduced for efficiency

improvement. However, it resulted in high value for time domain specifications and performance indices which were undesirable. Finally, an IMC-PID controller was combined with a Feed-forward controller. The Feed-forward controller was placed in the forward path of the system. This design shows an increase in efficiency of the system. Though the IMC-PID with Feed-forward controller had a superior performance as compared with IMC and IMC-PID, but introduction of more complex controllers led to high computational complexity.

Deshmukh & Kadu, (2017)proposed the use of 2DoFPID controller for achieving both disturbance rejection and setpoint tracking in the temperature control of a laboratory setup. The research used Chien-Hrones-Reswich (CHR) and Analytical Robotic Tuning (ART) techniques to tune the PID parameters while Integral Time Absolute Error (ITAE) was used as fitness function also ZN open loop method was adopted. Though from their result, using CHR for tuning the parameters of 2DoF PID controller gave improvedresponse in terms of percentage overshoot, load disturbance rejection and settling time. Nevertheless, determining step response parameters may be hard due to measurement noise.

Tridianto *et al.*, (2017) reported an experiment where cascaded (PID and PI) controllers were used to stabilize the outlet temperature of STHX. The choice of a cascaded control system was to stabilize the system, minimizeoscillation. The cascaded controller was only able to regulate the temperature, it had a poor time domain system performance.

Gupta *et al.*, (2017)proposed an optimal design of PID controller for a time delay system using Genetic Algorithm (GA). This system was designed to solve some shortcomings of classical

control theory method such as accuracy and reliability. Though the controller was able to stabilize the system, but it was intolerant to predominant disturbances.

Debnath *et al.*, (2017) proposed a 3DoF-PID Controller. The controller was used for an Automatic Generation Control (AGC) of a power system with a hybrid source. The system was designed for two area power system were each area consist of three varieties of generation sources (gas, hydro and thermal). The gain parameters of PID were optimized using Teaching Learning Based Optimization (TLBO) technique. A comparative study was conducted between PID, 2DoF-PID and 3DoF-PID controllers using ITAE as the objective function. From the obtained results, 3DoF PID controller showed a superior behavior in terms of settling time and peak overshoot as compared to PID and 2DoF-PID controllers. Though TLBO technique offers an effective solutions when solving problems associated with optimal power flow involving different complexities, it however, does not guarantee global optimal.

Suthar & Gadit, (2017b)proposed the optimized 2DoF controller using GA for STHX. Heat Exchanger was adopted as a test bench, hence the proposed controller was used to regulate its outlet fluid temperature irrespective of flowrate variation and temperature variation of the inlet fluid. The main objective of the work was achieving setpoint tracking and disturbance rejection simultaneously and comparing it with optimizing each control objective separately. Though the later method gives a better performance in peak overshoot, flow disturbance, and temperature disturbance, but it was formulated in form of as a single objective optimization problem.

Suthar & Gadit, (2017a)made an improvement over the work of 2017b. Here, with the same aim, formulated a multi-objective optimization problem for the 2DoF controllers and instead of using GA, they opted for NSGA II. The NSGA II is the multi-objective GA which has the ability

to obtain multiple optimal solutions for a multi-objective problem. This approach was able to overcome the previous problem of tuning the parameters twice, first for the serial compensator and second the feed-forward compensator. The developed design gave an improved result in peak overshoot, enhancement in both disturbance rejection and set point tracking as well as time required to optimize cost function under various criterion (IAE, ISE, and ITAE), but not considering noise in the design results to the system being sensitive to noise.

From the reviewed works, researchers have been able to develop different controlling methods for regulating the outlet fluid temperature of heat exchangers mostly in STHXs. Different design approaches have also been adopted from IMC, PID, 1DoF and 2DoF controllers with different tuning methods and optimization algorithms which produced reasonable results in terms of setpoint tracking, flow rate,and temperature variation disturbances. However, formulating a single objective optimization problem for a multiple objective problem and not considering process noise in the design of controllers leads to poor performance of the system in terms of peak overshoot, settling time and rise time in the presence of noise. Therefore, the need to develop a 3DoF controller for STHX using NSGA II to ensure better setpoint tracking, disturbance rejection and noise suppression.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter describes in detail, the procedure employed in developing the model configuration of the STHX for 3DoF controller and its implementation. The chapter presents the proposed 3DoF controller model and controller optimization methods.

3.2 Methodology

The steps adopted in achieving this work are:

1. Design a 2DoF multi-objective optimization controller for STHX using NSGA-II base on the work of Suthar & Gadit, (2017a)
    a. Adopting the standard transfer function of a heat exchanger and model of the 2DoF controller for optimization problem.
    b. Formulation of the multi-objective optimization problem for the STHX
    c. Conversion of the multi-objective to single objective optimization problem of a 2DoF controller for dominate-solution
    d. Formulation of multi-objective optimization problem considering vector of three objective functions for non-dominated solution using NSGA II
    e. Implementation and simulation for
        i. Determining dominate solution
        ii. Determining non-dominated set

iii. Obtaining the pareto optimal set

2 Design of a 3DoF multi-objective optimization controller for STHX using NSGA-II subjected to noise.

a. Adopting the standard transfer function of a heat exchanger.

b. Modeling of the 3DoF controller for optimization problem.

c. Formulation of the multi-objective optimization problem for the STHX.

d. Conversion of the multi-objective to single objective optimization problem of a 3DoF controller for dominate-solution.

e. Formulation of multi-objective optimization problem considering vector of four objective functions for non-dominated solution using NSGA II.

f. Implementation and simulation for:

i. Determining dominate solution

ii. Determining non-dominate solution

iii. Obtaining the parato optimal set

3. Performance comparison of objective 1 and 2 in terms of overshoot, rise time and settling time.

3.3 Controller Optimization Method Adopted

Genetic Algorithm (GA) is used to optimize the controller parameters in the case of 2DoF controller shown in Figure 3.3 and that of 3DoF controller presented in Figure 3.4. The objective is to minimize the set point tracking error, flow and temperature disturbances, and finally noise in the case of 3DoF control system using GA optimal tuning of controllers for dominated solution while Non-dominated Sort Genetic Algorithm (NSGA-II) for the solution of the multi-objective functions.

3.4 Two Degree of Freedom Controller Functional

The functional consist of three objective functions: the set point tracking error, flow disturbance rejections and temperature disturbance rejections.

Let:

S_P denotes set point,

$y(n)$ denots Process value output at n^{th} interval,

$y_{flow}\ (n)$ denotes Flow disturbance output at n^{th} interval and

$y_{temp}\ (n)$ denotesTemperature disturbance output at n^{th} interval

Then for each of the criterions we adopt the functional L for multi-objective function as Equations (3.23) to (3.25).

Criterion 1: IAE

$$L(K_p, K_i, K_d, \alpha, \beta) = L\left(\left[\sum_{n=0}^{N}[S_P - y(n)],\ \sum_{n=0}^{N} y_{folw}(n),\ \sum_{n=0}^{N} y_{temp}(n)\right]\right) \quad (3.23)$$

Criterion 2: ISE

$$L(K_p, K_i, K_d, \alpha, \beta) = L\left(\left[\sum_{n=0}^{N}[S_P - y(n)]^2,\ \sum_{n=0}^{N}\left[y_{folw}(n)\right]^2,\ \sum_{n=0}^{N}\left[y_{temp}(n)\right]^2\right]\right) \quad (3.24)$$

Criterion 3: ITAE

$$L(K_p, K_i, K_d, \alpha, \beta) = L\left(\left[\sum_{n=0}^{N}\left[t * \left(S_P - y(n)\right)\right],\ \sum_{n=0}^{N}[t * (n)],\ \sum_{n=0}^{N}\left[t * y_{temp}(n)\right]\right]\right) \quad (3.25)$$

For dominated solution, the multi-objective function is converted to a single objective function for each of the criterion by adding the three objective functions $g_{setpoint}$, g_{flow}, and g_{temp} for set point tracking, flow and temperature disturbance rejection respectively as given in Equation (3.26).

$$L(K_p, K_i, K_d, \alpha, \beta) = L\left(\left[[g_{setpoint}] + [g_{flow}] + [g_{temp}]\right]\right) \quad (3.26)$$

3.5 Three Degree of Freedom Controller Functional

In this configuration, noise is separated from the disturbance and added back to the system. For simplicity, the process noise ϵ_1 of figure 3.4, is assumed to be negligible compared to the measurement noise $\epsilon_2$thus, we refer to this as simply noise ϵ in the system. As a result, another (fourth) objective function is formulated in addition to those of set point tracking, flow disturbance and temperature disturbance rejection with respect to Equations (3.10) to (3.12).

Then for each of the criterions given, we develop new functional *L* for multi-objective function as presented in Equations (3.27) to (3.29).

Criterion 1: IAE

$$L(K_p, K_i, K_d, \eta, \zeta) = L\left(\left[\sum_{n=0}^{N}[S_P - y(n)],\ \sum_{n=0}^{N} y_{folw}(n),\ \sum_{n=0}^{N} y_{temp}(n),\ \sum_{n=0}^{N} y_{noise}(n)\right]\right) \quad (3.27)$$

Criterion 2: ISE

$$L(K_p, K_i, K_d, \eta, \zeta) = L\left(\left[\sum_{n=0}^{N}[S_P - y(n)]^2,\ \sum_{n=0}^{N}\left[y_{folw}(n)\right]^2,\ \sum_{n=0}^{N}\left[y_{temp}(n)\right]^2,\right.\right.$$

$$n=0Nynoisen2 \quad (3.28)$$

Criterion 3: ITAE

$$L(K_p, K_i, K_d, \eta, \zeta) = L\left(\left[\sum_{n=0}^{N}\left[t * \left(S_P - y(n)\right)\right],\ \sum_{n=0}^{N}\left[t * y_{folw}(n)\right], \sum_{n=0}^{N}\left[t *\right.\right.\right.$$

$$ytempn, n=0Nt*ynoisen \quad (3.29)$$

And for the dominated solution, the single objective function formed is given in Equation (3.30)

$$L(K_p, K_i, K_d, \eta, \zeta) = L\left(\left[[g_{setpoint}] + [g_{flow}] + [g_{temp}] + [g_{noise}]\right]\right) \quad (3.30)$$

3.6 Non-dominated Sorting Genetic Algorithm (NSGA II)

Optimization of Multi-Objective Problem (MOP) involves a simultaneous solution of a collection of objective functions. NSGA-II is the optimization algorithms that can be adopted to handle this problem.It is a population based search algorithm in which the fitness value of all chromosomes in each generation is evaluated as a performance metric. The parent chromosomes are selected over which crossover and mutation is applied in each generation to produce new set

of offspring chromosomes. Figure 3.5 shows the flowchart of NSGA II adopted from the work of Kannan *et al.*, (2009) and used in this work.

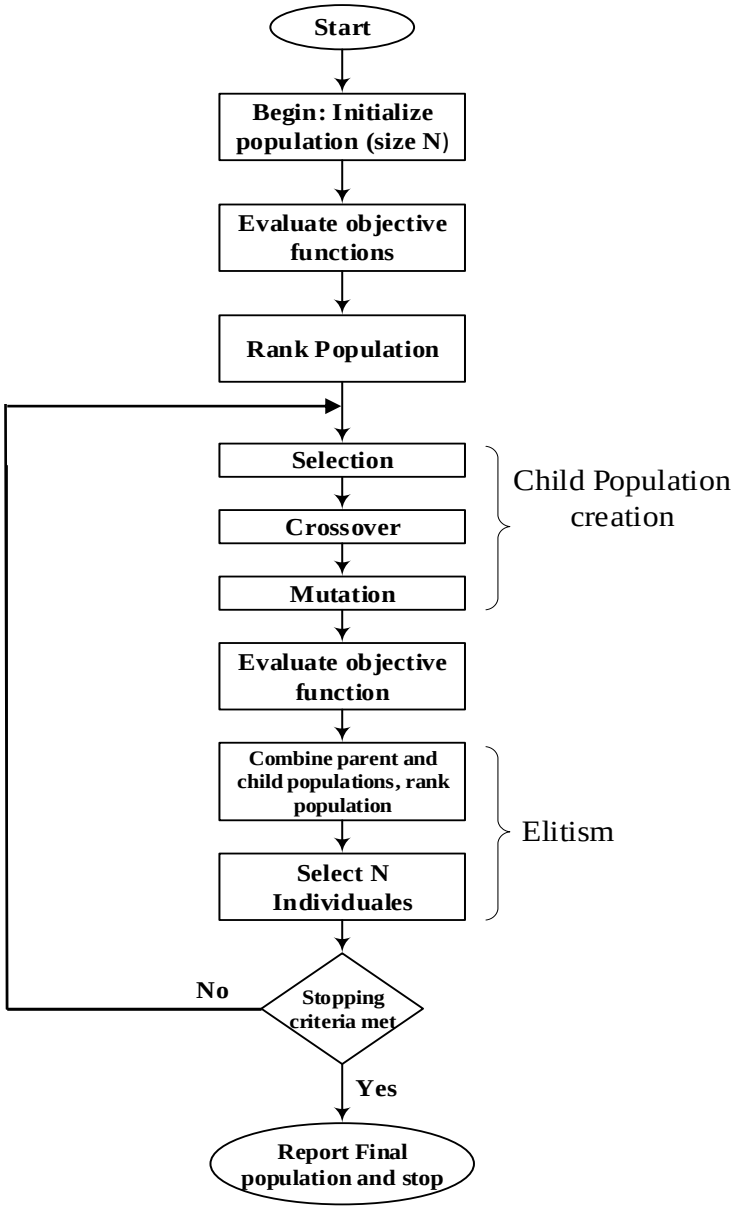


Figure 3. 3: NSGA II Flowchart (Kannan et al., 2009)

The NSGA II procedure is as follows:

i. Populating the first generation randomly

ii. Computing the objective function of the first generation

iii. Using the non-dominated sorting approach to sort the population

iv. Generate the population of parents using the binary tournament selection

v. Generation of offspring using crossover and mutation

vi. Calculation of objective function of the offspring

vii. Using the non-dominated sorting approach to sort

viii. Using Elitism to generate next generation

ix. Stopping criteria

The non-dominated sorting approach is based on the scheme that no solution of one objective function is better than the other. This will give birth to a set of non-dominated solution called pareto-optimal set. The resultant values of the objective functions of the pareto-optimal set are the pareto front of the NSGA-II solution.

3.7 Simulation Setup

The simulation scenario for the development was carried out in MATLAB environment. The step responses for set point tracking, flow disturbance and temperature disturbance and noise rejection were given step input of magnitude 1, 0.1 and 0.01 respectively, while the noise profile was generated for simulation purpose. For the turning of the NSGA-II on 3DoF controller parameters, the vector of lower bound values for $[K_p,\ K_i,\ K_d,\ \eta,\ \zeta]$ is $[10, 10,\ 10,\ 0,\ 0]$ while the upper bound vector is $[100,\ 200,\ 100,\ 1, 1]$. Further study, and trails show better result for fixed values of $[\eta,\ \zeta]$ set to $[0.02, 10^{-4}]$ run over a hundred generations. The NSGA-II

properties; crossover and mutation operators were set to 8 and 9 respectively. Important MALAB files (m-files) developed for the simulations are presented in Appendix A.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents simulation results of 3DoF control of STHX and discussion of results. A number of plots describing the condition of the STHX scenarios during simulations are generated, presented and discussed. Furthermore, the effectiveness of the developed 3DoF controller is validated by comparing with the existing 2DoF controller applied to the system of STHX. The results include both for the Single Objective Problem (SOP) and for the MOP solved by NSGA-II in graphs and tables.

4.2 Solution of SOP Optimization

With the four objective functions of the developed 3DoF control of STHX converted to a single objective function by adding them together, the solution obtained by GA is hereby presented. Figure 4.1 show the plot of fitness value verses number of generations for the two criterions IAE and ISE considered in this work.

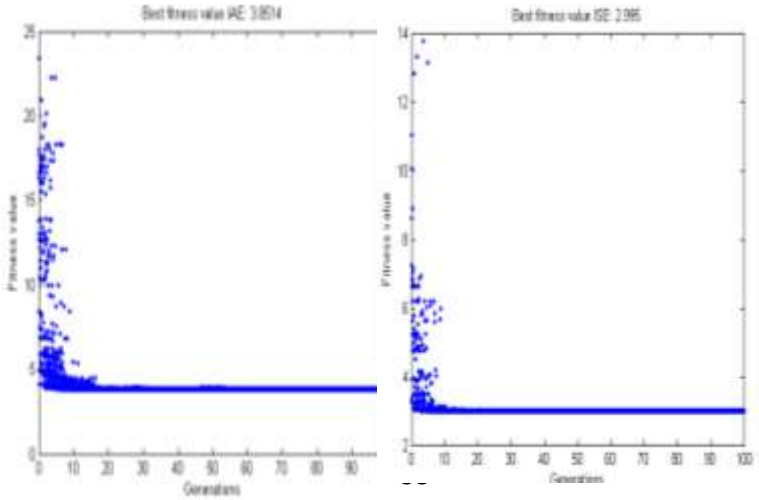


Figure 4. 1: Fitness Values for SOP Optimization of IAE and ISE Criterions

From Figure 4.1, it can be seen that the fitness values converge to nearly a single constant value for each of the criterions before the termination of the optimization process. Values of the best fitness values for the criterions considered are hereby presented as 3.8514, 2.995 and 2.99 for the IAE and ISE respectively. The lowest, being that of ISE is expected to exhibit better tracking response than those of the IAE and ITAE.

The results of the set point tracking, flow disturbance reduction and temperature disturbance reduction are presented in Figure 4.2, Figure 4.3 and Figure 4.4 as compared with those of 2DoF controller for each of the criterions.

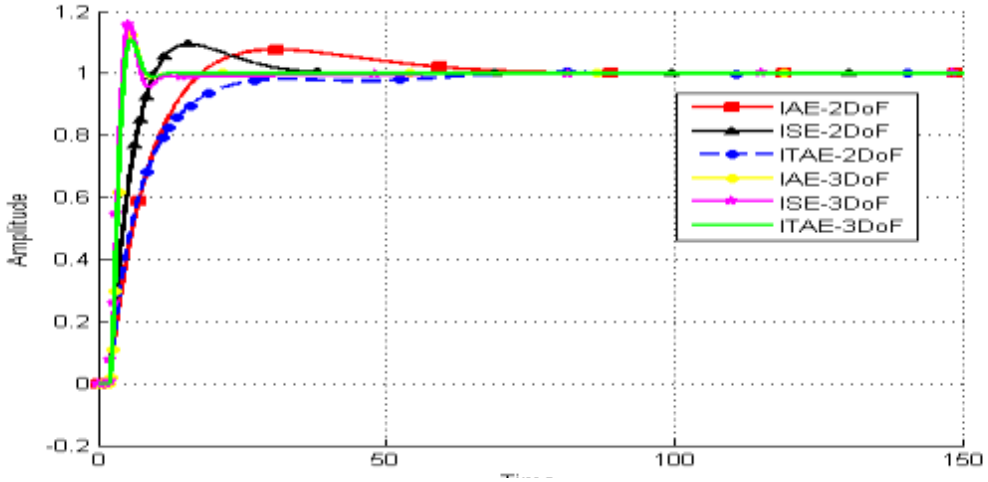


Figure 4. 2: Set Point Tracking Response to Step Input

From Figure 4.2, the set point tracking responses for IAE-3DoF, ISE-3DoF and ITAE-3DoF are faster than those of 2DoF. The 3DoF responses settle in less than 25 seconds (secs) compared to

those of 2DoF that settled at about 50 secs. The overshoots recorded in both scenarios for the SOP are almost the same, and fall within acceptable level (being less than 20% in all cases).

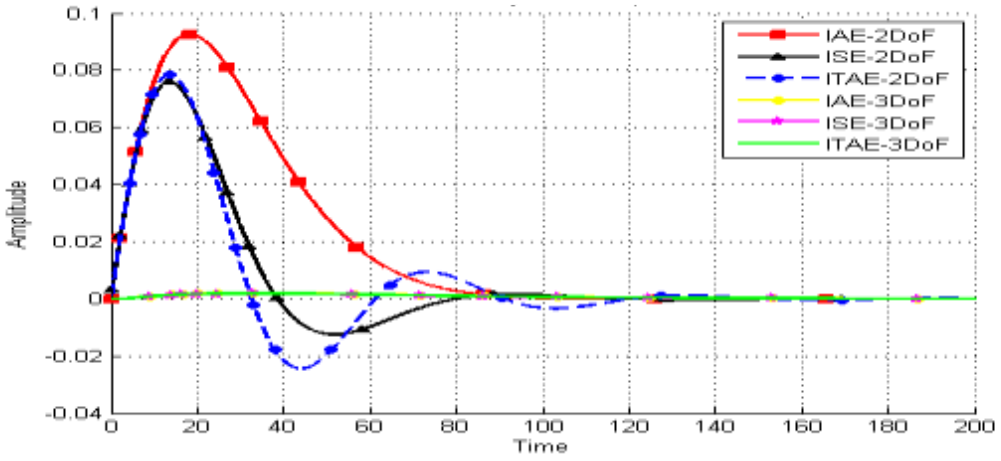


Figure 4. 3: Flow Disturbance Response

From Figure 4.3, the 3DoF controller gives 98% improvement in flow disturbance rejection characteristics. It gives approximately zero disturbance responses for all criterions which is a good measure of how insensitive the system is to flow disturbances compared to those of 2DoF that peaked up to 0.08 for ISE and ITAE respectively, and 0.09 for IAE. It means that the system will respond appreciably to flow disturbance under 2DoF controller before settling to zero at

about 100

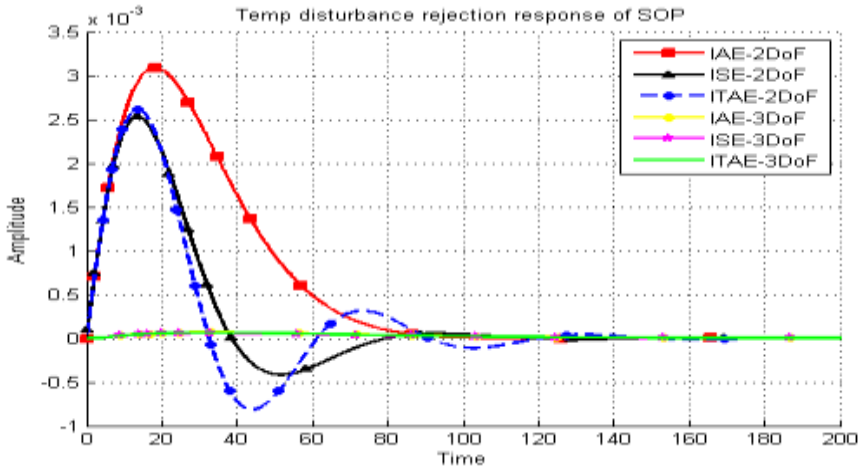


Figure 4. 4: Temperature Disturbance Response

Figure 4.4 is similar Figure 4.3, in the sense that the 3DoF controller gives better temperature disturbance rejection characteristics. It also gives approximately zero disturbance responses for all criterions as good measure of how insensitive the system is to temperature disturbances compared to those of 2DoF that peaked above 2.5 x 10^{-3} for IAE, ISE and ITAE criterions. The system will respond to some levels of temperature disturbance under 2DoF controller before settling to zero at about 100 secs. Other metrics from Figures 4.2, 4.3 and 4.4 are summarized in Table 4.1.

Table 4. 1: Optimized Parameter and Performance Metrics of the SOP for 2DoF and 3DoF Controllers Optimization in GA

Controllers parameters' values for each Criterions		**Best values of fitness function (g)**		**% Overshoot of step response**		**% Reduction of flow disturbance**		**% Reduction of temperature disturbance**	
2DoF	**3DoF**	**2DoF**	**3DoF**	**2DoF**	**3DoF**	**2DoF**	**3DoF**	**2DoF**	**3DoF**

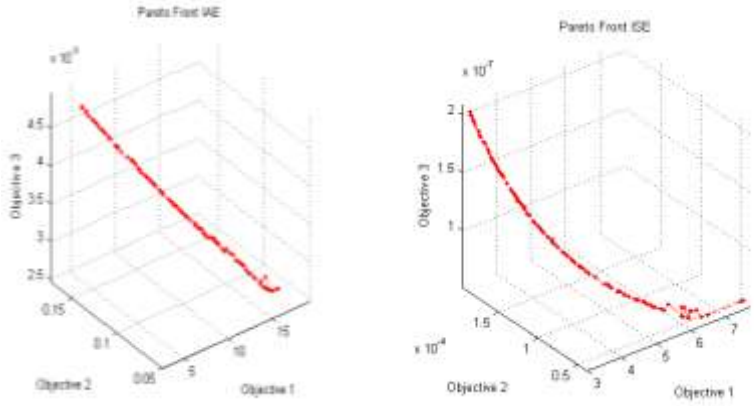
IAE $K_p = 0.530$ $K_i = 0.017$ $K_d = 3.339$ $\alpha = 0.094$ $\beta = 0.0068$	IAE $K_p = 87.71$ $K_i = 91.31$ $K_d = 54.83$ $\eta = 0.02$ $\zeta = 10^{-4}$	8.98	3.85	15.17	12.39	7.4	98	69	99
ISE $K_p = 0.854$ $K_i = 0.042$ $K_d = 5.242$ $\alpha = 0.424$ $\beta = 0.027$	ISE $K_p = 82.18$ $K_i = 101.4$ $K_d = 60.0$ $\eta = 0.02$ $\zeta = 10^{-4}$	40.85	2.99	17.39	16.17	24.1	98	75	99

The peak overshoot for set point tracking under 3DoF controller is lower in IAE and ISE compared to those of 2DoF controller while the percentage reduction in the overshoot for flow and temperature disturbances are at all-time higher in the 3DoF controller than in the 2DoF controller for all the three criterions. The result of noise suppression response is included in Appendix C.

4.3 Non-dominated Solution of MOP Optimization

The 3DoF control system of STHX formulated as MOP and the controller parameters optimized using NSGA-II. The pareto optimal front of three objective functions – set point tracking, flow

disturbance and temperature disturbance, obtained are presented in Figure 4.5 for each of the criterions.



(a) MOP for IAE (b) MOP for ISE

Figure 4. 5: Pareto Optimal Front of MOP for IAE and ISE (L-R)

Results of the set point tracking response, flow disturbance responses and temperature disturbance responses are presented from Figure 4.6 to Figure 4.14 for all criterions IAE, ISE and ITAE. The results are placed side by side for 2DoF and 3DoF control schemes in order to compare them visually.

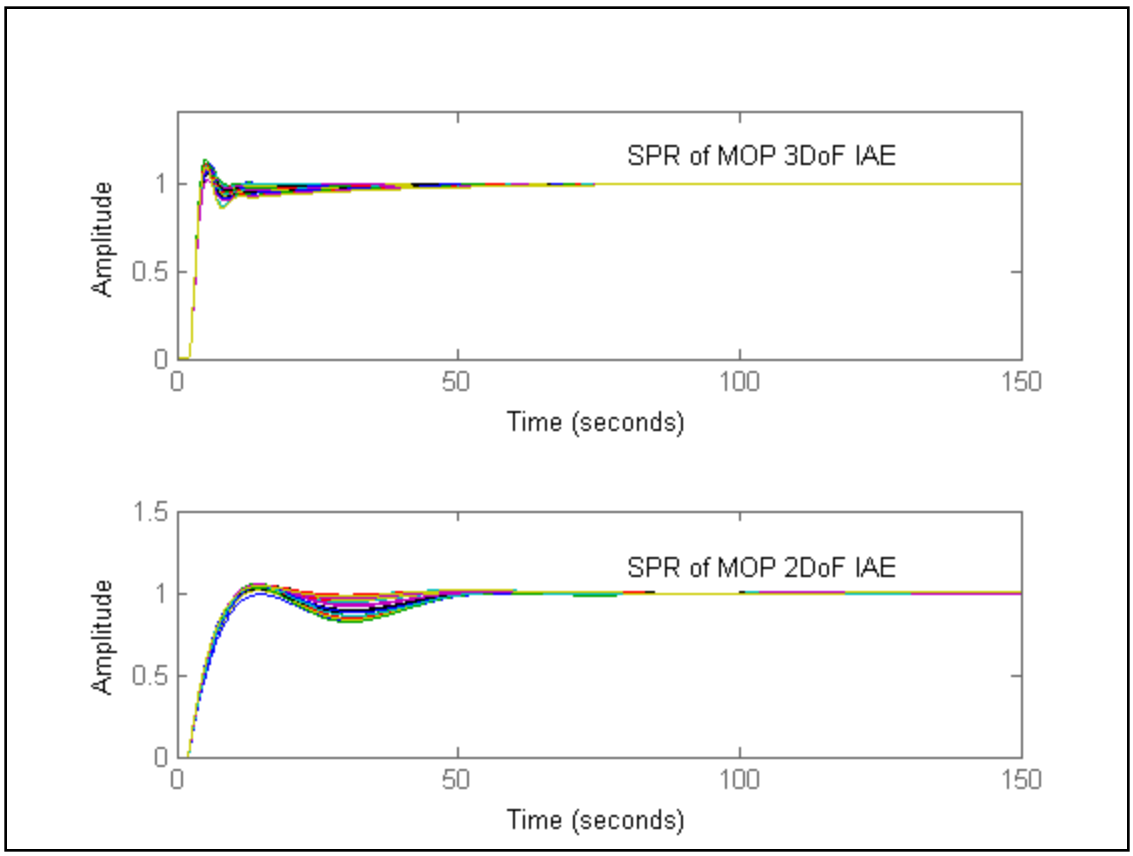


Figure 4. 6: Set Point Response of MOP under IAE for 2DoF and 3DoF Controllers

The set point responses (SPR) of the MOP of 3DoF controller as shown on Figure 4.6, responded faster compared to the response of MOP of 2DoF and settle in less than 20 secs for a set of 20 optimal non-dominated solutions under IAE presented in table B1 of Appendix B. The percentage overshoot for of the best controller parameters under 2DoF is however, better than that of the 3DoF counterpart with a difference of 1%, which is the only trade-off for the fastest response for the criterion IAE considered under 3DoF. The overshoot in both case are less than 10%. The flow disturbance rejection characteristics under this criterion for MOP, is presented in Figure 4.7 while that of the temperature rejection characteristic is given in Figure 4.8.

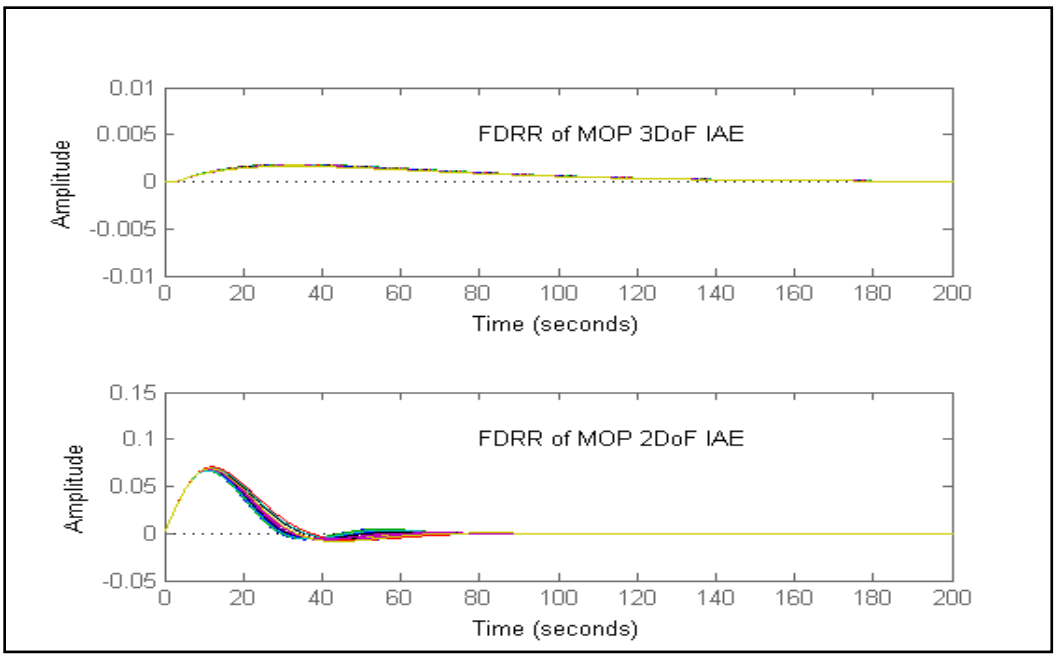


Figure 4. 7: Flow Disturbance Response of MOP under IAE for 2DoF and 3DoF Controllers

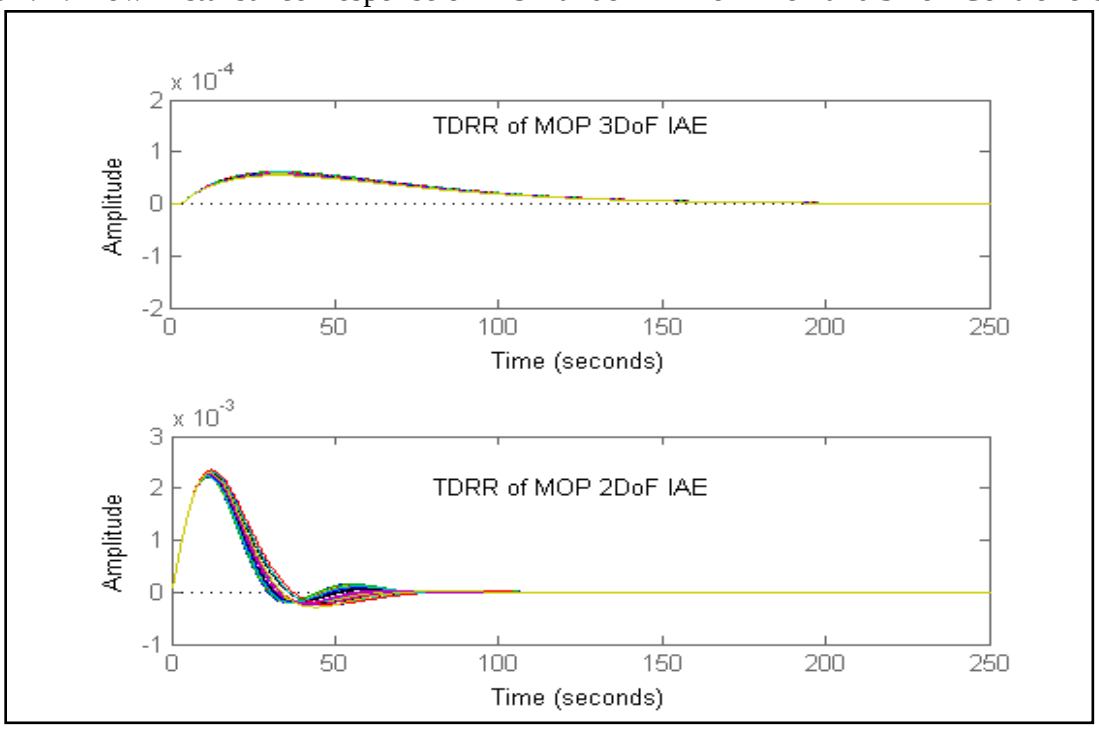


Figure 4. 8: Temperature Disturbance Response of MOP under IAE for the Controllers

Figure 4.7 shows the flow disturbance rejection responses (FDRR) of the MOP under IAE criterion. The percentage rejection in the case of 3DoF controller is 98% as against 33% in the case of 2DoF controller. This shows that the 3DoF controller is better at flow disturbance rejection with utmost certainty. The Figure also shows that the peak jittery for the 3DoF is at 0.02 while that of 2DoF is above 0.05 for step input 0.1.

Similarly, Figure 4.8 shows that the peak shoot of the temperature disturbance rejection response (TDRR) is less in the 3DoF controller than in the 2DoF controller by more than 10 peak value for a step input of 0.1. This amount to a 99% success in 3DoF controller compared to 78% in 2DoF controller for the criterion under consideration. For the ISE criterion, the set point tracking response is shown in Figure 4.9.

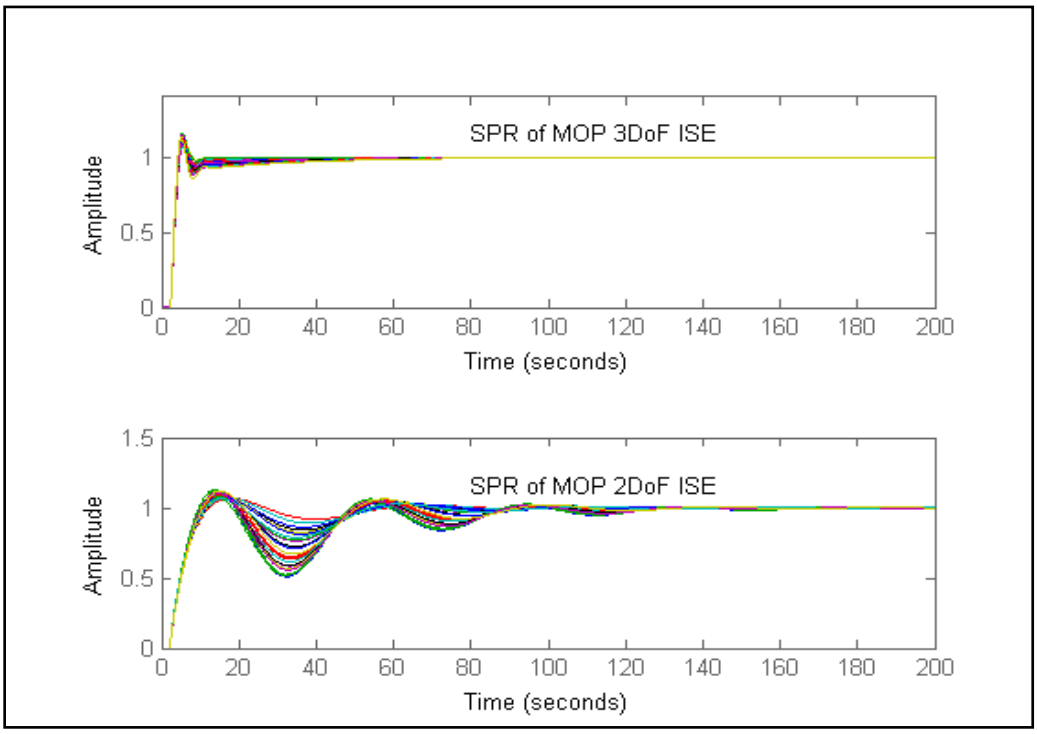


Figure 4. 9: Set Point Response of MOP under ISE for 2DoF and 3DoF Controllers

Figure 4.9 shows that the set point tracking responses for a set of 20 non-dominated optimal solutions set. The responses with 3DoF controller are faster (settling time less than 15 secs) for each solution set under criterion ISE. Whereas, with 2DoF controller, the responses' settling time is beyond 80 secs for each solution set. While the results with the 3DoF exhibit little overshoot, those of the 2DoF rose slowly. The flow disturbance rejection is shown in Figure 4.10.

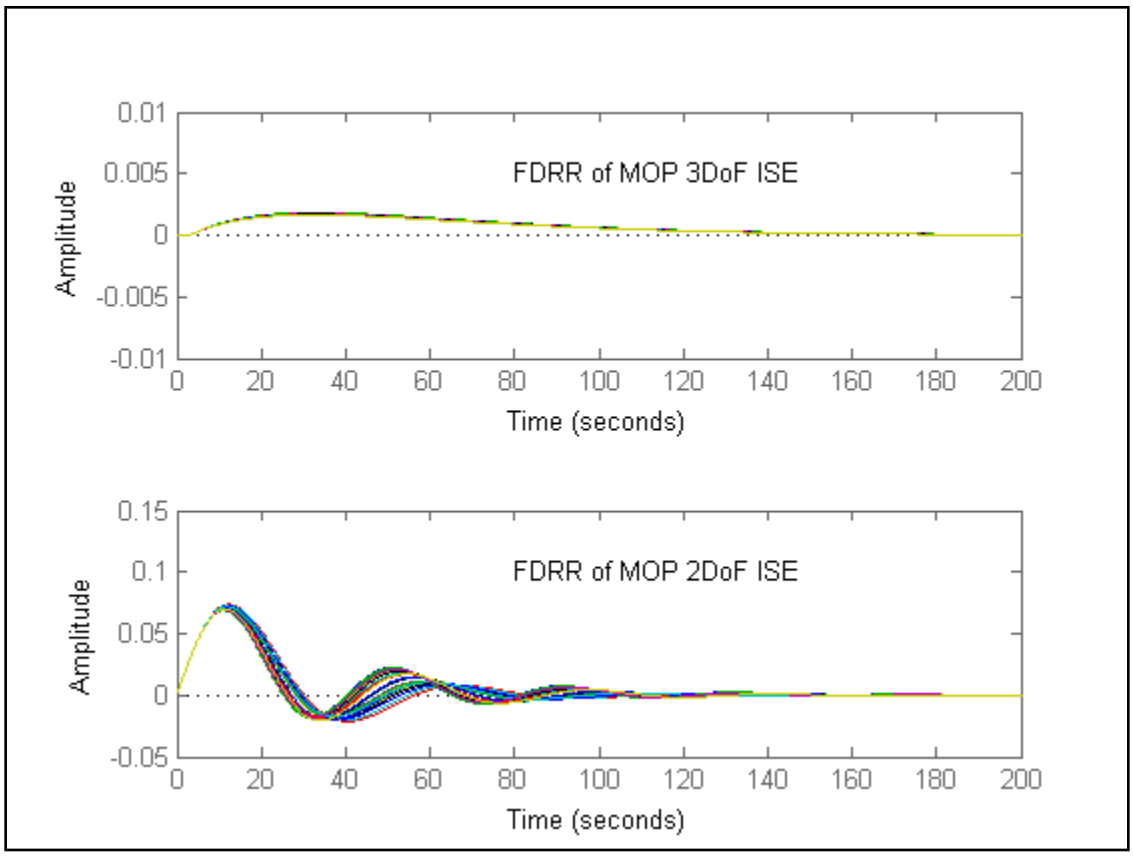


Figure 4. 10: Flow Disturbance Response of MOP under ISE for the Controllers

Figure 4.10 shows the flow disturbance rejection of the MOP under ISE criterion. The Figure shows that the peak value for the 3DoF is at 0.02 while that of 2DoF is above 0.05 for step input 0.1. The percentage rejection in the case of 3DoF controller is 98% while 31% is the success rate in the case of 2DoF controller.

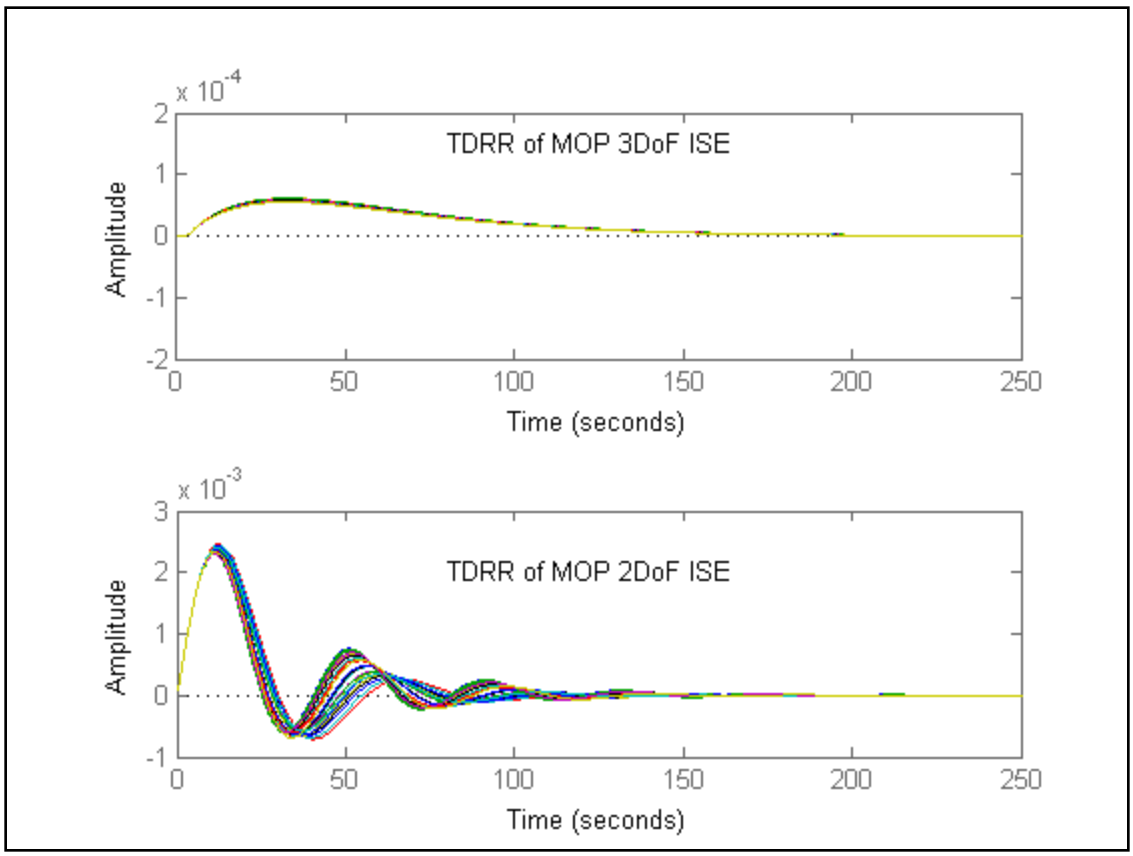


Figure 4. 11: Temperature Disturbance Response of MOP under ISE for the Controllers

Figure 4.11 shows that the temperature disturbance rejection response is more successful in the 3DoF controller than in the 2DoF controller. The peak disturbance rejection value is less by more than a factor of 10 units in 3DoF compared to the 2DoF rejection profile, for a step input of magnitude 0.1. This amount to a 99% temperature disturbance rejection success in 3DoF controller compared to 77% in 2DoF controller for the criterion ISE.

The set point tracking response for the last criterion ITAE is presented in Figure 4.12.

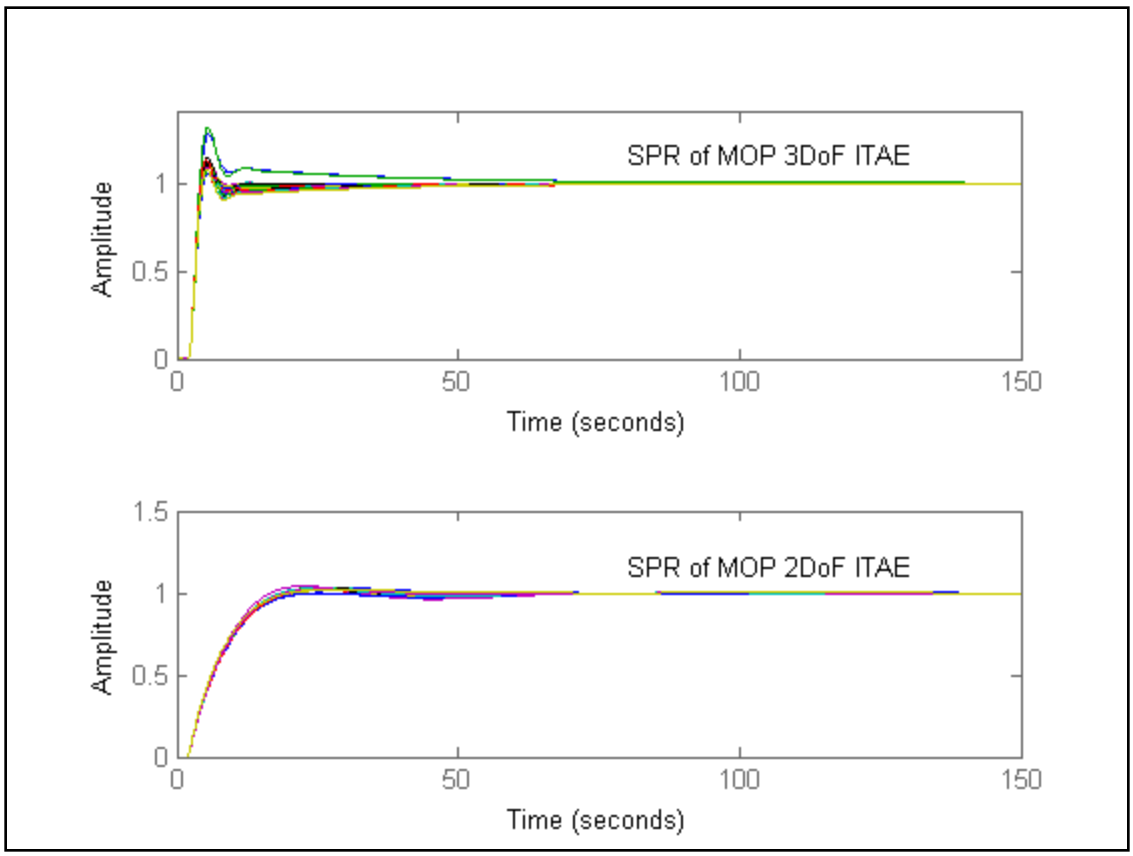


Figure 4. 12: Set Point Response of MOP under ITAE for 2DoF and 3DoF Controllers

Figure 4.12, like the other two Figures 4.6 and 4.9 shows the set point tracking responses for a set of 20 optimal non-dominated solutions for the MOP under the criterion ITAE considering 3DoF and 2DoF controllers. While the responses are faster (settling time less than 15 secs) in 3DoF controllers, they suffer significant amount of over shoot (more than 17%) compared to that of 2DoF controller. But set point tracking is not the only thing considered. Figures 4.13 and 4.14 present the flow disturbance rejection and temperature disturbance rejection characteristics respectively for the criterion ITAE.

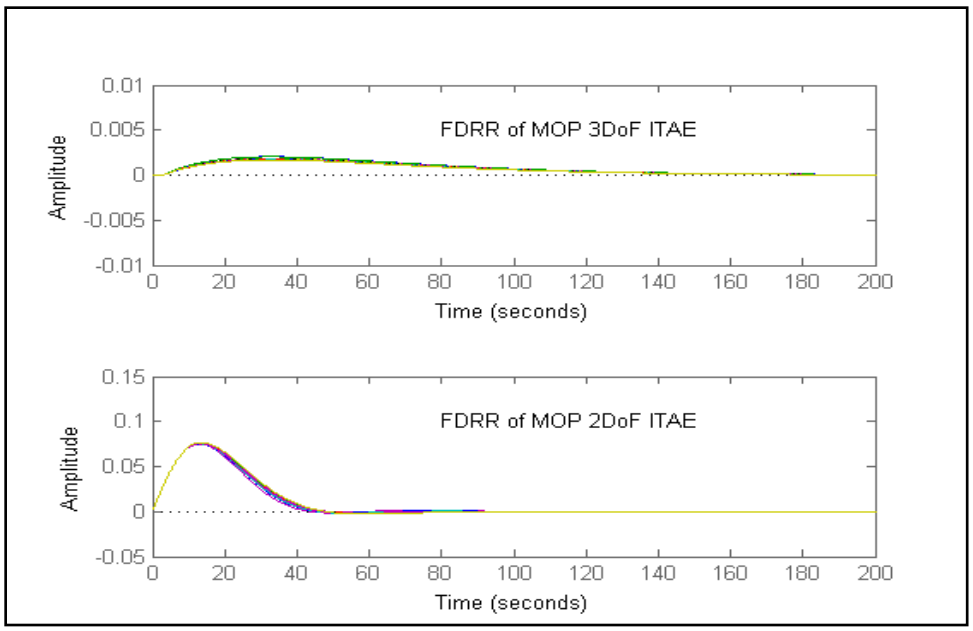


Figure 4. 13: Flow Disturbance Response of MOP under ITAE for the Controllers

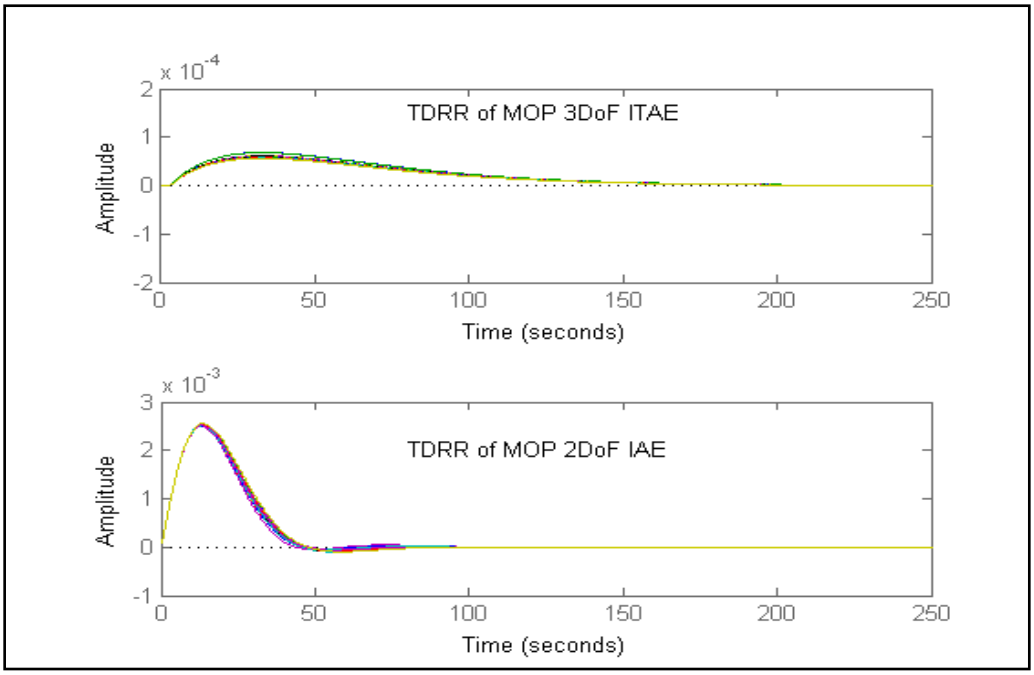


Figure 4. 14: Temperature Disturbance Response of MOP under ITAE for the Controllers

Figure 4.13 shows the flow disturbance rejection responses for the criterion ITAE with 98%rejection success in 3DoF controller application.

Similarly, Figure 4.14 shows up to 99% success rate in temperature disturbance rejection characteristic in the case of 3DoF controller. The performance metrics for Figure 4.6 to Figure 4.14 are summarized in Table 4.2 while the values of the 3DoF control parameters up to 20 optimal set of solutions are presented in Table B1, Table B2 and Table B3 of Appendix B for the respective IAE, ISE and ITAE criterions. Other results relating to the noise suppression responses of the 3DoF controllers are presented in Figures 4.15 to 4.17.

Table 4. 2: Optimized Parameter and Performance Metrics of the MOP for 2DoF and 3DoF Controllers Optimization in GA

Controllers parameters' values for each criterions		**% Overshoot of step response**		**% Reduction of flow disturbance**		**% Reduction of temperature disturbance**	
2DoF $[K_p, K_i, K_d, \alpha, \beta]$	**3DoF** $[K_p, K_i, K_d, \eta, \zeta]$	**2DoF**	**3DoF**	**2DoF**	**3DoF**	**2DoF**	**3DoF**
IAE [1.362, 0.052, 6.85, 0.601, 0.439] (Best Set point tracking & disturbance rejections)	IAE (S/N-19, Table B1) [100.00, 111.22, 60.00, 0.02, 10^{-4}] (Best Set point tracking & disturbance rejections)	4.79	7.71	33.43	98	78	99
ISE [1.676, 0.045, 4.88, 0.619, 0.215] (Best Set point tracking)	ISE (S/N-12, Table B2) [98.91, 105.53, 60.00, 0.02, 10^{-4}] (Best Set point tracking)	12.5	6.60	31.02	98	77	99
ISE [1.696, 0.045, 4.89, 0.604, 0.228] (Best disturbances rejections)	ISE (S/N-12, Table B2) [98.91, 105.53, 60.00, 0.02, 10^{-4}] (Best disturbances rejections)	15.63	6.60	31.17	98	77	99

4.4 Results Relating to Noise Suppression Responses of the 3DoF Controller

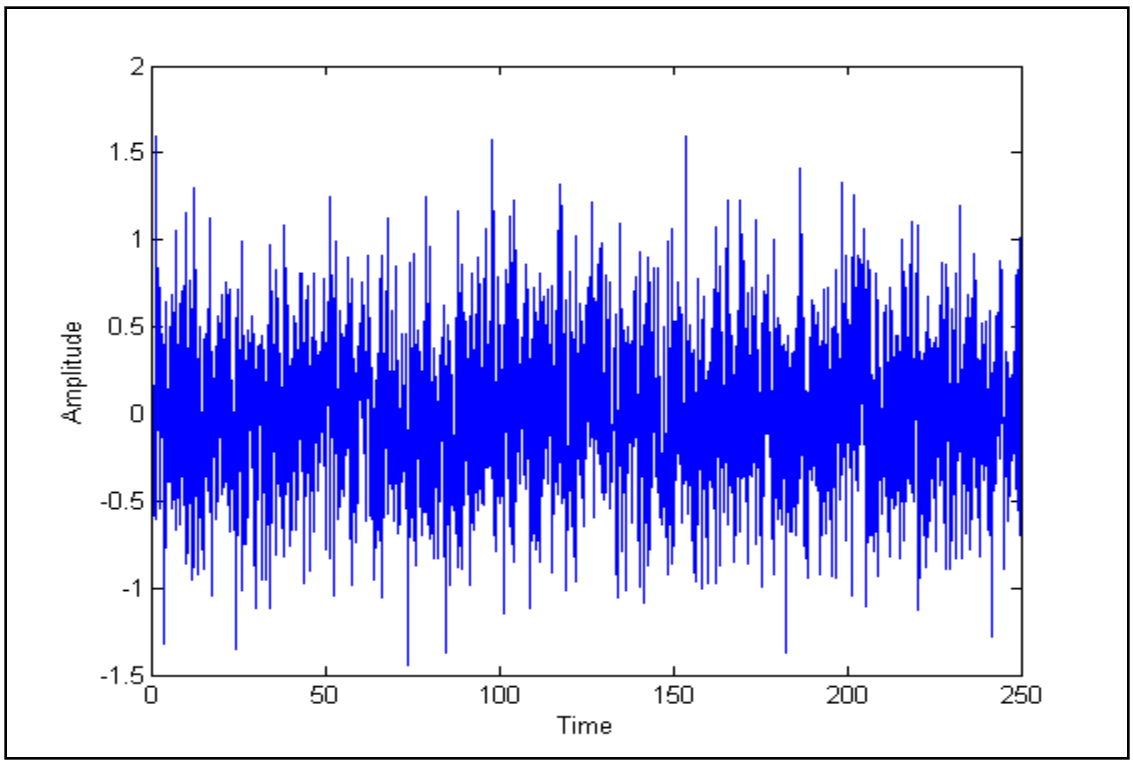


Figure 4. 15: Noise Profile

In 2DoF controller, noise is coupled with disturbances affecting the system, while in 3DoF controller, measurement and process noise is separated from the disturbances in the system. Figure 4.15 shows the generated Additive White Gaussian Noise (AWGN) profile injected into the system. The 3DoF controller has the capacity to suppress noise of this magnitude due to its in-built filter in the feedback path. Figure 4.16 shows the noise reduction responses of the SOP for all criterions.

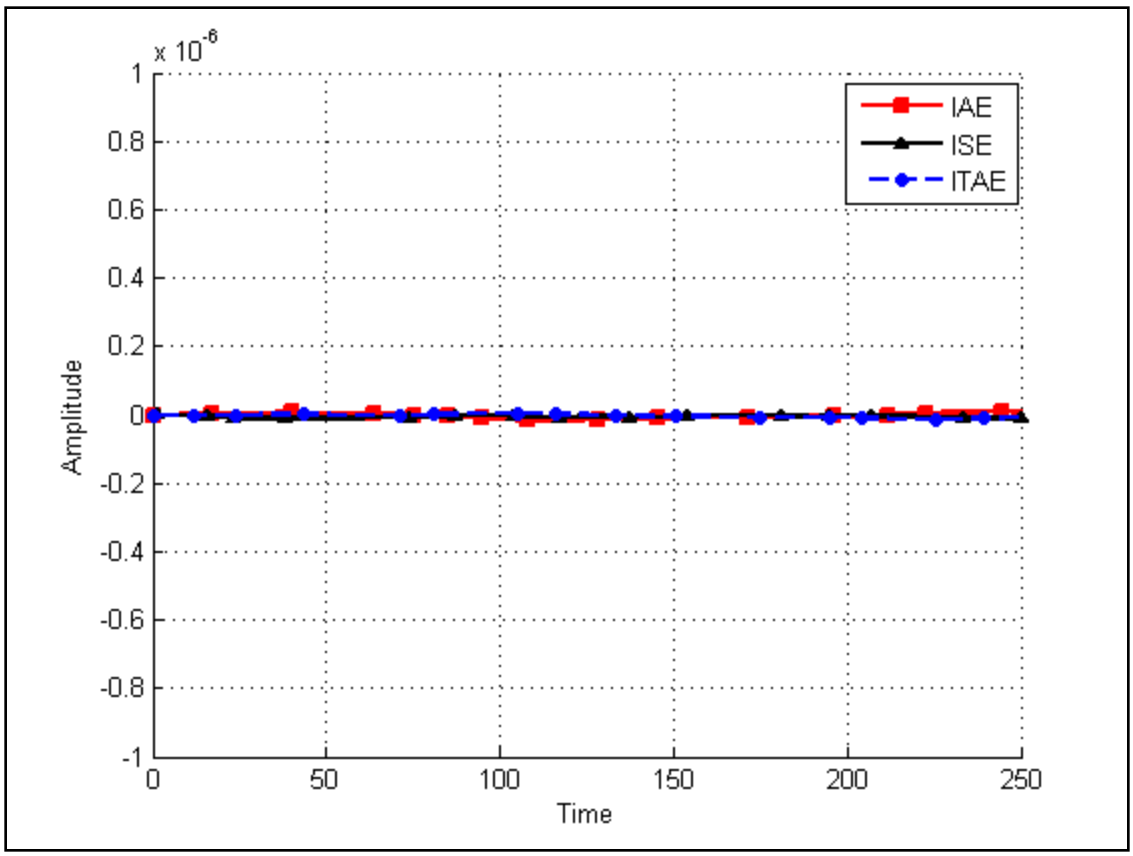


Figure 4. 16: Noise Reduction Responses of MOP formulated as SOP 3DoF Controller

This result showed significant suppression of noise under all the criterions considered for the SOP optimization. Even up to 10^{-6} the noise level remained approximately at zero level. This means that the system is insensitive to measurement and process noise under SOP formulations and optimization of the 3DoF controller. Figure 4.17 shows the noise profile and its reduction responses for MOP 3DoF controller optimization.

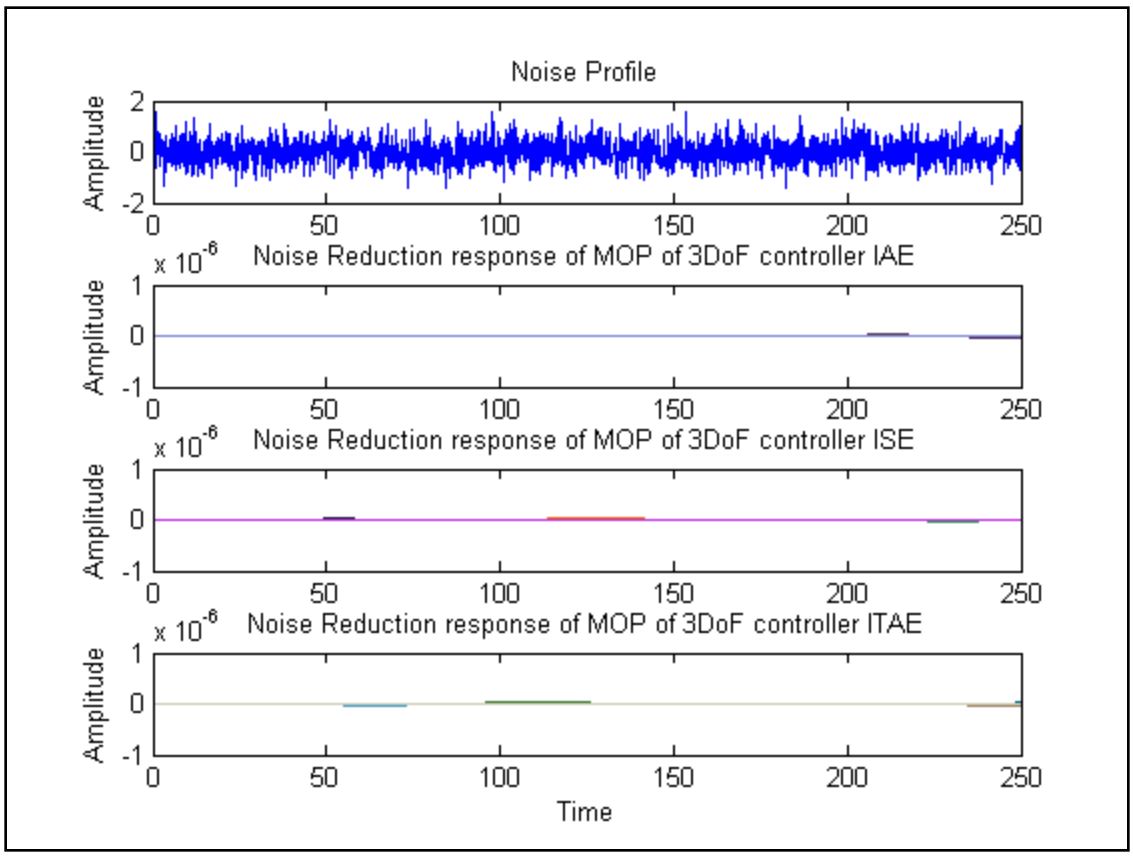


Figure 4. 1716: Noise Reduction Responses of MOP 3DoF Controller IAE,ISE and ITAE

For the noise profile of magnitude up to 2 units, Figure 4.17 shows that the noise reduction responses for the criterions IAE, ISE and ITAE flattened out even with the view up to the micro-level (10^{-6}), for a set of 20 non-dominated optimal solutions considered for all the respective criterions. This shows the system's ability to function well even in the presence of process noise and measurement noise.

CHAPTER FIVE

CONCLUTION AND RECOMMENDATION

5.1 Summary

This research presents the development of a three degree of freedom controller for regulating the temperature of the outlet fluid of a Shell and Tube Heat Exchanger. An experimental data was adopted from previous works to design the model. Both single and multiple objectives problems were formulated while using Non-Dominated Sorting Genetic Algorithm to tune controller parameters. The designed controller was simulated under three criterions IAE, ISE and ITAE. Though percentage overshoot of the best result for 3DoF under IAE was slightly higher than in 2DoF, while under ISE and ITAE overshoot were quite lower. Flow and temperature disturbances were greatly reduced, with performance in the range of 90% to 99% for 3DoF controllers considering all criterions. In the case of 2DoF controllers, the performance is in the range 25% to 78%. The designed controller was also able to suppress noise.

5.2 Conclusion

This research developed a 3DoF controller which is able to optimally maintain a desired temperature value of the outlet fluid of an STHX. The controller is able to adequately respond to flow disturbance, temperature disturbance and suppress noise. Non-dominated sorting genetic algorithm was used to optimize the controller parameters which minimized IAE, ISE. The results obtained under all the three criterions were compared with a 2DoF controller which showed significant improvement in set point tracking, flow disturbance response and temperature disturbance response using overshoot, rise time and settling time as performance metrics.

5.3 Significant Contributions

The significant contributions of this work are as follower:

1. Development of 3DoF controller for STHX with improved performance of 90% to 99% in teams of setpoint tracking, flow disturbance response and temperature disturbance response compared with the existing 2DoF controller.
2. The developed controller is able to suppress noise by 99% which enhances its effectiveness.
3. This research has provided basis for further improvement in terms of noise suppression in the design of controllers for heat exchangers.

5.4 Recommendations for Further Work

The following are recommended for consideration in future work:

i. Comparison of NSGA II to other meta-heuristic optimization algorithm to determine the optimal tuning parameter for PID Controller

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APPENDIX A

MATLAB m-files

Main_nsga_2.m

```
%% Main Program
% Main program to run the NSGA-II Multi-Objective Algorithm.
clear all
close all
clc
global M;
global V;
global lb;
global ub;
global pop;
global idx;
global Eta;
global zeta;
Eta = 0.02;
zeta = 1e-4;
txt1 = {' IAE ',' ISE ',' ITAE '};

for id = 1:3
   idx = id;
   disp (' ')
   disp (['FOR',txt1(id)])
   disp (' ')
   pop = 100;

   M = 4;
   V = 3;
   lb = [50 50 50];
   ub = [100 200 60];
   gen = pop*V; %1000;
   % Initialize the population
   chromosome = initialize_variables(pop);
   %initial_size_chromosome = size(chromosome)

   %% Sort the initialized population
   % Sort the population using non-domination-sort. This returns two columns
   % for each individual which are the rank and the crowding distance
   % corresponding to their position in the front they belong.

   chromosome = non_domination_sort_mod(chromosome);
   %sort1_size_chromosome = size(chromosome)
   %% Start the evolution process

   % The following are performed in each generation
```

```
% Select the parents
% Perform crossover and Mutation operator
% Perform Selection

for i = 1 : gen
   % Select the parents
   % Parents are selected for reproduction to generate offspring. The
   % original NSGA-II uses a binary tournament selection based on the
   % crowded-comparision operator. The arguments are
   % pool - size of the mating pool. It is common to have this to be half the
   %       population size.
   % tour - Tournament size. Original NSGA-II uses a binary tournament
   %       selection, but to see the effect of tournament size this is kept
   %       arbitary, to be choosen by the user.
   pool = round(pop/2);
   tour = 4; %2;
   parent_chromosome = tournament_selection(chromosome,pool,tour);

   % The distribution indices for crossover and mutation operators as mu = 20
   % and mum = 20 respectively.
   mu = 8; %20;
   mum = 9; %20;
   offspring_chromosome = genetic_operator(parent_chromosome,mu,mum);

   % Intermediate population is the combined population of parents and
   % offsprings of the current generation. The population size is almost 1 and
   % half times the initial population.
   [main_pop,temp] = size(chromosome);
   [offspring_pop,temp] = size(offspring_chromosome);
   intermediate_chromosome(1:main_pop,:) = chromosome;
   intermediate_chromosome(main_pop + 1 : main_pop + offspring_pop,1 : M+V) = ...
      offspring_chromosome;

   % The intermediate population is sorted again based on non-domination sort
   % before the replacement operator is performed on the intermediate
   % population.
   intermediate_chromosome = ...
      non_domination_sort_mod(intermediate_chromosome);

   % Perform Selection
   % Once the intermediate population is sorted only the best solution is
   % selected based on its rank and crowding distance. Each front is filled in
   % ascending order until the addition of population size is reached. The
   % last front is included in the population based on the individuals with
   % least crowding distance
   chromosome = replace_chromosome(intermediate_chromosome,pop);
```

```
        %
        %size_chromosome3 = size(chromosome)
        if ~mod(i,10)
            disp(['Running ', num2str(i), ' of ', num2str(gen)])
        end
    end
%
%% Result
% Save the result in ASCII text format (columns 1 - 3: alpha,beta,gama),
%(column 4-7 is obj fns: sp_tracking, Flow_dist, Temp_dist and Noise_reductn).
    switch idx
        case 1
            IAE_Sol = chromosome;
            save('IAE_Sol.mat');
            save solution_IAE.txt chromosome -ASCII
            Filename = 'Solution_IAE.xlsx';
            xlswrite(Filename,chromosome);
        case 2
            ISE_Sol = chromosome;
            save('ISE_Sol.mat');
            save solution_ISE.txt chromosome -ASCII
            Filename = 'Solution_ISE.xlsx';
            xlswrite(Filename,chromosome);
        case 3
            ITAE_Sol = chromosome;
            save('ITAE_Sol.mat');
            save solution_ITAE.txt chromosome -ASCII
            Filename = 'Solution_ITAE.xlsx';
            xlswrite(Filename,chromosome);
    end
end
run dominate_solution
```

inintialize_variables.m

```
function f = initialize_variables(N)

global M;
global V;
global lb;
global ub;
min = lb; %[0 1 2 3 4 5]; %0;
max = ub; %[1 8 9 10 34 60]; %1;
K = V + M;

for i = 1 : N
    % Initialize the decision variables
```

```
    for j = 1 : V
        f(i,j) = min(j) + (max(j) - min(j))*rand(1);
    end
    % Evaluate the objective function
    f(i,V + 1: K) = evaluate_objective(f(i,:));
end
```

non_domination_sort_mod.m

```
function f = non_domination_sort_mod(x)
[N,m] = size(x);
global M;
global V;
global lb;
global ub;

    front = 1;

    % There is nothing to this assignment, used only to manipulate easily in
    % MATLAB.
    F(front).f = [];
    individual = [];
    for i = 1 : N
        % Number of individuals that dominate this individual
        individual(i).n = 0;
        % Individuals which this individual dominate
        individual(i).p = [];
        for j = 1 : N
            dom_less = 0;
            dom_equal = 0;
            dom_more = 0;
            for k = 1 : M
                if (x(i,V + k) < x(j,V + k))
                    dom_less = dom_less + 1;
                elseif (x(i,V + k) == x(j,V + k))
                    dom_equal = dom_equal + 1;
                else
                    dom_more = dom_more + 1;
                end
            end
            if dom_less == 0 & dom_equal ~= M
                individual(i).n = individual(i).n + 1;
            elseif dom_more == 0 & dom_equal ~= M
                individual(i).p = [individual(i).p j];
            end
        end
        if individual(i).n == 0
```

```
        x(i,M + V + 1) = 1;
        F(front).f = [F(front).f i];
    end
end
% Find the subsequent fronts
while ~isempty(F(front).f)
  Q = [];
  for i = 1 : length(F(front).f)
     if ~isempty(individual(F(front).f(i)).p)
         for j = 1 : length(individual(F(front).f(i)).p)
            individual(individual(F(front).f(i)).p(j)).n = ...
               individual(individual(F(front).f(i)).p(j)).n - 1;
            if individual(individual(F(front).f(i)).p(j)).n == 0
               x(individual(F(front).f(i)).p(j),M + V + 1) = ...
                  front + 1;
               Q = [Q individual(F(front).f(i)).p(j)];
            end
         end
     end
  end
  front =  front + 1;
  F(front).f = Q;
end
[temp,index_of_fronts] = sort(x(:,M + V + 1));
for i = 1 : length(index_of_fronts)
   sorted_based_on_front(i,:) = x(index_of_fronts(i),:);
end
current_index = 0;
z = [];
% Find the crowding distance for each individual in each front
for front = 1 : (length(F) - 1)
   objective = [];
   distance = 0;
   y = [];
   previous_index = current_index + 1;
   for i = 1 : length(F(front).f)
      y(i,:) = sorted_based_on_front(current_index + i,:);
   end
   current_index = current_index + i;
   % Sort each individual based on the objective
   sorted_based_on_objective = [];
   for i = 1 : M
      [sorted_based_on_objective, index_of_objectives] = ...
         sort(y(:,V + i));
      sorted_based_on_objective = [];
      for j = 1 : length(index_of_objectives)
```

```
            sorted_based_on_objective(j,:) = y(index_of_objectives(j),:);
        end
        f_max = ...
            sorted_based_on_objective(length(index_of_objectives), V + i);
        f_min = sorted_based_on_objective(1, V + i);
        y(index_of_objectives(length(index_of_objectives)),M + V + 1 + i)...
            = Inf;
        y(index_of_objectives(1),M + V + 1 + i) = Inf;
         for j = 2 : length(index_of_objectives) - 1
            next_obj  = sorted_based_on_objective(j + 1,V + i);
            previous_obj  = sorted_based_on_objective(j - 1,V + i);
            if (f_max - f_min == 0)
                y(index_of_objectives(j),M + V + 1 + i) = Inf;
            else
                y(index_of_objectives(j),M + V + 1 + i) = ...
                    (next_obj - previous_obj)/(f_max - f_min);
            end
         end
    end
    distance = [];
    distance(:,1) = zeros(length(F(front).f),1);
    for i = 1 : M
        distance(:,1) = distance(:,1) + y(:,M + V + 1 + i);
    end
    y(:,M + V + 2) = distance;
    y = y(:,1 : M + V + 2);
    z(previous_index:current_index,:) = y;
end

if numel(z)==0 || max(z(:,M + V + 1)) < 1
    z = x;
end
f = z();
```

tournament_selection.m

```
function f = tournament_selection(chromosome,pool_size,tour_size)

[pop,variables] = size(chromosome);
rank = variables - 1;
distance = variables;
for i = 1 : pool_size
    for j = 1 : tour_size
        candidate(j) = round(pop*rand(1));
        if candidate(j) == 0
            candidate(j) = 1;
        end
```

```
        if j > 1
            while ~isempty(find(candidate(1 : j - 1) == candidate(j)))
                candidate(j) = round(pop*rand(1));
                if candidate(j) == 0
                    candidate(j) = 1;
                end
            end
        end
    end
    for j = 1 : tour_size
        c_obj_rank(j) = chromosome(candidate(j),rank);
        c_obj_distance(j) = chromosome(candidate(j),distance);
    end
    min_candidate = ...
        find(c_obj_rank == min(c_obj_rank));
    if length(min_candidate) ~= 1
        max_candidate = ...
        find(c_obj_distance(min_candidate) == max(c_obj_distance(min_candidate)));
        if length(max_candidate) ~= 1
            max_candidate = max_candidate(1);
        end
        f(i,:) = chromosome(candidate(min_candidate(max_candidate)),:);
    else
        f(i,:) = chromosome(candidate(min_candidate(1)),:);
    end
end
```

genetic_operator.m

```
function f  = genetic_operator(parent_chromosome,mu,mum)
%
global M;
global V;
global lb;
global ub;

[N,m] = size(parent_chromosome);

p = 1;
was_crossover = 0;
was_mutation = 0;
l_limit = lb;
u_limit = ub;
for i = 1 : N
    if rand(1) < 0.9
        child_1 = [];
        child_2 = [];
```

```
    parent_1 = round(N*rand(1));
    if parent_1 < 1
       parent_1 = 1;
    end
    parent_2 = round(N*rand(1));
    if parent_2 < 1
       parent_2 = 1;
    end
    while isequal(parent_chromosome(parent_1,:),parent_chromosome(parent_2,:))
       parent_2 = round(N*rand(1));
       if parent_2 < 1
          parent_2 = 1;
       end
    end
    parent_1 = parent_chromosome(parent_1,:);
    parent_2 = parent_chromosome(parent_2,:);
    for j = 1 : V
       % Generate a random number
       u(j) = rand(1);
       if u(j) <= 0.5
          bq(j) = (2*u(j))^(1/(mu+1));
       else
          bq(j) = (1/(2*(1 - u(j))))^(1/(mu+1));
       end
       child_1(j) = ...
          0.5*(((1 + bq(j))*parent_1(j)) + (1 - bq(j))*parent_2(j));
       child_2(j) = ...
          0.5*(((1 - bq(j))*parent_1(j)) + (1 + bq(j))*parent_2(j));
       if child_1(j) > u_limit(j)
          child_1(j) = u_limit(j);
       elseif child_1(j) < l_limit(j)
          child_1(j) = l_limit(j);
       end
       if child_2(j) > u_limit(j)
          child_2(j) = u_limit(j);
       elseif child_2(j) < l_limit(j)
          child_2(j) = l_limit(j);
       end
    end
    child_1(:,V + 1: M + V) = evaluate_objective(child_1);
    child_2(:,V + 1: M + V) = evaluate_objective(child_2);
    was_crossover = 1;
    was_mutation = 0;
 else
    parent_3 = round(N*rand(1));
    if parent_3 < 1
```

```
        parent_3 = 1;
      end

      child_3 = parent_chromosome(parent_3,:);
      for j = 1 : V
        r(j) = rand(1);
        if r(j) < 0.5
          delta(j) = (2*r(j))^(1/(mum+1)) - 1;
        else
          delta(j) = 1 - (2*(1 - r(j)))^(1/(mum+1));
        end
        child_3(j) = child_3(j) + delta(j);
        if child_3(j) > u_limit(j)
          child_3(j) = u_limit(j);
        elseif child_3(j) < l_limit(j)
          child_3(j) = l_limit(j);
        end
      end
      child_3(:,V + 1: M + V) = evaluate_objective(child_3);
      was_mutation = 1;
      was_crossover = 0;
    end
    if was_crossover
      child(p,:) = child_1;
      child(p+1,:) = child_2;
      was_cossover = 0;
      p = p + 2;
    elseif was_mutation
      child(p,:) = child_3(1,1 : M + V);
      was_mutation = 0;
      p = p + 1;
    end
end
f = child;
```

replace_chromosome.m

```
function f  = replace_chromosome(intermediate_chromosome,pop)
%
global M;
global V;
[N,v] = size(intermediate_chromosome);

% Get the index for the population sort based on the rank
[temp,index] = sort(intermediate_chromosome(:,M + V + 1));

% Now sort the individuals based on the index
```

```
for i = 1 : N
   sorted_chromosome(i,:) = intermediate_chromosome(index(i),:);
end

% Find the maximum rank in the current population
max_rank = max(intermediate_chromosome(:,M + V + 1));

% Start adding each front based on rank and crowing distance until the
% whole population is filled.
previous_index = 0;
for i = 1 : max_rank
   current_index = max(find(sorted_chromosome(:,M + V + 1) == i));
   if current_index > pop
      remaining = pop - previous_index;
      temp_pop = ...
         sorted_chromosome(previous_index + 1 : current_index, :);
      [temp_sort,temp_sort_index] = ...
         sort(temp_pop(:, M + V + 2),'descend');
      for j = 1 : remaining
         f(previous_index + j,:) = temp_pop(temp_sort_index(j),:);
      end
      return;
   elseif current_index < pop
      f(previous_index + 1 : current_index, :) = ...
         sorted_chromosome(previous_index + 1 : current_index, :);
   else
      f(previous_index + 1 : current_index, :) = ...
         sorted_chromosome(previous_index + 1 : current_index, :);
      return;
   end
   previous_index = current_index;
end
```

APPENDIX B

Tables of Controller Parameters for the Criterions IAE, ISE and ITAE

Table B. 1: Non Dominated Set of Solutions Obtained for IAE

S/N	K_p	K_i	K_d	η	ζ
1	96.5951	99.8830	59.9919	0.0200	0.0001
2	99.8741	99.5600	59.8109	0.0200	0.0001
3	99.8359	100.8293	59.8004	0.0200	0.0001
4	100.0000	101.2115	60.0000	0.0200	0.0001
5	99.8629	102.0241	60.0000	0.0200	0.0001
6	99.8612	102.9957	60.0000	0.0200	0.0001
7	95.9638	103.5272	60.0000	0.0200	0.0001
8	90.3284	104.1617	59.9179	0.0200	0.0001
9	95.6545	104.8861	60.0000	0.0200	0.0001
10	100.0000	105.6012	60.0000	0.0200	0.0001
11	98.4508	106.1982	59.9460	0.0200	0.0001
12	92.4130	106.6060	59.9002	0.0200	0.0001
13	98.6139	107.3189	59.9830	0.0200	0.0001
14	96.8295	108.2072	59.9191	0.0200	0.0001
15	92.0309	108.7548	60.0000	0.0200	0.0001
16	70.5487	110.6132	59.9998	0.0200	0.0001
17	75.8777	111.2969	60.0000	0.0200	0.0001
18	77.8118	111.7467	60.0000	0.0200	0.0001
19	100.0000	111.2175	60.0000	0.0200	0.0001
20	75.7501	112.9716	60.0000	0.0200	0.0001

Table B. 2: Non Dominated Set of Solutions Obtained for ISE

S/N	K_p	K_i	K_d	η	ζ
1	82.1756	101.8520	60.0000	0.0200	0.0001
2	82.7291	101.5471	59.9804	0.0200	0.0001
3	83.6129	102.3839	59.9983	0.0200	0.0001
4	81.8620	103.5150	59.9968	0.0200	0.0001
5	80.0590	104.1168	60.0000	0.0200	0.0001
6	92.7200	100.3252	59.9298	0.0200	0.0001
7	95.1378	100.8129	59.9084	0.0200	0.0001
8	82.0368	104.4471	59.9984	0.0200	0.0001
9	95.9613	100.8882	59.9089	0.0200	0.0001
10	81.7313	105.2024	60.0000	0.0200	0.0001
11	84.2020	107.2249	60.0000	0.0200	0.0001
12	98.9137	105.5288	60.0000	0.0200	0.0001
13	82.3535	108.0148	59.9789	0.0200	0.0001
14	88.2245	106.6963	59.5824	0.0200	0.0001
15	82.2485	108.6354	59.9973	0.0200	0.0001
16	84.0986	109.2213	59.9789	0.0200	0.0001
17	84.1314	109.8149	59.9796	0.0200	0.0001
18	84.2844	110.3740	59.9305	0.0200	0.0001
19	82.4987	110.9540	59.9783	0.0200	0.0001
20	69.9027	111.5183	60.0000	0.0200	0.0001

Table B. 3: Non Dominated Set of Solutions Obtained for ITAE

S/N	K_p	K_i	K_d	η	ζ
1	81.1287	89.9772	60.0000	0.0200	0.0001
2	72.1097	90.3733	59.9104	0.0200	0.0001
3	100.0000	104.0037	59.9022	0.0200	0.0001
4	96.1077	99.7728	59.9174	0.0200	0.0001
5	100.0000	99.7466	59.9182	0.0200	0.0001
6	96.2787	100.5305	59.9282	0.0200	0.0001
7	87.4163	101.1985	59.9978	0.0200	0.0001
8	96.2000	101.9688	59.9173	0.0200	0.0001
9	94.3716	102.4127	59.9133	0.0200	0.0001
10	100.0000	103.3940	59.8950	0.0200	0.0001
11	100.0000	104.0037	59.9022	0.0200	0.0001
12	97.5019	104.2121	59.9222	0.0200	0.0001
13	89.8450	104.7180	59.9390	0.0200	0.0001
14	87.3052	105.3346	59.9452	0.0200	0.0001
15	100.0000	105.9238	59.9222	0.0200	0.0001
16	94.9108	106.3985	60.0000	0.0200	0.0001
17	76.7004	107.1081	59.9114	0.0200	0.0001
18	88.5197	107.7271	60.0000	0.0200	0.0001
19	86.5642	108.4306	59.9457	0.0200	0.0001
20	87.5684	108.9736	59.9536	0.0200	0.0001