A NEW TUNING METHOD FOR TWO-DEGREE-OF-FREEDOM INTERNAL MODEL CONTROL UNDER PARAMETRIC UNCERTAINTY

JUWARI

DOCTOR OF PHILOSOPHY

UNIVERSITI MALAYSIA PAHANG

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JUWARI

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We certify that the thesis entitled "A New Tuning Method for Two-Degree-of-Freedom Internal Model Control under Parametric Uncertainty" is written by Juwari. We have examined the final copy of this thesis and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of "Doctor of Philosophy in Chemical Engineering". We herewith recommend that it be accepted in fulfillment of the requirements for the degree of Doctor of Philosophy in Chemical Engineering.

Signature 6/5/2011

External examiner:

Prof.Dr.Mohd Azlan bin Hussain
Institution: Department of Chemical Engineering,
Faculty of Engineering
Universiti Malaya, UM

PROF IR. DR. MOHD. AZLAN HUSSAIN
Lecturer
Department of Chemical Eng.
Faculty of Engineering
University of Malaya
50603 Kuala Lumpur.

Signature 09/05/11

Internal examiner:

Dr. Ramesh Kanthasammy
Institution: Universiti Malaysia Pahang, UMP

DR. K. RAMESH
Senior Lecturer
Faculty of Chemical & Natural Resources Engineering
Universiti Malaysia Pahang

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy in Chemical Engineering.

Prof Badhrulhisham Abdul Aziz
Supervisor
Date : 6-5-2011

PROFESSOR DR. BADHRULHISHAM BIN ABDUL AZIZ
DEPUTY VICE - CHANCELLOR
(ACADEMIC & INTERNATIONAL)
UNIVERSITI MALAYSIA PAHANG
LEBUHRAYA TUN RAZAK
26300 GAMBANG, KUANTAN, PAHANG, MALAYSIA

Dr. Chin Sim Yee
Co Supervisor
Date: 5/5/11

DR. CHIN SIM YEE
Timbalan Dekan (Penyelidikan & Pengajian Siswazah)
Fakulti Kejuruteraan Kimia & Sumber Asli
Universiti Malaysia Pahang
Lebuhraya Tun Razak, 26300 Gambang
Kuantan, Pahang

PROF. MADYA DR. ROSBI BIN MAMAT
Jabatan Kejuruteraan Mekatronik & Robotik
Fakulti Kejuruteraan Elektrik
Universiti Teknologi Malaysia
81310 UTM Skudai, Johor Darul Takzim

PM Rosbi Mamat
Faculty of Electrical Engineering, Universiti Teknologi Malaysia, UTM
Co Supervisor
Date : 6/5/11

STUDENT'S DECLARATION

I hereby declared that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

Juwari
ID: PKC06002
Date: 5/5/2011

Dedicated to my parents, my grand parents, my beloved wife, my children and my big family.

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ABSTRACT

The purpose of controller tuning is to determine the parameters of controller in order to ensure the time response of close-loop control system at the desired performance. Proportional Integral Derivative (PID) controller has been used in the industry since 1940's for this purpose. However, the PID controller can not completely compensate for the complexity of industrial processes and desired high product quality due to interactions, nonlinearities, and time delay of the process variables. Internal model control (IMC) has been developed to overcome the deficiencies of the PID. Unfortunately, IMC yields very good performance for set point tracking, but gives sluggish response for disturbance rejection problem. The present study has developed a controller for disturbance rejection based on feedback / feedforward IMC structure. The controller is then called as feedback 2DOF-IMC. A new tuning method has been proposed for the controller. The proposed tuning method consists of three steps: Firstly, determine the worst case of the model uncertainty. Secondly, specify the parameter of set point controller using maximum peak (Mp) criteria. And thirdly, obtain the parameter of the disturbance rejection controller using gain margin (GM) criteria. The proposed method is called Mp-GM tuning method.

The effectiveness of the proposed feedback 2DOF-IMC and Mp-GM tuning method has evaluated and compared with standard 2DOF-IMC using IMCTUNE and Kaya 2DOF-IMC using Mp-GM tuning as bench mark. The evaluation and comparison are investigated through simulation and implementation on a number of first order plus dead time (FOPDT) and higher order processes. The FOPDT process tested include processes with controllability ratio in the range 0.7 to 2.5. The higher processes include second order with underdamped and third order with nonminimum phase processes. Although the two of higher order process are considered difficult processes, the proposed feedback 2DOF-IMC and Mp-GM tuning method were able to obtain the optimal controller even under process uncertainties. The proposed feedback 2DOF-IMC and the proposed Mp-GM tuning are also successfully implemented in real-time on a laboratory scale air heater pilot plant. The process model is divided into two regions. The time responses show that the proposed feedback 2DOF-IMC and the proposed Mp-GM tuning gave faster set point tracking and disturbance rejection responses than 1DOF-IMC and standard 2DOF-IMC in both regions.

ABSTRAK

Tujuan dari talakan kontroler adalah untuk menentukan parameter pengawal iaitu memastikan waktu sambutan sistem kawalan gelung tertutup pada prestasi yang dikehendaki. Kawalan kamiran terbitan berkadaran (PID) telah digunakan dalam industri sejak tahun 1940 an untuk tujuan ini. Namun, pengawal PID tidak boleh sepenuhnya mengimbangi kekompleksan proses-proses industri dan kualiti produk yang dikehendaki. Ini karena tingginya interaksi antara proses, proses tak lelurus, dan masa tunda pembolehubah proses yang lama. Kawalan model dalam (IMC) telah dibangunkan untuk mengatasi kekurangan PID. Malangnya, IMC memberikan sambutan lamban untuk masalah penolakan gangguan. Penyelidikan ini telah membangunkan sebuah pengawal untuk penolakan gangguan berdasarkan struktur suap balik / suap depan IMC. Pengawal ini kemudian disebut sebagai suap balik 2DOF-IMC. Sebuah kaedah penalaan yang kuat dan sederhana telah dicadangkan untuk pengawal ini. Kaedah penalaan yang dicadangkan terdiri daripada tiga langkah: Pertama, menentukan kes terburuk dari ketidakpastian model.Kedua, menentukan parameter daripada pengawal titik set menggunakan kriteria puncak maksimum (Mp). Dan ketiga, menentukan parameter daripada pengawal penolakan gangguan menggunakan kriteria jidar gandaan (GM). Kaedah penalaan yang dicadangkan ini disebut Mp-GM.

Keberkesanan daripada suap balik 2DOF-IMC dan kaedah penalaan Mp-GM yang dicadangkan dikaji dan dibandingkan dengan piawai 2DOF-IMC dengan penala IMCTUNE dan Kaya 2DOF-IMC dengan penala Mp-GM. Pengkajian dan perbandingan dilakukan melalui penyelakuan dan pelaksanaan di beberapa proses urutan pertama plus waktu mati (FOPDT) dan proses urutan yang lebih tinggi. Proses FOPDT yang diuji termasuk proses dengan nisbah kebolehkawalan daripada 0.7 sehingga 2.5. Proses urutan tinggi yang diuji adalah proses urutan kedua dengan tak teredam dan proses urutan ketiga dengan sistem fasa tak minimum. Walaupun dua proses urutan tinggi itu termasuk proses yang sukar, suap baik 2DOF-IMC dan kaedah penalaan Mp-GM yang dicadangkan boleh memberikan parameter pengawal yang optimum pada ketakpastian proses. suap baik 2DOF-IMC dan kaedah penalaan Mp-GM yang dicadangkan juga berjaya dilaksanakan secara masa nyata dengan skala makmal pada loji pandu pemanas udara. Model proses dibagi menjadi dua daerah. sambutan waktu menunjukkan bahawa maklum balas yang dicadangkan suap balik 2DOF-IMC dengan penala Mp-GM memberi sambutan penolakan yang lebih cepat dan mencapai set yang lebih cepat dibandingkan oleh 1DOF-IMC atau piawai 2DOF-IMC pada kedua-dua daerah.

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LIST OF SYMBOLS

d	Disturbance input
e	Error between measurement and model
E	Error between e and set point
Gc	Transfer function of controller
Gc_1	Transfer function of set point controller
Gc_2	Transfer function of disturbance rejection controller
Gc_f	Transfer function feedforward controller
Gd	Transfer function of disturbance
Gp	Transfer function of process
Gp_m	Treansfer function of model
k	Gain of process
Kc	Proportional gain
*l*a	Additive uncertainty
*l*m	Multiplicative uncertainty
N	Order of Butterworth filter
r	Order of controller
s	Laplace domain
S	Sensitivity function
T	Complementary sensitivity function
w	Weighting function
y	Measurement
y_{sp}	Set point

Δ	Any stable transfer function which at each frequency is less than or equal to 1 magnitude
α	Lead constant of Gc_2 controller
β	Lead constant of adding transfer function
λ	Filter time constant
θ	Time delay
τ	Time constant of process
τ_D	Derivative time constant
τ_I	Integral time constant
ω	Frequency

LIST OF ABBREVIATIONS

1DOF-IMC	One- degree-of-freedom Internal Model Control (generally as IMC)
2DOF-IMC	Two-degree-of-freedom Internal Model Control
AFPT	Air Flow Pressure Temperature Control system Pilot Plant
FOPDT	First Order plus Dead Time
GM	Gain Margin
IAE	Integral Absolute Error
IMC	Internal Model Control
MIMO	Multi Input Multi Output
Mp	Maximum peak (or resonant peak)
MPC	Model Predictive control
PID	Proportional Integral Derivative
SISO	Single Input Single Output
SOPDT	Second Order Plus Dead Time
SP	Smith Predictor controller

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

A chemical industry generally consists of many unit operations, which must be operated on a specific operating condition such as: temperature, pressure, and flow. This operating condition(s) is maintained for the purpose of safety and product quality. Proportional Integral Derivative (PID) controller has been used in the industry since 1940's for this purpose because the PID controller uses a simple algorithm (Willis, 1999). Various designs and tuning strategies were developed for the PID controller so that the controller can be used for various process characteristics. However, the PID controller can not completely compensate for the complexity of industrial processes and desired high product quality due to interactions, nonlinearities, and time delay of the process variables (Anandanatarajan et al., 2006; Normey-Rico and Camacho, 2007). The rapid development of computer technologies has encouraged the development of various types of controllers to overcome the deficiencies of the PID. These controllers include Artificial Neural Network (ANN) controller (Hussain and Ho, 2004; Mohanty, 2009), Fuzzy Logic controller (Galluzzo and Cosenza, 2009; Sarma and Rengaswamy, 2000) and Model Predictive Control (MPC) (Bezzo et al., 2005; Nikandrov and Swartz, 2009; Qin and Badgwell, 2003).

Internal Model Control (IMC) is a class of model based control proposed by Garcia and Morari (1982). The structure of IMC controller is shown in Figure (1.1). IMC uses a model explicitly and it is internally stable. This implies that if a plant is stable, the stability of the process response can be guaranteed by using a controller with stable model.

1.2 INTERNAL MODEL CONTROL (IMC)

The principle of IMC structure can be explained from (Figure 1.1); Gp_m is process model. Difference between model response and actual measurement (e) is used as input signal to IMC controller (Gc_1). In general, $e \neq 0$, due to the modeling error and unknown disturbances (d Gd) that are not accounted in the process model (Seborg et al., 2004). Unfortunately, IMC controller provides a very slow response to the case of disturbance rejection. Therefore, several researchers have attempted to overcome this weakness by developing two-degree-of freedom-IMC (2DOF-IMC) (Morari and Zafiriou, 1989). Figure 1.2 shows the standard structure of 2DOF-IMC controller.

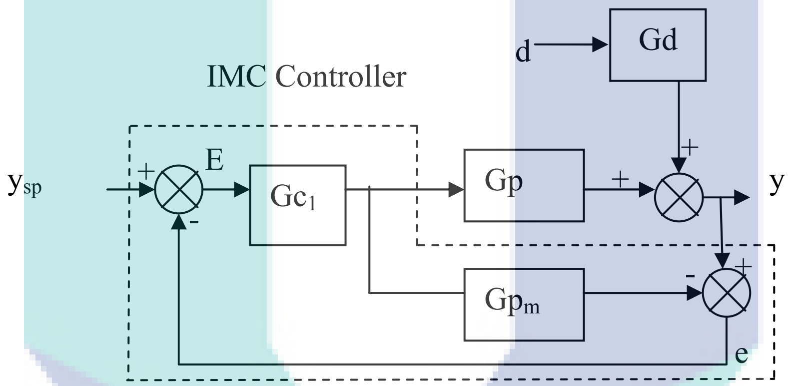


Figure 1.1 Structure of standard IMC controller

Where e is error between measurement and model, E is error between set point and e, Gp is transfer function of the process, Gp_m is transfer function of the model and Gc_1 is transfer function of the controller, y_{sp} is set point value, y is controlled variable, d is disturbance input, and Gd is disturbance transfer function.

1.3 TWO-DEGREE-OF- FREEDOM INTERNAL MODEL CONTROL (2DOF-IMC)

Figure 1.2 shows the controller for set point (Gc_1) and the controller for disturbance rejection (Gc_2) in a 2DOF-IMC structure. The set point controller is in an open loop form and the disturbance rejection controller is in a feedback structure. The parameter of set point controller is designed as 1DOF-IMC controller, while the disturbance rejection controller is designed such that the disturbance can be rejected as soon as possible.

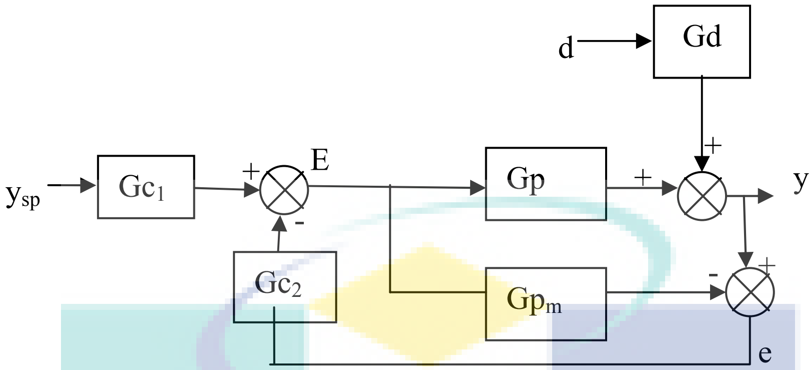


Figure 1.2 Structure of standard 2DOF-IMC

These tuning parameters can be easily obtained in the case of no error in the model. However, the setting of parameter becomes a complicated matter if there is an uncertainty model. On the other hand, the models developed will always contain inaccuracies or contain uncertainty.

The model uncertainty comes from several sources as follows (Laughlin et al, 1986);

(i) The variation of real parameters affecting plant operation.
(ii) The inherent non-linearity of the processes.
(iii) The experimental identification of the process.
(iv) The mathematical model development.

1.4 PROBLEM STATEMENTS

As mentioned in the previous section the tuning parameters in the case of model uncertainty is difficult to obtain. Many researchers have tried at different ways in tuning of 1DOF-IMC based on model uncertainty (Brosilow and Joseph, 2001; Laughlin et al., 1986; Liu et al., 1998; Morari and Zafiriou, 1989). Several works concentrating on the 2DOF-IMC tuning based on model uncertainty has done by Brosilow and Joseph (2001), Morari and Zafiriou (1989) and Stryczek et al. (2000). One of the difficulties of Morari and Zafiriou's method is the use of weighting transfer function in the formulation of robust performance. Stryczek (1996) has introduced Mp-tuning method to facilitate the completion of tuning that does not involve the weighting transfer function. This method is easily applied in obtaining the parameter of 1DOF-IMC based on model uncertainty. Unfortunately, for 2DOF-IMC structure, the Mp-tuning method uses partial sensitivity function that involved disturbance transfer function (Stryczek et al., 2000). Disturbance is very difficult to be modeled, because disturbance can come from more than one sources. Besides, the use of partial sensitivity function is restricted to overdamped system (Brosilow and Joseph, 2001). As a consequence, tuning of 2DOF-IMC using Mp-tuning method has its limitation. Recent research on the structure and tuning of 2DOF-IMC is very limited. Kaya (2004b) has developed a 2DOF-IMC structure and how to design the controller based on the gain and phase margins. He used IMC algorithm for controller tuning, however PD (Proportional Derivative) was used for this structure. It was because the structure and the tuning were only tested on integrating process. Meanwhile, the attention of recent researchers is the application of IMC on specific cases rather than on IMC tuning, for example unstable and integrating process (Chia and Lefkowitz, 2010; Liu and Gao, 2011; Tan, 2010; Tan et al., 2003; Wang and Watanabe, 2007), nonlinear process (Cheng and Chiu, 2007; Ganeshreddy Kalmukale et al., 2005; Toivonen et al., 2003). Therefore, study on the structure and tuning of 2DOF-IMC for general purpose (stable process) is needed to develop a tuning method which simplifies the existing tuning of the 2DOF-IMC under model uncertainty.

1.5 OBJECTIVES AND SCOPE OF THE RESEARCH

The main objectives of the research are stated as follows:

1. To develop and analyze the 2DOF-IMC based on feedback control structure for both set point and disturbance rejection controllers.
2. To develop tuning method for 2DOF-IMC to meet robust performance criteria.
3. To implement and validate the performance and tuning method of 2DOF-IMC.

The scope of this research covers the followings:

1. Theoretical development of the structure of 2DOF-IMC

2. Theoretical review of the maximum peak and gain margin for 2DOF-IMC tuning.
3. Determine the optimal constants that involved in the tuning of 2DOF-IMC.
4. Simulation of several process characteristics that employ the structure and the tuning method of 2DOF-IMC.
5. Application of the proposed method to experimental study in AFPT (air flow pressure and temperature control system) pilot plant made by Syntec Sdn Bhd. The plant is installed in laboratory of Chemical and Natural Recourses Engineering University Malaysia Pahang. The experimental process is modeled as FOPDT.

1.6 METHODOLOGY OF THE RESEARCH

The objectives of the research can be realized by creating a new structure of 2DOF-IMC into feedback control structure. By using feedback control structure, the principle of robust performance that is usually used in conventional control such as maximum peak (Mp) or resonant peak and gain margin (GM) can be applied.

Resonant peak (Mp) and its relationship between time responses of IMC structure has been studied by (Brosilow and Joseph, 2001) using Mp-Tuning (maximum peak) method. The maximum peak is the maximum of magnitude of frequency response of complementary sensitivity function set as 1.05. This value corresponds to about 10% overshoot of time response. With this method the parameters of the set point controller on the model uncertainty can easily be determined.

The difficulties in tuning of disturbance rejection controller can be solved by the principle of Gain Margin. Gain margin is a criterion that often used to measure the stability of a control system (Kuo, 1995). In the Nyquist plot, gain margin is the frequency response of open loop transfer function on the real and imaginary axis (Seborg et al., 2004). Open loop transfer function of proposed feedback 2DOF-IMC can be derived easily. The disturbance rejection controller parameters can be determined using this method after the set point controller parameter is calculated.

There are three specifications in the Mp-GM tuning that needs to be specified i.e; Mp, λ_2/λ_1 and GM. The best Mp value is determined where the overshot of the worst case should not exceed than 10%. The value of the λ_2/λ_1 and GM is determined from the closed loop response, where the corresponding minimum average of ISE (Integral Square Error) value in the worst case, nominal case and slowest case will be selected as tuning parameter. The Specifications above are selected with FOPDT simulation process with $\theta/\tau = 1$, $\theta/\tau > 1$ and $\theta/\tau < 1$.

The proposed feedback 2DOF-IMC structure and proposed Mp-GM tuning method are evaluated both in simulation and experimental. For simulation, this work studies;

(i) FOPDT (first order plus dead time) transfer function. It is because; typically chemical process can be approximated by FOPDT form. Three characteristics of FOPDT are analyzed i.e FOPDT with θ/τ (ratio between time delay and time constant) equal to 1, less than 1 and more than 1.

(ii) Higher order process i.e SOPDT (second order plus dead time) with underdamped and third order with non-minimum phase system.

The proposed structure and tuning method is also evaluated in nonlinear process of AFPT (air flow pressure temperature) control system pilot plant. The detail of AFPT pilot plant is presented in experimental study (Chapter 4).

Closed-loop response of the proposed feedback 2DOF-IMC with Mp-GM tuning is compared with the standard 2DOF-IMC with IMCTUNE and Kaya 2DOF-IMC with Mp-GM tuning. However, when IMCTUNE could not calculate the controller parameters then standard 1DOF-IMC with IMCTUNE is performed. If standard 1DOF-IMC with IMCTUNE still could not calculate the parameters then 1DOF-IMC with Mp-GM is applied.

1.7 CONTRIBUTIONS OF THE RESEARCH

The main research contributions from this study are as follows:

1. New 2DOF-IMC structure based on feedback/feedforward control structure was proposed. It is designed and simulated for open loop stable process which commonly representing the chemical process system.
2. New robust and simple method to tune parameters of 2DOF-IMC was employed using Mp-GM (Maximum peak and Gain Margin) criteria.
3. An air heater control system has been developed in laboratory for experimental study in order to validate the above finding.

1.8 STRUCTURE OF THE THESIS

Chapter 2 reviews the related literatures about the weaknesses, advantages, design and tuning of 1DOF-IMC controller structure. The design and tuning of 2DOF-IMC under model uncertainty are reviewed and the chemical process uncertainty is described.

Chapter 3 discusses the proposed Mp-GM tuning for 2DOF-IMC. The proposed tuning method is derived from proposed design of 2DOF-IMC based on feedback/feedforward structure control system (feedback 2DOF-IMC). The method can then be implemented to a standard 2DOF-IMC structure. The results are compared with some existing tuning method of 2DOF-IMC. The Mp-GM tuning is applied to several FOPDT process from small to long time delay. There are three specifications that affect to closed loop time response using Mp-GM tuning i.e; maximum peak (Mp), ratio filter time constant of set point and disturbance rejection controller (λ_1/λ_2), and gain margin's values. The specifications are determined by simulating of FOPDT model. The effects of simplification model are described with examples by using simulation of difficult higher order process such as underdamped and nonminimum phase system. The closed loop responses of proposed structure 2DOF-IMC and Mp-GM method are compared to standard 2DOF-IMC with IMCTUNE and Kaya 2DOF-IMC with Mp-GM.

Chapter 4 describes the implementation of feedback 2DOF-IMC and Mp-GM tuning method to the air heater system in AFPT pilot plant. The AFPT pilot plant is a nonlinear plant particularly in the low to medium temperature range. It has nearly linear model at high temperature range. Therefore, the effects of nominal model selection in different range of operating conditions are presented in this chapter.

Finally, chapter 5 concludes the research study. Summarizes the results obtained from previous chapters. The recommendations for future work are outlined. The recommendations are given based on assessment of the significant findings, limitations, conclusions obtained and difficulties encountered in this study.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The IMC was developed by Morari and coworkers (Garcia and Morari, 1982; Morari and Zafiriou, 1989; Rivera et al., 1986). Internal Model Control (IMC) is a type of model based control that has applied in the process industry (Brosilow and Joseph, 2001). IMC uses model explicitly in controller algorithm. This controller is actually a generation of Smith predictor (SP) controller which was designed for a process with long time delay (Smith O, 1959). The standard PID controller can not handle them optimally because (Kaya, 2003; Normey-Rico and Camacho, 2007; Romagnoli and Palazoglu, 2005);

- The disturbances are not detected immediately (detected until certain time with delay).
- The control actions based on the delay is not in accordance with the purposes of information.
- The control action took some time to determine its effects on the process.

Smith (1959) proposed delay compensator that aims to eliminate the delay element of the feedback loop. This was done by including delay model in the controller algorithm (Romagnoli and Palazoglu, 2005). SP controller has some weaknesses. If the primary controller is not properly tuned, may be unstable when a small mismatch in the dead time is considered (Palmor, 1980) and the disturbance rejection response can not be faster than the open loop (Normey-Rico and Camacho, 2007). These weaknesses could be overcome by IMC. SP can be considered as part of IMC. Modified version of SP controller such as Filtered-SP (FSP), Filtered Predictive Proportional Integral (FPPI), Two Degree of Freedom-Dead Time compensator (2DOF-DTC) and Dead Time Observer disturbance compensator (DO-DTC) can be represented by the 2DOF- IMC (Normey-Rico and Camacho, 2007). The advantages and weaknesses of IMC are further discussed in section 2.2.

2.2 STRUCTURE OF STANDARD INTERNAL MODEL CONTROL

2.2.1 Principle of IMC controller

The structure of a standard IMC controller illustrated in Figure 1.1 can be simplified into classical control feedback (Figure 2.1) (Chia and Lefkowitz, 2010).

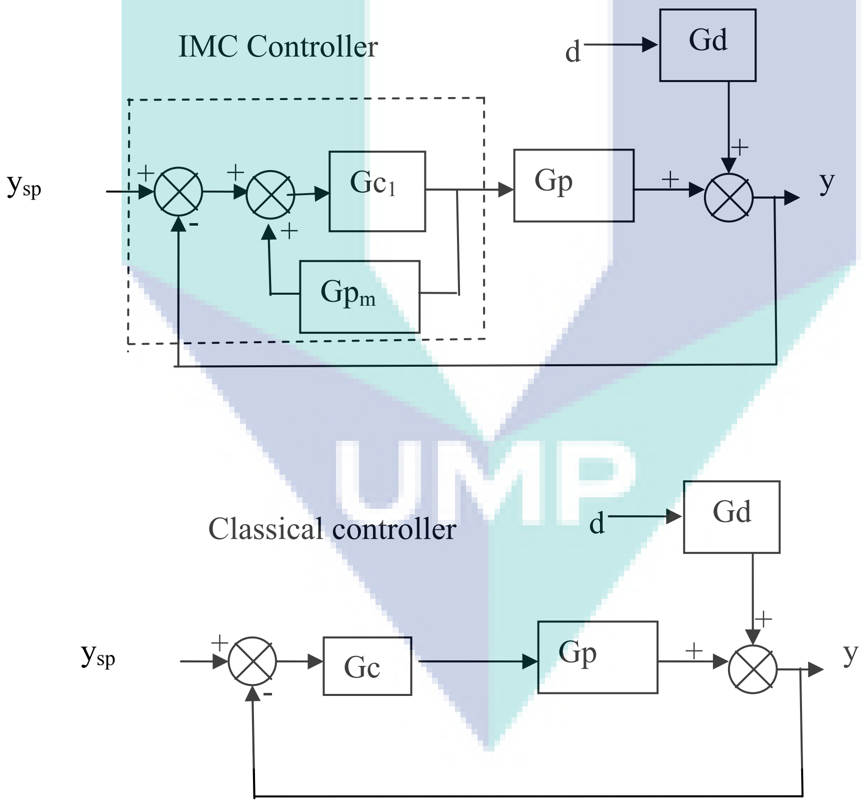


Figure 2.1 Simplified IMC controller to classical feedback control

From Figure 2.1 the classical controller (Gc) can be derived as follow

$$Gc = \frac{Gc_1}{1 - Gc_1.Gp_m} \quad (2.1)$$

It shows that the classical controller can be derived from IMC controller structure, or the IMC controller can be analogous to the classical controller Gc. However, it is very easy to design Gc_1 than to design Gc. this is because some properties following IMC structure (Economou and Morari, 1986):

Property 1: Assuming that the process model is the same as the plant then the closed loop stability can be guaranteed if the plant and the controller is stable.

Property 2: Assuming that the controller $Gc_1 = 1 / Gp_m$ generate a stable IMC structure, then a perfect set point controller can be achieved.

Property 3: For all Gc_1 with $Gc_1 (0) = 1 / Gp_m (0)$ produces a stable IMC structure, then an offset free control can be achieved.

The first property can be seen from equation 2.1 in which the stability of the closed loop response is only affected by the stability of the plant and controller. While the second character can be derived as follows. For the SISO system, the IMC controller can be derived from Eq. (2.2) to (2.4) (Morari and Zafiriou, 1989).

$$y_{sp} - e = E \quad (2.2)$$

$$e = y - Gp_m Gc_1 E \quad (2.3)$$

Then,

$$y_{sp} - y = E - Gp_m Gc_1 E \quad (2.4)$$

$$E^* = (1 - Gp_m Gc_1) E \quad (2.5)$$

Where e is error between measurement and model, E is error between set point and e (see Figure 1.1), Gp is transfer function of the process, Gp_m is transfer function of the model and Gc_1 is transfer function of the controller. The other abbreviations that are used in Figure 2.1 and in the next figures are; Gd is transfer function of disturbance, d input of the disturbance, y_{sp} is setpoint input and y is a process variable (measurement / controlled variable).

In the nominal case $Gp = Gp_m$. Gc_1 is designed to yield minimum value of E*;

$$\min_{Gc_1} \|E^*\|_2 = \min_{Gc_1} \|(1 - Gp_m Gc_1)E\|_2 \tag{2.6}$$

In order to get minimal value of E*,

$$Gc_1 = 1/Gp_m. \tag{2.7}$$

Eq. (2.6) states that optimal controller can be achieved if $Gc_1 = 1/Gp_m$ (Eq.2.7) or the error will be zero. It means that the process variable is always the same with set point. However, $Gc = 1/Gp_m$ does not apply in some cases such as processes which has right half plane zero and time delay. Fortunately, It can be done by following two steps as below (Rivera et al., 1986):

Step 1. Factor the model,

$$Gp_m = Gp_m^+ Gp_m^- \tag{2.8}$$

The Gp_m^+ consists of all of the time delay and the right half plane (RHP) zeros. It has the general form of

$$Gp_m^+ = e^{-\theta s} \prod_i (-\beta_i s + 1) \quad \mathrm{Re}(\beta_i) > 0 \tag{2.9}$$

Where θ is time delay of the process, β_i is zeros constants of the process transfer function.

Step 2. Make the IMC controller with,

$$Gc_1 = \frac{1}{Gp_m^-} f \tag{2.10}$$

Where, f is the low pass filter which must be chosen so Gc_1 is proper. The simplest form of filter is

$$f(s) = \frac{1}{(\lambda s+1)^r} \tag{2.11}$$

Where, r is a scalar to make Gc_1 proper.

The value of λ affects the speed of response. The smaller is the value of λ, the faster is the response (more sensitive controller). In order to maintain stability of the system, for FOPDT model, Rivera et al.(1986) suggested that $\lambda = 0.8\ \theta$, Chien and Fruehauf (1990) proposed $\tau > \lambda > \theta$ and Skogestad (2003) recommended $\lambda = \theta$.

2.2.2 Advantages of IMC controller

The relationship between the response variable (y) and set point (y_{sp}) and disturbance (d) can be expressed by Eq. (2.12)

$$y = \frac{GpGc_1}{1+Gc_1(Gp-Gp_m)} y_{sp} + \frac{1-Gp_mGc_1}{1+Gc_1(Gp-Gp_m)} d \tag{2.12}$$

Eq. (2.12) shows that, if there is no error in the model ($Gp = Gp_m$), the IMC structure is open-loop system for set point tracking. In this situation, the speed of time response is function of filter time constant. The smaller in the filter time constant the faster time response will be achieved. IMC structure is internally stable, if both of the model and controller are stable. A control system is internally stable if bounded signals is injected at any point of the control system generates bounded responses at any other point. The internally stable is more comprehensive than the usual stability concept, where the stability of the system is checked by examining the root of characteristic equation (Morari and Zafiriou, 1989).

IMC can be analogous to PID algorithms, and then parameters of PID controller can be determined using IMC tuning. Many tuning method have been proposed for PID controller based on IMC structure (IMC-PID). More detail about IMC-PID tuning will be presented in section 2.2.4.

Another advantage of the IMC is it can be designed for disturbance rejection with 2DOF-IMC. The structure of standard 2DOF-IMC is depicted in Figure 1.2. With 2DOF-IMC, the disturbance rejection response can be accelerated. The effect of a 2DOF-IMC structure is to include one lead lag transfer function to the feedback loop. The parameters of the lead lag transfer on 2DOF-IMC can be derived easily if there is no error in the model (Horn et al., 1996). More details will be discussed in Section 2.2.5.

Improvement of filter design in IMC for disturbance rejection can be done adding one more filter in Gc_1 which can generally be written as follows (Horn et al., 1996);

$$f(s) = \frac{\beta s + 1}{(\lambda s + 1)^r} \tag{2.13}$$

For FOPDT model, r = 2, the value of β is selected to cancel the open lop pole at s =-1/τ that causes the sluggish response to load disturbances.

$$\beta = \frac{\lambda 2\theta + 2\tau\left(\theta(\tau - \lambda) + \lambda(2\tau - \lambda)\right)}{\tau(\theta + 2\tau)} \tag{2.14}$$

2.2.3 Limitations of 1DOF-IMC

When the model is not perfect, the closed-loop response of IMC control structure is much more complicated and can even be unstable if the filter is not detuned sufficiently (Brosilow and Joseph, 2001). Since, almost all chemical processes are non linear, then the linearization of the plant model makes the model no longer perfect. Other factor that makes the model inaccurate is different operating conditions, for example, change in flow rate, temperature and or pressure. Therefore, the model uncertainty needs to be considered in designing the IMC controller. Section 2.3 describes model uncertainty in more detail. While tuning method for robust performance criteria are described in Section 2.4.

IMC has weakness in an unstable process. Internally stable is only valid for a stable process. IMC structure can not be implemented on unstable processes (Morari and Zafiriou, 1989; Tan et al., 2003), because the input in a point (disturbance) will cause an infinite response if the process is unstable. The IMC structure may be able to be used for unstable process if the following conditions are met:

a. Gc_1 is stable
b. $GpGc_1$ is stable
c. $(1-GpGc_1)Gp$ is stable

However the above requirements are not easy to achieve. Tan et al. (2003) has proposed a modification to IMC structure for unstable processes. However the structure and tuning of the modified IMC was complicated. Several researchers investigated of implementation IMC for unstable process are Chia and Lefkowitz (2010), Liu and Gao, (2011), Tan (2010), Tan et al. (2003) and Wang and Watanabe (2007).

Another weakness of IMC is it may fail on handling disturbance rejection. Since the feedback signal of IMC structure is the difference between plant output with disturbance and plant model, the disturbance therefore should be anticipated by the controller. However, IMC design is only to the set point problem, and in many cases the disturbance rejection response is not as expected. Therefore, IMC modification is needed to cater the disturbance rejection problem. Some methods have been proposed to improve disturbance rejection in IMC structure. These methods include specifying a difference IMC filter design procedure (Horn et al., 1996) and using 2DOF (two-degree-of-freedom) IMC (Kaya, 2004b; Morari and Zafiriou, 1989). Horn et al. (1996) added a lead transfer function (numerator) in the controller of 1DOF-IMC structure. The extra lead constant was selected to cancel an open-loop pole at $s = 1/\tau$ that causes the sluggish response to load disturbances. However, it made excessive overshot in the set point response (Shamsuzzoha and Lee, 2007). 2DOF-IMC was designed to improve both disturbance and set point performance, since the set-point and disturbance controller can be set 'independently'.

2.2.4 2DOF-IMC

The 2DOF-IMC structure can be seen in Figure 1.2. The figure shows that it only required a forward path if no error in the model and no disturbances. Since there are no perfect models for the real plant, the feedback path is always required. Therefore, it is clear that 2DOF-IMC is designed for disturbance rejection.

The closed loop response of 2DOF-IMC is expressed as follow

$$y = \frac{(GpGc_1)y_{sp} + (1 - Gc_2Gp_m)d}{1 + Gc_2(Gp - Gp_m)} \tag{2.15}$$

If $Gp = Gp_m$ then

$$e = (1 - GpGc_2)d - (1 - GpGc_1)y_{sp} \tag{2.16}$$

From equation (2.16), it can be concluded that Gc_2 is designed to compensate the disturbance d. In order to reject the disturbance then $Gc_2 = 1/Gp_m$ or it is equal to the design of Gc_1. However, if $Gc_2 = Gc_1$ then the disturabnce can not be rejected optimally. Therefore, design and tuning 2DOF-IMC needs to be taken attention by the researcher. In detail, tuning standard 2DOF-IMC presented in section 2.4.2.

2.2.5 1DOF and 2DOF IMC for PID controller design

One of advantage of IMC is that it can be analogous with PID controller (see Figure 2.1). The IMC structure is simplified to conventional feedback structure and the algorithm then analogous to PID algorithm. There are many PID tuning method based on the principles of IMC (Arbogast et al., 2008; Chen and Seborg, 2002; Chien et al., 2002; Fruehauf et al., 1994; Kaya, 2004a; Lee et al., 2006; Panda et al., 2004; Rivera et al., 1986; Skogestad, 2003; Vilanova, 2008; Wang et al., 2001). Broadly speaking, tuning of IMC-PID can be done with analogous IMC in PID structure as

$$Gc = \frac{Gc_1}{1 - Gc_1 Gp_m} \tag{2.17}$$

This Gc form can then be converted into PI/PID controller. For first order plus dead time (FOPDT) model, $Gp = \frac{ke^{-\theta s}}{\tau s + 1}$, the classic controller Gc can be expressed as (Chen and Seborg, 2002).

$$Gc = \frac{\tau s + 1}{k(\lambda + \theta)s} \tag{2.18}$$

Where τ is process time constant, λ filter time constant and k is gain process.
Then the PI controller setting are

$$Kc = \frac{\tau}{k(\lambda + \theta)} \tag{2.19}$$

$$\text{and } \tau_I = \tau \tag{2.20}$$

Where Kc is proportional gain and τ_I is integral gain.

For second order plus dead time (SOPDT), $Gp = \frac{ke^{-\theta s}}{(\tau_1 s + 1)(\tau_2 s + 1)}$, give PID controller with parameter are

$$Kc = \frac{1}{k}\frac{\tau_1 + \tau_2}{\theta + \lambda} \tag{2.21}$$

$$\tau_I = \tau_1 + \tau_2 \tag{2.22}$$

$$\tau_D = \frac{\tau_1 \tau_2}{\tau_1 + \tau_2} \tag{2.23}$$

Where τ_D is derivative gain

An IMC-PID tuning for any processes are summarized by Rivera et al. (1986) and Skogestad (2003). Various types of PID controller for FOPDT and SOPDT in various types of process are reviewed by Panda et al. (2004). Tuning of 2DOF-PID based on 2DOF-IMC for integrator and dead time process is proposed by Zhang et al.(2006). While IMC-PID tuning for disturbance rejection for time delay process with various process characteristics is proposed by Shamsuzzoha and Lee (2007).

2.3 CHEMICAL PROCESS UNCERTAINTY

Inaccuracies between model and real plant are called model uncertainty. Model uncertainty comes from several sources as follows (Laughlin et al., 1986);

(i) The variation of real parameters affecting to plant operation.
(ii) The inherent non-linearity of the processes.
(iii) The experimental identification of the process.
(iv) The mathematical model development.

Most importantly, the real process is non linear. If the process model obtained via linearization, then this is accurate only in the neighborhood of the currently selected linear condition. In some cases the process may be accurately represented by linear models, but different operating conditions will cause changes in the parameters of linear models. For example, increasing the flow rate will result in dead time and time constant will be smaller (Morari and Zafiriou, 1989).

Various sources of uncertainty can be classified in two categories namely parametric (real) uncertainty and dynamic (frequency-dependent) uncertainty. Parametric uncertainty, here the model structure is known but some parameters are uncertain. It is quantified by assuming that each uncertain parameter is bounded within some regions. Dynamic uncertainty, here the dynamic model error because miss understanding of the physical process (Skogestad and Postlethwaite, 2005).

Parametric uncertainty is usually referred to as structured uncertainty, because the model is made in the form of structured uncertainty. In the plant, it is described by a set of unknown parameters that lie within some bound. A set Π representing real parameter variations in the linearization process around different steady state for FOPDT model is given by (Brosilow and Joseph, 2001; Laiseca, 1994):

$$\Pi = \left\{ Gp(s) \middle| Gp(s) = \frac{ke^{-\theta s}}{\tau s + 1} \right\} \tag{2.24}$$

Uncertainties of all three parameters are;

$k\min \le k \le k\max$
$\tau\min \le \tau \le \tau\max$
$\theta\min \le \theta \le \theta\max$

Dynamic uncertainty can be described with norm bound complex gain and phase perturbations or uncertainty bound (Laiseca, 1994). The norm-bound uncertainty includes additive and multiplicative uncertainty (see Figure 2.2) (Morari and Zafiriou, 1989; Skogestad and Postlethwaite, 2005). Mathematically additive uncertainty can be written as;

$$Gp = Gp_m + la \tag{2.25}$$

Where *l*a is additive uncertainty.

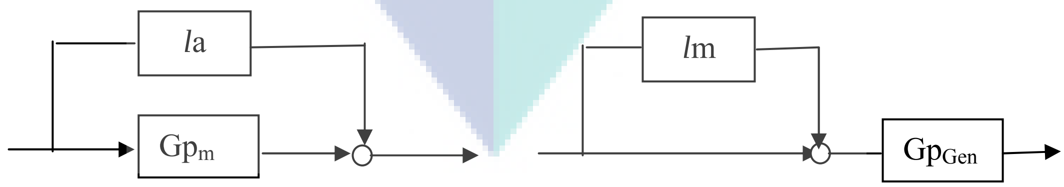


Figure 2.2 Additive (*l*a) dan multiplicative (*l*m) uncertainty.

And multiplicative uncertainty can be written as;

$$Gp = Gp_m(1 + lm) \tag{2.26}$$

Where *l*m is multiplicative uncertainty.

Skogestad and Postlethwaite (2005), summarized that if all sources of uncertainty included in the multiplication then the general form of model uncertainty is;

$$\Pi : Gp(s) = G(s)(1 + w_I(s)\Delta_I(s)); \quad |\Delta_I(j\omega)| \le 1 \forall \omega \tag{2.27}$$

Where, Δ_I is any stable transfer function which at each frequency is less than or equal to 1 magnitude. Subscript I indicate input, nevertheless for a single input single output (SISO) system does not matter whether the perturbation in input or output of the plant. ω is frequency. Some examples of transfer function of Δ_I which qualify with H_∞ norm less than 1, are

$$\frac{1}{\tau s + 1}, \frac{1}{(5s+1)^3}, \frac{0.1}{s^2 + 0.1s + 1} \tag{2.28}$$

Whereas, w_I is weighting transfer function that can be derived from the multiplication uncertainty that is often expressed by:

$$lm(\omega) = \max_{Gp \in \Pi} \left| \frac{Gp(j\omega) - Gpm(j\omega)}{Gpm(j\omega)} \right| \tag{2.29}$$

Where, jω means that the transfer function is in frequency domain.
with rational weight

$$|w_I(j\omega)| \ge lm(\omega), \forall \omega \tag{2.30}$$

An example of weighting transfer function that is eligible for inequalities above for the gain and time delay uncertainty is as follow

$$w_I(s) = \frac{\left(1+\frac{r_k}{2}\right)\theta_{max} s + r_k}{\frac{\theta_{max}}{2} s + 1} \tag{2.31}$$

Where, $r_k = \frac{(k_{max} - k_{min})/2}{\bar{k}}, \ \bar{k} = \frac{k_{min} + k_{max}}{2}$ (2.32)

In general, the weighting function form of modeling dynamic uncertainty can be expressed as

$$w_I(s) = \frac{\tau s + r_o}{(\tau / r_\infty)s + 1} \tag{2.33}$$

Where, r_o is relative uncertainty at steady state, $1/\tau$ is approximate the frequency at which uncertainty reaches 100%, and r_∞ is the magnitude of the weight at high frequency. However, (Skogestad and Postlethwaite, 2005) stated that it is necessary to revise the formulas because the formulas are not always qualified for all frequency.

2.4 TUNING OF IMC UNDER MODEL UNCERTAINTY

2.4.1 Tuning of 1DOF-IMC

From section 2.2.5, the choice of smaller λ gives faster process response. With the previous guidelines for the λ, then stability would be no problem, but it is not necessarily optimal for all cases. Consequently, tuning parameter based on robust performance should be applied.

Laughlin et al., (1986) proposed mapping uncertainty regions for SISO robust controller design. The method then was applied to IMC structure. The mapping uncertainty procedure consists of several steps:

1. Locate process uncertainty region $\pi(\omega)$. The process uncertainty can be located with
   (i). Locating polynomial rectangles
   (ii). Inverting the denominator rectangle
   (iii). Locating the rational uncertainty region
   (iv). Multiplying by the time-delay uncertainty
2. Once process uncertainty regions $\pi(\omega)$ have been located, then controller design can begin. The procedure involves the step
   (i). Specifying performance criteria
   (ii). Designing a controller for nominal plant
   (iii). Selecting the IMC filter
   (iv). Determining the controller $Gc_1(j\omega)$
   (v). Mapping the regions $\pi(w)$ $Gc_1(j\omega)$
   (vi). Testing performance robustness
   (vii). Testing stability robustness
   (viii). Testing performance robustness

Uncertainty region at a frequency value usually can be described as in Figure 2.3 and expanded for a range of frequency the mapping region illustrated in Figure 2.4. While Figure 2.5 shows the mapping region after robust performance is achieved.

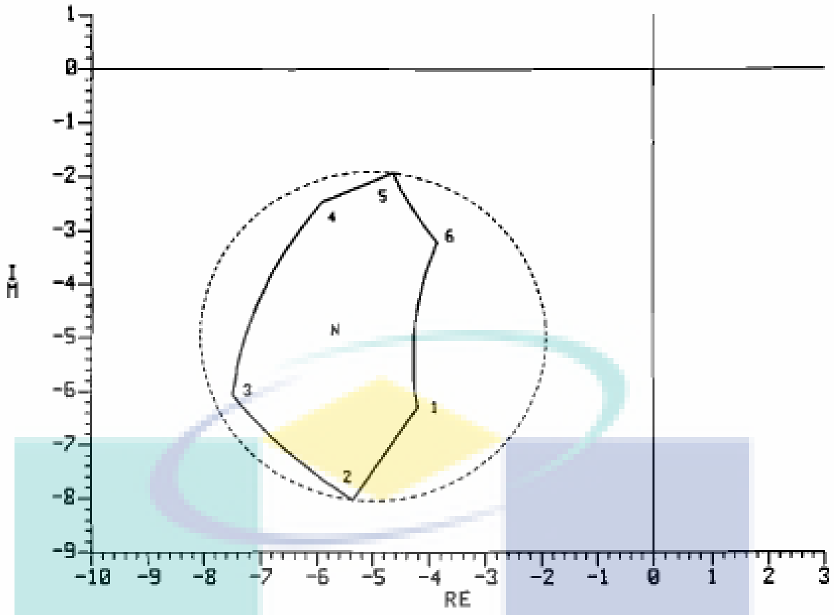


Figure 2.3 The uncertainty region π(ω) evaluated at a ω value. The smallest circle containing π(ω) could be used as a norm-bounded approximation to the actual uncertainty.(Laughlin et al., 1986).

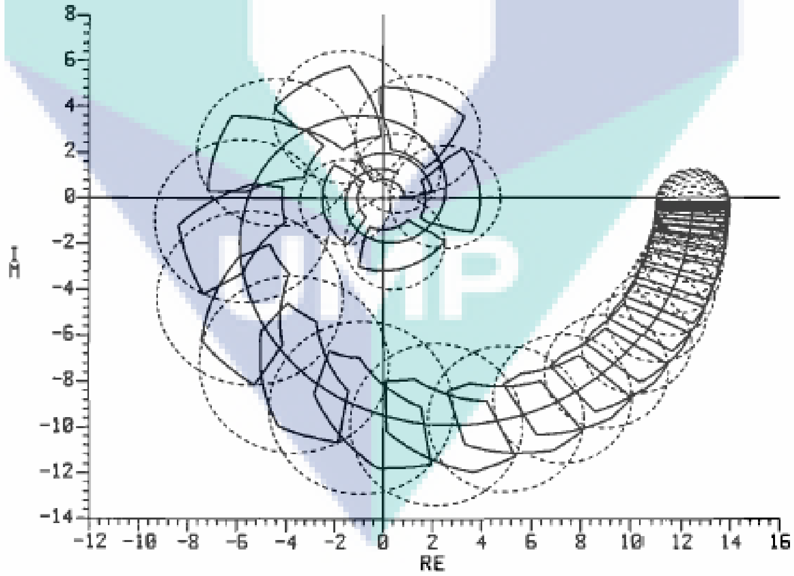


Figure 2.4 Uncertainty region π(ω) for 30 frequencies range 0.001-1. The nominal model passes through the center of each region.(Laughlin et al., 1986).

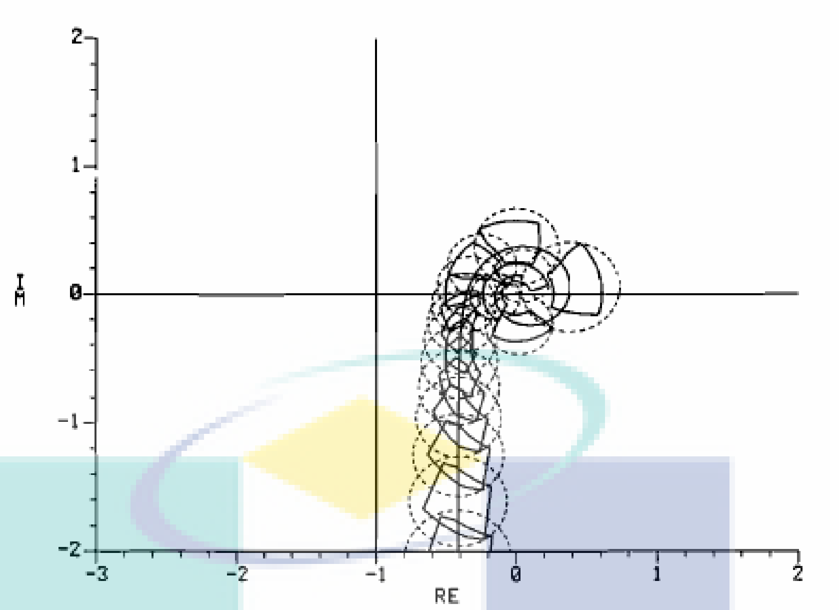


Figure 2.5 Uncertainty region $\pi(\omega)\ Gc_1(j\omega)$ on Nyquist plane. Robust stability requires that none of the regions contain the critical (-1,j0).(Laughlin et al., 1986).

The mapping region method is very complicated for the computational. The method for checking robustness suffers either from conservatism or from exponential increase in computational complexity with the size of problem.

Morari and Zafiriou (1989) summarized the IMC design procedure as follows;

a. Required information:

1. Process model
2. Type of input (set point and disturbance) affecting the process output.
3. Performance specifications:
    - closed loop system (no offset for step)
    - maximum allowed peak weigh (w^{-1}) of the sensitivity function S (typically $0.3 < w < 0.9$)
4. Uncertainty information lm (w)

    Family of plant considered for robust design

$$\Pi = \left\{ Gp : \left| \frac{Gp(iw) - Gp_m(iw)}{Gp_m(iw)} \right| \le lm(w) \right\} \tag{2.34}$$

b. Design procedure for robust stability and performance:

1. Robust stability:

Check if

$$\left|Gp_m Gc_1\, lm\right| < 1 \text{ for } w = 0 \tag{2.35}$$

This condition is necessary and sufficient for filter time constant λ >0 to exist for which the system is robustly stable.

2. Robust performance:

Increase λ just enough to meet the condition

$$\left|Tlm\right| + \left|Sw\right| < 1 \quad \forall w \tag{2.36}$$

$$\left|Gp_m Gc1lm\right| + \left|(1 - Gp_m Gc1)w\right| < 1 \quad \forall w \tag{2.37}$$

i.e. choose λ to make the above equation an equality for some specific of w.
Where S is sensitivity function and T is complementary sensitivity function. For IMC controller S and T are response y to d and response y to r respectively, expressed as:

$$S = \frac{y}{d} = \frac{1 - Gp_m Gc}{1 + Gc(Gp - Gp_m)} \tag{2.38}$$

And $$T = \frac{y}{r} = \frac{GpGc}{1 + Gc(Gp - Gp_m)} \tag{2.39}$$

While w is weighted function and *l*m is a bound of multiplicative uncertainty. To design the filter for robust performance is difficult. It is because, there might not exist any filter to satisfy Eq. (2.37) for the particular choices of weights w and *lm* (Morari and Zafiriou, 1989).

Brosilow and Joseph (2001) used principal of resonant peak of complementary sensitivity function also called as maximum peak (Mp-tuning or Mp-synthesis). In Mp-synthesis, robust performance specified using maximum peak (Mp) of the closed loop transfer function such as sensitivity function (S) and complementary sensitivity function (T). The Mp-synthesis can be summarized as:

Select the filter time constant, λ for the IMC controller Gc_1 so that the magnitude of the complementary sensitivity function T(jω) is equal to or less than a specified value Mp for all process Gp(s) in a predefined set Π. For at least one process in P the magnitude of T(jω) must equal the specified Mp at one or more frequencies. That is

$$|T(jw,\lambda)| \le Mp \quad \forall P \in \Pi, \forall w \tag{2.40}$$

and

$$|T(jw,\lambda)| = Mp \text{ for some } Gp \in \Pi \text{ and} \tag{2.41}$$

some frequencies, ω_c

Mp-tuning procedure to find filter time constant is summarized as

1. A process model
2. An uncertainty description in term of upper-bound on process parameter
3. An initial value for the filter time constant. The default is the value of filter time constant that satisfies the maximum noise amplification specification.
4. An Mp specification and tolerance. The default are Mp = 1.05 and tolerance = $\pm$ 0.005.
5. The maximum allowable high frequency controller noise amplification (i.e. $(|Gc1(\infty,\lambda)/Gc1(0,1)|)$. The default is 20.
6. Upper and lower bond of the frequency range for the optimization. The default are:

   Low frequency: reciprocal of 10 times the largest time constant or dead time

   High frequency: 1000 times the low frequency

   Number of point and scale for plotting: 30, logarithmic

7. Upper and lower bound of the frequency range for plotting. The default are
   Low frequency: one-tenth the break frequency
   High frequency: 100 times the break frequency
   Number of point and scale for plotting: 30, logarithmic

Liu et al. (1998) proposed IMC tuning filter by using combination of maximum peak (Mp) of T(jω) and integral square error (ISE). The ISE is determined by

$$J_{ISE} = \int_0^{\infty} \left(y(t) - r(t)\right)^2 dt \tag{2.42}$$

Based on the block diagram of controller system, the system error E(s) can be written as

$$E(s) = \frac{1}{1 + Gp(s)Gc(s)} Y(s) = \left(1 + Gpm_{+}(s) F(s)\right) Y(s) \tag{2.43}$$

$$= \left[1 - \frac{b_0 s^m + b_1 s^{m-1} + \ldots + b_m}{a_0 s^k + a_1 s^{k-1} + \ldots + a_k} \frac{1}{(\lambda s + 1)}\right] R(s) = \frac{N(s)}{D(s)}$$

$$= \frac{c_0 s^p + c_1 s^{p-1} + \ldots + c^{p-1} s + c_p}{d_0 s^{2p-2} + d_1 s^{2p-4} + \ldots + d_p}$$

The ISE will be obtain as

$$J_{ISE} = (-1)^{p-1} \frac{H_d}{2 c_0 H_p} = f(\lambda) \tag{2.44}$$

Where Hp is the Hurwitz determinant of D(s) with dimension of p x p, and Hd is a matrix obtained by replacing the first row Hp (c_1, c_2, … 0, …) with (d_0, d_1, …, d_{p-1}). Because J_{ISE} is a function of parameter λ, then the performance can be use for adjusting the parameter λ.

While the Mp of T (jω) is formulated as

$$Mp = \max_{w > w_0} |T(jw)| = f(\lambda) \tag{2.45}$$

In order to obtain the optimal λ, it is necessary to make combination between the two measures. That is

$$\min_{\lambda}(Mp + \gamma . J_{ISE}) \tag{2.46}$$

Where γ is a weighting function.

Chawankul et al. (2005) proposed integration of design and controller in IMC structure, which they use optimization to minimize operating costs and also capital cost. As for getting the output controller when there is a disturbance they used the following criteria;

$$|Gc1(j\varpi).Gd(j\varpi)| \left| \frac{1}{\sqrt{\tau^2 \varpi^2 + 1}} \right| < 1, \forall \varpi \tag{2.47}$$

One disadvantage of this method is to obtain optimal Gc_1 then we must have a disturbance transfer function.

Liu et al. (2010) proposed iterative learning for design IMC controller with uncertainty in time delay. In the iterative learning, in addition to Gc_1 controller design is also need for corrective value of set point and controller output. Figure 2.6 shows the block diagram of the proposed iterative learning on IMC controller.

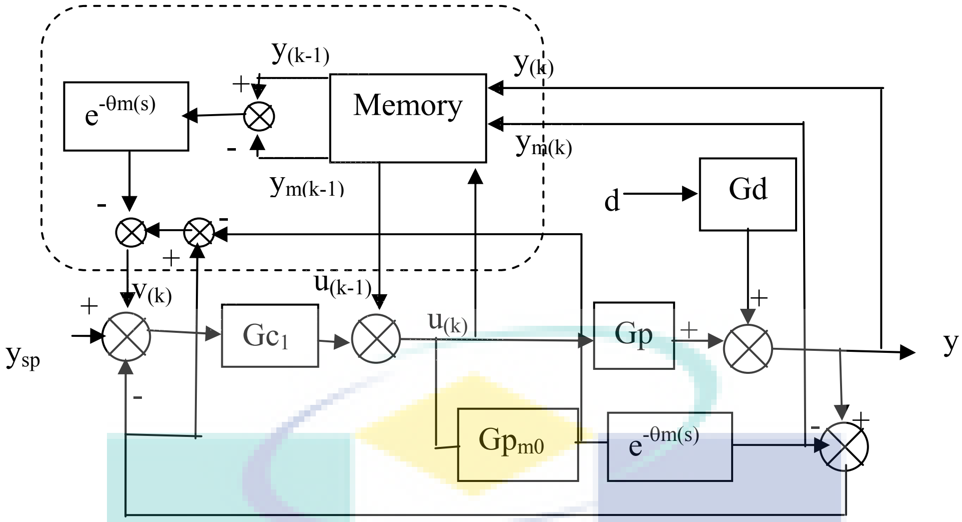


Figure 2.6 Iterative learning IMC controller by Liu et al. (2010)

From Figure 2.6 an iterative learning controller is done in block dashed line, the iterative learning controller (ILC) is added to the set point and output controller. If the transfer function model are stated in

$$Gp_m = Gp_{m0}.e^{-\theta m(s)} \text{ with } Gp_{m0} = \frac{k.N_+N_-}{D} \tag{2.48}$$

Where all zeros of D and N_- are located in the complex left-half-plane (LHP) and all zeros of N_+ are located in the right-half-plane (RHP).

Gc_1 can be stated as;

$$Gc_1 = \frac{A}{k.N_-N_+.(\lambda s+1)^{m-n}} \tag{2.49}$$

Where m is order of D and n is order of N_-. In ILC controller the Gc_1 will be G_{ILC} as equation (2.50) below;

$$G_{ILC} = \frac{kc.A}{k.N\_N_{+}.(\lambda s+1)^{m-n}} \tag{2.50}$$

Where kc and λ are designed such that the equation (2.51) below is satisfy.

$$\left|1+\frac{kcN_{+}(j\varpi)}{N_{+}(j\varpi)(\lambda(j\varpi)+1)^{m-n}}\right| > \left|1-\frac{kc.N_{+}(j\varpi)\Delta m(j\varpi)}{N_{+}(j\varpi)(\lambda(j\varpi)+1)^{m-n}}\right|, \forall \varpi \le \varpi_b \tag{2.51}$$

From this equation shows that for design IMC controller is needed to find the value of kc and λ. Besides, it is needed to calculate the v (k) and u (k) using iterative learning. These make this method more complicated.

2.4.2 Tuning of 2DOF-IMC

Morari and Zafiriou (1989) summarized that the design problems for nominal performance are independent. If the H_∞ performance objective is chosen then Gc_1 and Gc_2 are designed to satisfy

$$\left\|(1-Gp_m Gc_1)w_r\right\|_\infty < 1 \tag{2.52}$$

$$\left\|(1-Gp_m Gc_2)w_d\right\|_\infty < 1 \tag{2.53}$$

Robust stability depends only on Gc_2

$$\left\|Gp_m Gc_2 l_m\right\|_\infty < 1 \tag{2.54}$$

The robust performance for disturbance rejection is

$$\left\|Sw_d\right\|_\infty < 1 \quad \forall Gp \in \Pi \tag{2.55}$$

Which equivalent to

$$|Sw_d| + |Tl_m| < 1 \quad \forall \omega \tag{2.56}$$

2DOF-IMC design for robust tracking performance specification is

$$\left| \left[1 - \frac{Gp_m Gc_1 (1 + l_m)}{1 + Gp_m Gc_2 l_m} \right] w_r \right| < 1 \quad \forall l_m \in \Lambda_m, \forall \varpi \tag{2.57}$$

Where the set $\Lambda m(i\varpi)$ is defined by

$$\Lambda_m(i\varpi) = \{ l_m(i\varpi) : |l_m(i\varpi)| < l_m(\varpi) \} \tag{2.58}$$

From above equations can be derived for the condition

$$|(1 - Gp_m Gc_1) w_r| + |Gp_m Gc_2 l_m| \left[1 + \left| 1 - \frac{Gc_1}{Gc_2} \right| w_r \right] < 1 \quad \forall \varpi \tag{2.59}$$

The first term expresses nominal performance. The second term is proportional to the multiplication uncertainty lm and to disturbance controller magnitude i.e the disturbance controller Gc_2 affects the robust setpoint tracking performance. Thus the design of Gc_2 and Gc_1 are not independent when the objective is robust performance.

Stryczek et al. (2000) stated that the simplest controller design for speeding up the response to disturbance is to choose Gc_2 as Gc_1, but to select λ_2 to be smaller than λ_1. The smaller filter time constant is feasible because the filtering action of the disturbance lag Gd(s) reduce the amplitude of the disturbance frequencies that enter the feedback loop. This reduces the magnitude of loop oscillations and allows the selection of a smaller filter time constant, thereby speeding up the disturbance rejection.

Stryczek et al. (2000) and Brosilow and Joseph (2001) stated that to tune the feedback loop of 2DOF-IMC for good disturbance rejection, it seems reasonable to focus on the disturbance to output transfer function, called the sensitivity, which is given by

$$S = \frac{y(s)}{d(s)} = \frac{(1 - Gp_m Gc_2)Gd}{(1 + Gc_2(Gp - Gp_m))} \qquad (2.60)$$

The controller tuning seeks to achieve a specified, frequency-dependent, upper bound on the magnitude of the sensitivity function. Unlike complementary sensitivity function, the maximum magnitude of the sensitivity function is often greater than 1, even when there is a perfect model. Maximum magnitude of sensitivity function is model dependent. Because it is not a simple matter to set bounds on the magnitude of the sensitivity function so as to achieve desirable time domain behavior, they introduced modification of sensitivity function also called partial sensitivity function. The partial sensitivity function is defined as

$$\text{Partial Sensitivity Function} \equiv \frac{Gp(s)Gc_2(s)Gd(s)/Gd(0)}{(1 + Gc_2(Gp(s) - Gp_m(s)))} \qquad (2.61)$$

The above definition is motivated by the first term of the sensitivity function $\frac{Gd(s)}{(1 + Gc_2(Gp(s) - Gp_m(s)))}$ is output response to the disturbance, as modified by the closed-loop. The second term, $\frac{Gp(s)Gc_2(s)Gd(s)}{(1 + Gc_2(Gp(s) - Gp_m(s)))}$ represent the response of the output to the control effort. This term is the negative of the model output response to a set point that is filtered by the disturbance lag Gd(s). If the model in numerator is replaced with Gp(s) and if the IMC controller is taken as Gc_2, then this term is the same as a complementary sensitivity function filtered by a lag. This observation suggests the possibility of applying the Mp-tuning to partial sensitivity function. The controller tuning is very dependent on its disturbance model. The zeros of Gc_2 controller, α, is (are) selected to makes zeros of (1- Gp_m Gc_2) cancels selected poles in Gd:

$$Gc_2 = Gc_1 . \frac{\sum_{i=0}^{n} \alpha_i s^i}{(\lambda_2 s + 1)^n} \qquad (2.62)$$

Where n is number of poles in Pd to be canceled by the zeros of (1- Gp_mGc_2). Mp-tuning software developed by Stryczek et al. (2002) is presented in Appendix C namely as IMCTUNE.

Tuning of the standard 2DOF-IMC is not easy task then Kaya (2004b) proposed 2DOF-IMC structure as in Figure 2.7 below. After this the IMC proposed by Kaya (2004b) is known as Kaya 2DOF-IMC.

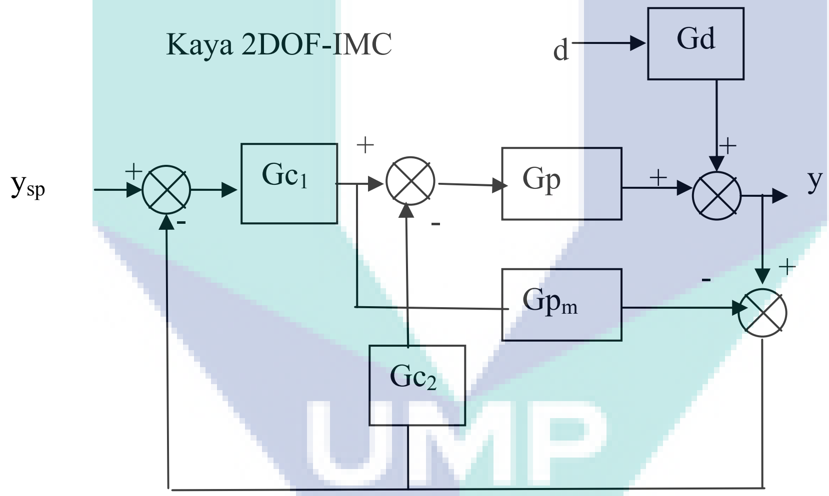


Figure 2.7 2DOF-IMC proposed by Kaya (2004).

The closed loop transfer of Kaya 2DOF-IMC can be written as;

$$y = \frac{Gp.Gc1.(1 + Gpm.Gc2)}{1 + Gc2.Gp + Gc1.(Gp - Gpm)} y_{sp} + \frac{Gp.(1 - Gpm.Gc1)}{1 + Gc2.Gp + Gc1.(Gp - Gpm)} d.Gd \qquad (2.63)$$

The Kaya 2DOF-IMC structure proposed for integrating processes and used proportional derivative (PD) controller. The PD parameters were determined using principle of gain and phase margin theory.

Shreesha and Gudi (2003) proposed control relevant identification methodology and used the model for 2DOF-IMC in controller. The objective is to minimize the model mismatch which is most relevant from closed loop performance. The structure of 2DOF controller is described in Figure 2.8 below.

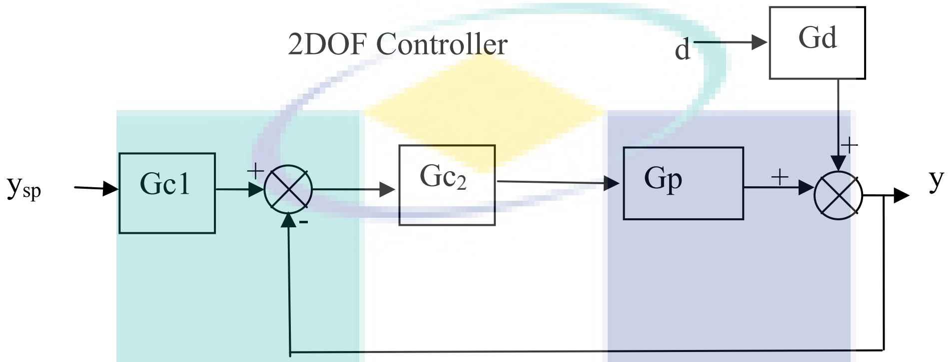


Figure 2.8 2DOF controller used by Shreesha and Gudi (2003).

The models are estimated using prefilter based on specification for set point and disturbance rejection. Then the 2DOF-IMC is designed based on Morari and Zafiriou (1989).

Gorez (2003) proposed 2DOF controller (such in Figure 2.8) from IMC structure which the dead time is approximate by a first order parameterization or the FOPDT model transfer function is expressed as below;

$$Gp_m = \frac{k}{\tau s+1} e^{-\theta s} = \frac{k}{\tau s+1} \frac{1-\theta_N s}{1+\theta_D s} \tag{2.64}$$

Here, the pole zero are transformed to a variable called model adaptation parameter (v) = θ_N/θ, then equation (2.64) became;

$$Gp_m = \frac{k}{(\tau s+1)} \frac{1-v\theta s}{(1+(1-v)\theta s)} \tag{2.65}$$

The Gc_1 can be expressed in equation (2.66) below.

$$Gc_1 = \frac{1}{k}\frac{(\tau s+1)(1+\theta_D s)}{1-\theta_N s} = \frac{1}{k}\frac{(\tau s+1)(1+\theta_D s)}{1+\theta_C s} \tag{2.66}$$

where $\theta_C = (\mu\text{-}1)\,\theta_N = (\gamma\text{-}v)\theta$

The value of μ and v are set to determine the parameters of PID controller. The μ has correlation with sensitivity (S) of closed loop transfer function as below;

$$S = \frac{(\theta_C+\theta_N)s}{1+\theta_C s} = \frac{(\theta_C+\theta_N)s}{1+(\mu-1)\theta_N s} \tag{2.67}$$

If Mp is the maximum value of S at frequency domain then the μ can be related to the desired sensitivity by

$$\mu = \frac{Mp}{Mp-1} \tag{2.68}$$

Where μ is set as 2 for time responses with a small amount of oscillatory transients, and μ = 3.5 for more robust but slower responses with no or negligibly small oscillations. While, the value of v = 0.5 for PID controller and v = 1 for PI controller.

2.5 SUMMARY

In the case of no error in the model, IMC can be tuned to be a perfect controller. However, the perfect controller can only be valid if there is no disturbance. If any disturbances occur, then it is retuned that the 2DOF-IMC structure to reject the disturbances quickly. In the case of model uncertainty, 2DOF-IMC may produce a controller that is not optimal or even produce the unstable response. Therefore, to optimize the controller it is necessary to pay attention to model uncertainty (robust performance). However, the existing methods were mathematically complicated.

Various structures and tuning of 2DOF controller using IMC structure have been investigated. However, among them even adds specifications and parameters become more than the standard 2DOF-IMC and some of their objective is to find the parameters of PID controller. Therefore, a robust and simple tuning method for a 2DOF-IMC is a challenge for the researcher and is urgently needed.

CHAPTER 3

NEW Mp-GM TUNING METHOD FOR 2DOF-IMC

3.1 INTRODUCTION

The purpose of controller tuning is to determine the parameters of controller in order to ensure the time response of close-loop control system at the desired performance. Performance of a controller is considered good if the controlled variable is always at the desired set point (Marlin, 2000). Therefore, if there are disturbances entered to the system, both predicable and unpredictable disturbances, the control system with proper controller tuning will be able to eliminate it quickly. Likewise, if there is a change of set point then the control system can also quickly reach the desired set point.

In IMC controller, there are several factors that affect the performance of the control system. These factors are structure, algorithm and parameter of the controller. As mentioned in Chapter 2, there are two standard IMC structures available namely, 1DOF-IMC and 2DOF-IMC. A new proposed structure of 2DOF-IMC based on principle of feedback / feedforward control system will be presented in subsection 3.4.1. The algorithm for disturbance rejection controller (Gc_2) is setpoint controller (Gc_1) multiplied with a lead lag transfer function. In order to generate a good performance of time response, it needs a tuning approach that meets the robust performance criteria. One of the approaches of tuning that is typically used in the control system is frequency response.

Frequency response analysis is an important technique in control system design in the frequency domain. One of the quantity that can be analyzed in frequency response is complementary sensitivity function (T), where the maximum value of |T (jω)| is called the resonant peak (Mp). Resonant peak indicates the stability of closed-loop system (Kuo, 1995). Another quantity that is often used to determine the controller parameters with frequency response is gain margin (GM). Gain Margin is a criterion that is often used to measure the stability of a control system (Kuo, 1995). In the Nyquist plot, gain margin is the frequency response of open loop transfer function on the real and imaginary axis (Seborg et al., 2004).

In the present study, the method proposed for tuning 2DOF-IMC uses Mp criteria for tuning of set point controller and GM criteria for tuning of disturbance rejection controller. The brief theory of Mp and GM will be discussed in subsection 3.2 and 3.3. Section 3.4 presents derivation of proposed feedback/feedward 2DOF-IMC, tuning method and tuning implementation to several types of plant.

3.2 MAXIMUM PEAK (Mp)

Mp is defined as the maximum magnitude of the closed-loop frequency response. In general, the magnitude of Mp gives an indication of the relative stability of a stable system. The closed loop transfer function (Gcl) is the response between controlled variable (y) to desired set point (y_{sp}). In feedback control structure shown in Figure.3.1, Gcl(s) has transfer function given in Eq. (3.1) below (Levine, 1995):

$$Gcl(s) = \frac{y(s)}{y_{sp}(s)} = \frac{Gol(s)}{1+Gol(s)} = \frac{Gc(s)Gp(s)}{1+Gc(s)Gp(s)} \tag{3.1}$$

where

$$\text{Mp} = \max_{\omega>0} \left| Gcl(j\omega) \right| \tag{3.2}$$

$$\omega\text{p} = \arg\left\{ \max_{\omega>0} \left| Gcl(j\omega) \right| \right\} \tag{3.3}$$

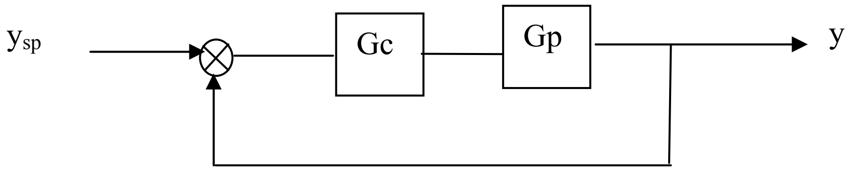


Figure 3.1 General structure of a feedback control system.

Figure 3.2 shows the typical closed loop response, $|G_{cl}(j\omega)|$, in frequency domain. It has a peak value (Mp) at certain frequency (ω_p).

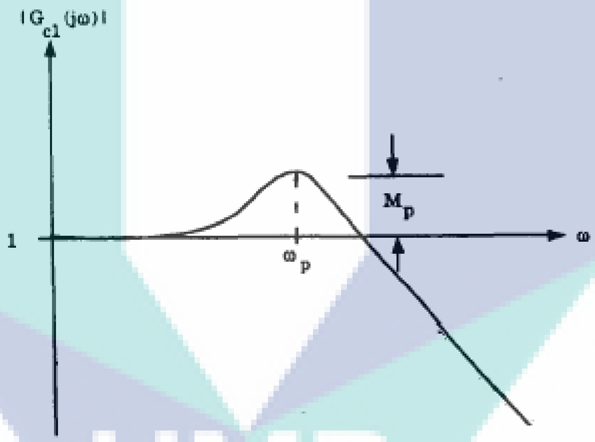


Figure 3.2 Resonant peak (Mp) Vs frequency (Levine, 1995).

Mp has strong correlation with the time response of system which can be presented in second order transfer function. Normally, a large Mp corresponds to a large maximum overshoot of the step response in the time domain (Levine, 1995). A system that has Mp value of 1 to 1.4 will have damping ratio (ζ) value of 0.4 to 0.7 in the time response while when Mp is more than 1.5 then the time response will be oscillatory and has a large overshoot (Subrahmanyam, 1996). The mathematical relationship between damping ratio and overshoot (OS) can be written as follows (Nagrath and Gopal, 2006):

$$OS = \exp\left(-\pi\zeta / \sqrt{1-\zeta^2}\right) \qquad 0 \le \zeta \le 1 \tag{3.4}$$

OS is fractional overshoot, OS = (maximum change in output – change in set point) / change in set point.

Correlation between Mp and OS can be described as (Brosilow and Joseph, 2001);

$$OS = \exp\left(-\pi Mp\left(1 - \sqrt{1 - 1/Mp^2}\right)\right), \qquad Mp > 0 \tag{3.5}$$

Whereas the relationship between damping ratio of the second order response and Mp can be written as;

$$\zeta = \sqrt{\frac{1 - \sqrt{1 - \frac{1}{Mp^2}}}{2}} \tag{3.6}$$

Figure 3.3 shows the correlation between Mp, OS and ζ .

From this correlation, if the models of the process (Gp) and the controller algorithm (Gc) in Eq. (3.1) are known then the value of controller parameter can be arranged so that Mp meet to its performance criteria. For most control systems, it is generally accepted in practice that the desired Mp should be in the range between 1.1 to 1.5 (Kuo, 1995).

For the IMC structure as shown in Figure 2.1, the closed-loop response between y and y_{sp} can be expressed as follows;

$$y = \frac{GpGc}{1 + Gc(Gp - Gpm)} y_{sp} \tag{3.7}$$

For the case of no error in the model, the Gc parameter can be easily set as explained in section 2.2.5. For the case at which model uncertainty exists, the principle of Mp can be applied. Brosilow and Joseph (2001) proposed that the Mp value of 1.05 and this Mp value gave overshoot in time response domain about 10%. Selection and effect of Mp value to overshoot is described in section 3.4.4.

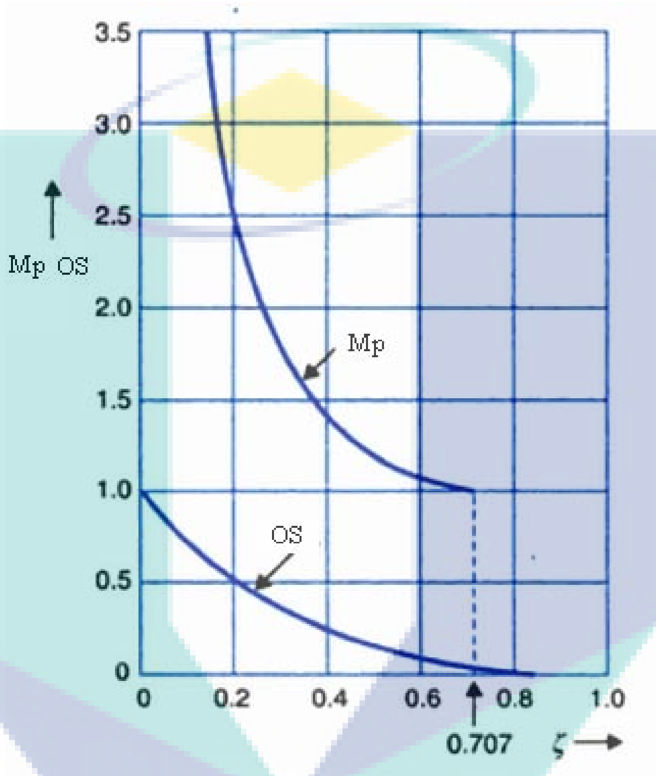


Figure 3.3 Correlations between Mp, OS and ζ (Nagrath and Gopal, 2006).

3.3 GAIN MARGIN

Gain margin is one of the frequency response specifications to determine the stability of the control process. Gain margin can be described through Nyquist plot. Nyquist plot of open loop transfer function (Gol (s)) is plotted in a polar coordinates of the imaginary of |Gol (jω)| versus the real of |Gol (jω)| with the frequency, ω, from 0 to ∞. If G (s) is the forward path and H (s) is the feedback path, the Gol (s) can be written as

$$Gol(s) = G(s)\,H(s) \tag{3.8}$$

The stability of the closed-loop system can be obtained if the frequency response of Gol in Nyquist plot do not circle of point (-1, j0) (Kuo, 1995).The gain margin in the Nyquist plot is shown in Figure 3.4.

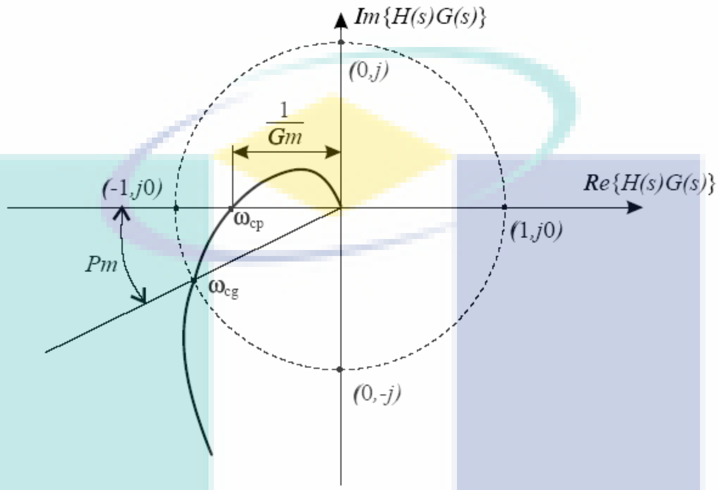


Figure 3.4 Gain and phase gain margins on nyquist plot (Seborg et al., 2004).

Gain margin is also commonly used for tuning the parameters of controller. Typical value of GM for well tuned controller is 2 (Marlin, 2000), 1.7 - 4 (Seborg et al., 2004), or 2 – 5 (Astrom et al., 1998). Many researchers used GM criteria for PID tuning. These researchers included Hang et al. (1994), Hang et al. (1994), Ho et al. (1995), Ho et al. (1998), Wang et al. (1999) and Yaniv and Nagurka (2004).

The usage of gain margin for the tuning of 2DOF-IMC has not been previously investigated. This is probably caused by two reasons. Firstly, in the structure of the standard 2DOF-IMC, Gc_1 is not in the feedback path, but it is in the forward path. On the other hand, from the equation of the closed-loop response, Eq. (3.9), the open-loop transfer function Gol(s) is Gc_2 $(Gp-Gp_m)$. It seems that Gc_1 is not involved in the Gol (s), even Gc_1 is not involved in sensitivity function of 2DOF-IMC (see Eq. (2.54)).

$$y = \frac{(GpGc_1)r + (1 - Gc_2Gp_m)d}{1 + Gc_2(Gp - Gp_m)} \tag{3.9}$$

In section 3.4.1 a new proposed structure of 2DOF-IMC based on the feedback / feedforward control will discuss to clarify the effect of Gc_1 on the closed loop response.

The second reason for GM has not been used for the tuning of 2DOF-IMC might be due to the Gol (s) is equal to 0 when no error in the model. In this case, it is not possible to use GM principle for tuning purpose. On the other hand, the form of Gol(s) which contains ($Gp-Gp_m$) has advantageous to GM analysis. It is because the GM can be used easily to prove that the system is stable for any process modeling error (Marlin, 2000). Therefore, the use of the GM for tuning 2DOF-IMC can be seen as a great opportunity in improving the overall performance. Selection and effect of GM value to output response is described in section 3.4.6.

3.4 MP-GM TUNING METHOD OF 2DOF-IMC

3.4.1 Structure of feedback/feedforward 2DOF-IMC

One of drawback of feedback control is that there is no action before the deviation between controlled variable and its set point occurs. It does not provide prediction effect to compensate the disturbance. For the situation where feedback control by itself is not satisfactory, feedforward control can be added (Seborg et al., 2004). The main target of feedforward control is to initiate action before disturbing the process. The weakness of feedforward control is that it needs measurable disturbance. The usage of feedback /feedforward combination becomes an alternative to increase performance. Classic scheme of feedback/feedforward control is shown in Figure 3.5.

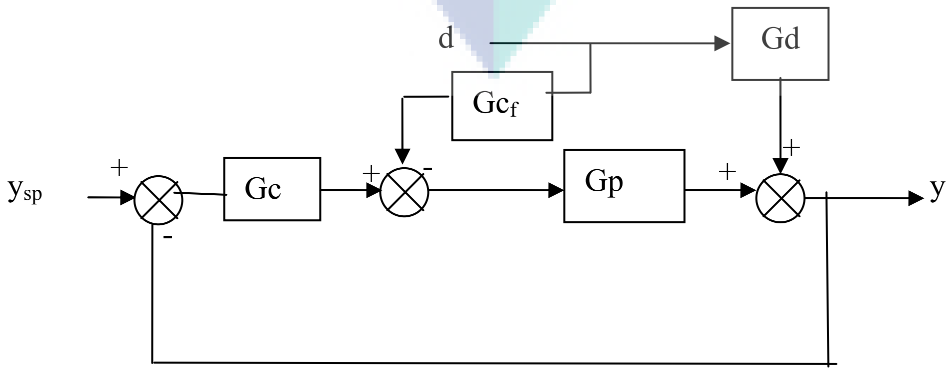


Figure 3.5 Classic feedback/feedforward control structure.

Effect of disturbance to output response is:

$$\frac{y}{d}=\frac{Gd-Gc_f Gp}{1+GpGc} \tag{3.10}$$

In order to get perfect disturbance compensation, the feedforward controller (Gc_f) can be expressed by:

$$Gc_f=\frac{Gd}{Gp} \tag{3.11}$$

The optimal Gc_f depends on the feedback controller Gc and the disturbance d. For IMC structure, Morari and Zafiriou (1989) recommended feedback/feedforward IMC controller as presented in Figure 3.6. The advantage of feedback/feedforward IMC parameterization is that it separates the effect of the feedforward controller (Gc_f)and the feedback controller Gc and allows them to be designed independently. The effect of the disturbance on the output is described by:

$$\frac{y}{d}=\frac{Gd_m GcGp-Gc_f Gp+Gd-GdGp_m Gc}{1-Gp_m Gc+GcGp} \tag{3.12}$$

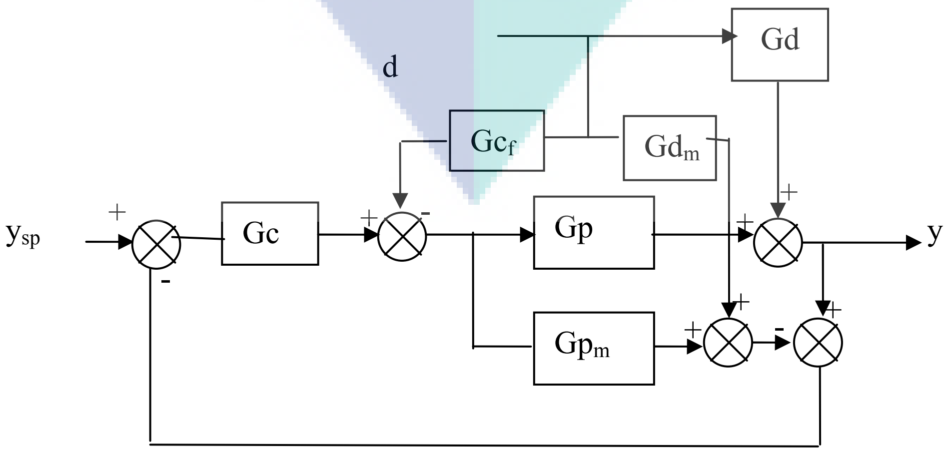


Figure 3.6 Feedback/feedforward IMC controller.

If there is no error in the model or Gd_m (disturbance model) = Gd and Gp_m = Gp then

$$\frac{y}{d} = \frac{Gd - Gc_f Gp}{1 - Gp_m Gc + GcGp} \tag{3.13}$$

From Eq. (3.13) it is clear that the optimal Gc_f is similar to the classic feedback/feedforward control.

$$Gc_f = \frac{Gd}{Gp} \tag{3.14}$$

Morari and Zafiriou (1989) concluded that if perfect feedforward compensation is possible then IMC feedback/feedforward structure does not offer any specific advantage over the classic structure. This is because the performance of a feedforward controller is more sensitive to model mismatch than that of a feedback controller. Model error forces the feedback controller to be detuned for robustness and nominal performance to be sacrificed.

A new proposed controller structure has been proposed in the present study based on an idea that the deviation between y and output plant model is unknown disturbance and it is assumed as e = d Gd (see Figure 3.7) (Juwari et al., 2008). A feedback controller is depicted in Figure 3.7. Response y can be expressed by

$$y = \frac{eGcGp - eGc_f Gp + dGd - dGdGp_m Gc}{1 - Gp_m Gc + GcGp}. \tag{3.15}$$

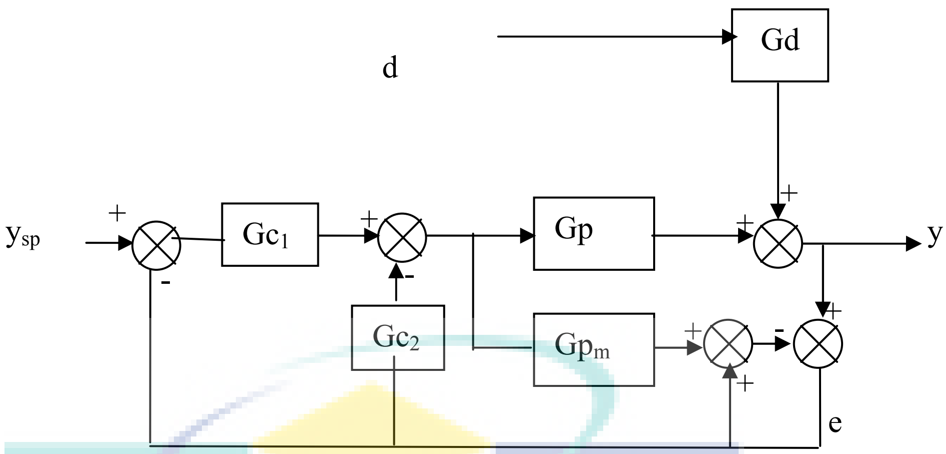


Figure 3.7 2DOF IMC from feedback/feedforward structure.

$$y = \frac{rGpGc_1 + \left(1 - \frac{Gp_m}{2}(Gc_1 + Gc_2)\right)d}{\left(1 - \frac{Gp_m}{2}(Gc_1 + Gc_2) + \frac{Gp}{2}(Gc_1 + Gc_2)\right)} \tag{3.16}$$

From Figure 3.7 it can be seen that although the development of this structure is from feedback / feedforward form, the result is identical with the feedback control system (no feedforward controller is needed). Therefore, this structure is denoted as proposed feedback 2DOF-IMC. In this structure, those disturbances introduced to the process are estimated and included in the controller algorithm. It is expected that the disturbances can be rejected in a short time. Figure 3.7 and Eq. (3.16) show that Gc_1 is involved in the feedback loop. The development of Mp-GM tuning (see section 3.4.2) was derived from this structure. Nevertheless, Mp-GM method also can be applied to the standard structure of 2DOF-IMC.

3.4.2 Procedure Mp-GM tuning method for 2DOF-IMC

The proposed tuning method consists of three steps:

(i) Determine the 'worst case' of the model uncertainty;

(ii) Specify the parameter of set point controller (Gc_1) using Mp criteria; and

(iii) Obtain the parameter of the disturbance rejection controller (Gc_2) using GM criteria.

Second and third steps are conducted based on the worst case model uncertainty as Gp and nominal model as Gp_m. The first step is determining the 'worst case' of uncertainty model. The worst case can be found from the limit of the uncertainty model in terms of upper and lower on process model parameters. The worst case is the nearest condition that unstable responses will occur. This condition usually occurs at the uncertainty model with the larger (upper limit) steady state gain process, the larger (upper limit) time delay and the smaller (lower limit) process time constant. The worst case of a set process uncertainty can be identified at the biggest maximum value of magnitude of frequency response of complementary sensitivity function. When determining the worst case, filter time constant (λ) value is set equal to the time delay of nominal model. Here, the θ (time delay of nominal model) is as initial value of λ_1 as in second step.

The second step is specifying the parameter of set point controller (Gc_1) using 1DOF-IMC structure, based on the Mp-Tuning criteria as follow;

- Set λ_1 (filter time constant Gc_1) initial value i.e λ_1 is set equal to the time delay (θ) of nominal model.
- Calculate max $|T(j\omega)|$ in the range of frequency $\omega = 10^{-3}$ to 10^{3}.
- If max $|T(j\omega)| > 1.05$ then add λ_1 with small number, for example $\lambda_1 + 0.01$.

The third step is obtaining parameter of disturbance rejection controller (Gc_2) using feedback 2DOF-IMC structure, based on the GM criteria as follow:

- Set λ_2 (filter time constant Gc_2) smaller than λ_1. In this study $\lambda_2 = 0.9\ \lambda_1$ was used. It is reasonable value, because a better performance for disturbance rejection can be obtained if λ_2 is always smaller than λ_1 (Brosilow and Joseph, 2003).
- Set initial α equal to λ_2. Add α with small number such that the value of GM for the open loop system of 2DOF-IMC is equal to 2.4 (section 3.4.5). Here, the open loop system $Gol = 0.5(Gc_1 + Gc_2)(Gp - Gp_m)$

The proposed method is called (Mp-GM tuning method) because it uses the principle of Mp criterion for tuning the set point controller (Gc_1) and the principle of GM criterion for tuning disturbance rejection controller (Gc_2). Mp value is set to be 1.05 based on the recommendation of Brosilow and Joseph (2001). The number of variables that affect the performance of Mp-GM tuning such as the ratio λ_1 / λ_2 and the value of GM will be demonstrated through the examples below. These examples reflect the First Order plus Dead Time (FOPDT) process with $\theta/\tau = 1$, $\theta/\tau > 1$, and $\theta/\tau < 1$. Difficult higher order i.e second order with underdamped and nonminimum phase third order process are also presented in this chapter. Whereas, implementation of the proposed method to a real plant will be discussed in Chapter 4.

3.4.3 Comparison of parameter and time response of proposed feedback and standard 2DOF-IMC

Comparison of parameter of proposed feedback and standard 2DOF-IMC structure is done by using proposed Mp-GM and IMCTUNE (Stryczek et al., 2002).The IMCTUNE design has been explained in section 2.4.2. The proposed method also could be implemented on standard 2DOF-IMC. Matlab code of the proposed method is presented in Appendix B. Meanwhile, the procedure of IMCTUNE method is enclosed in appendix C. Comparison of parameters and time responses of two controller structures to a process plant is shown through the case study of FOPDT. Consider a blending system investigated by Chang et al., (1998) with $\theta/\tau > 1$:

$$Gp = \frac{ke^{-\theta s}}{0.2s+1}, \qquad 14.96 \le k \le 22.44 \;\; and \;\; 0.4 \le \theta \le 0.6 \tag{3.17}$$

$$Gp_m = \frac{18.7e^{-0.5s}}{0.2s+1} \tag{3.18}$$

Figure 3.8 shows tuning output of the proposed feedback 2DOF-IMC controller using Matlab. The worst case of uncertainty is determined from the largest value of the magnitude Mp or max |T(jω)| i.e 4^{th} case.

```
.:                 Robust and Simple Tuning of                :.
.:        The Proposed Feedback 2DOF-IMC Controller           :.
.:====================By Juwari======================= :.

Case( 1) k=15.0,theta= 0.4, max|T (jw)|=1.0000
Case( 2) k=15.0,theta= 0.6, max|T (jw)|=1.0000
Case( 3) k=22.4,theta= 0.4, max|T (jw)|=1.0000
Case( 4) k=22.4,theta= 0.6, max|T (jw)|=1.0654

The wosrt case is case ( 4)

 1. The wosrt case plant and nominal model are
     Gp  = 22.4400*exp(-0.6000*s)/(0.2000*s+1)
     Gpm = 18.7000*exp(-0.5000*s)/(0.2000*s+1)

 2. The controller transfer functions are ;
     Gc1 = (1/18.7000) * (0.2000*s+1)/(0.5240*s+1)
     Gc2 = Gc1 * (1.5616*s+1)/(0.4716*s+1)

 3. Additional informations
    See the figures
          lamda2=0.9000 *lamda1
          max|T (jw)| = 1.0495
          GM          = 2.3884
```

Figure 3.8 Tuning output of the proposed feedback 2DOF-IMC controller.

Transfer functions of Gp, Gp_m, Gc_1, and Gc_2 used in the control system are displayed on the output of the programming i.e in command window (Figure 3.8). Additional information are the set of Mp-GM specifications i.e λ_2/λ_1, Mp and GM.

Table 3.1 shows the comparison of parameter values by using proposed Mp-GM tuning method for the proposed feedback 2DOF-IMC, the standard 2DOF-IMC and Kaya 2DOF-IMC structure. In the proposed Mp-GM tuning method, there are 3 parameters that are specified i.e. the value of Mp, λ_2/λ_1 and GM. Where, the Mp value is set equal to 1.05 (see section 3.4.4), λ_2/λ_1 is specified equal to 0.9 (see section 3.4.5), and GM is set equal to 2.4 (see section 3.4.6). In the table for the standard 2DOF-IMC, the IMCTUNE by Stryczek et al. (2002) was also investigated. The Gc_2 transfer function of (Stryczek et al., 2002) is expressed as;

$$Gc_2 = \frac{\tau s+1}{\lambda_2 s+1}\frac{\alpha s+1}{\lambda_2 s+1} \tag{3.19}$$

Table 3.1 Parameters of 2DOF-IMC, FOPDT with $\theta/\tau > 1$

Structure	λ_1	λ_2	α
Proposed Feedback 2DOF-IMC			
- Proposed Mp-GM	0.524	0.4716	1.5616
Standard 2DOF-IMC			
- Proposed Mp-GM	0.524	0.4716	1.0216
- IMCTUNE	0.8091	0.2765	0.6825
Kaya 2DOF-IMC			
- Proposed Mp-GM	0.524	0.4716	0.4816

A typical frequency response for the FOPDT transfer function model of $|T(j\omega)|$ and GM are shown in Figure 3.9 and 3.10 respectively. The Kaya 2DOF-IMC gives GM value less than 2.4 (see Figure 3.11). This occurs because λ_2/λ_1 has been set, in the initial iteration this structure gives the GM close to less than 2.4 (as GM criteria). It is evident from table 3.1 that the α value nearly equal to λ_2. The difference between α and λ_2 is just because the first iteration.

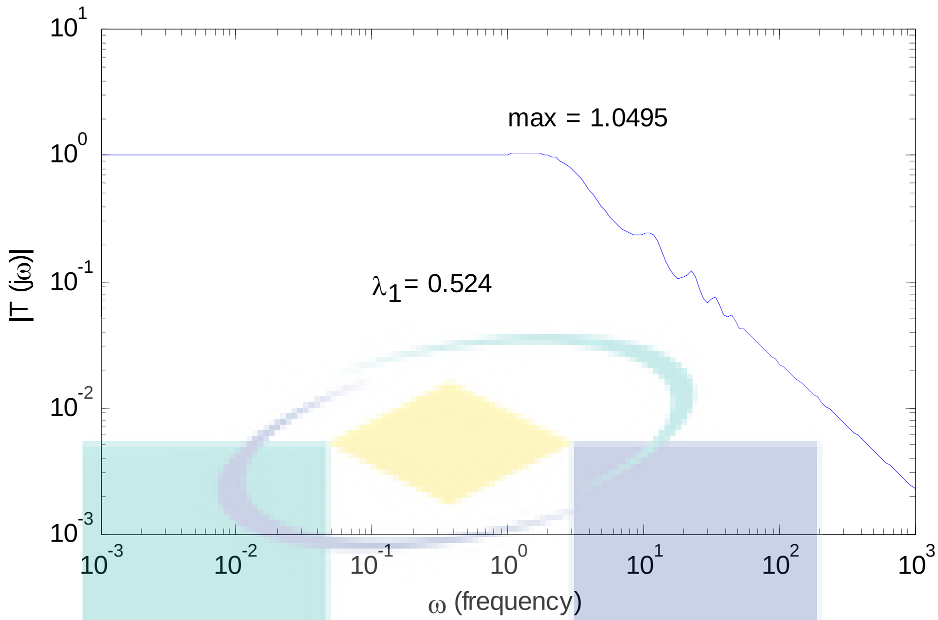


Figure 3.9 The magnitude of |T (jω)| vs frequency (ω).

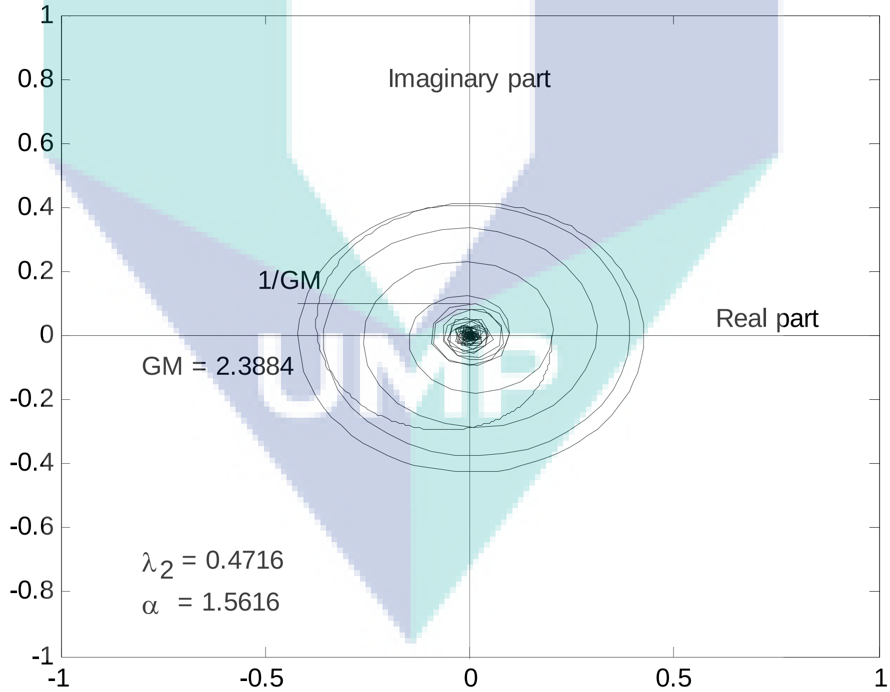


Figure 3.10 Interpretation gain margin of FOPDT process on Nyquist plot of proposed feedback 2DOF-IMC

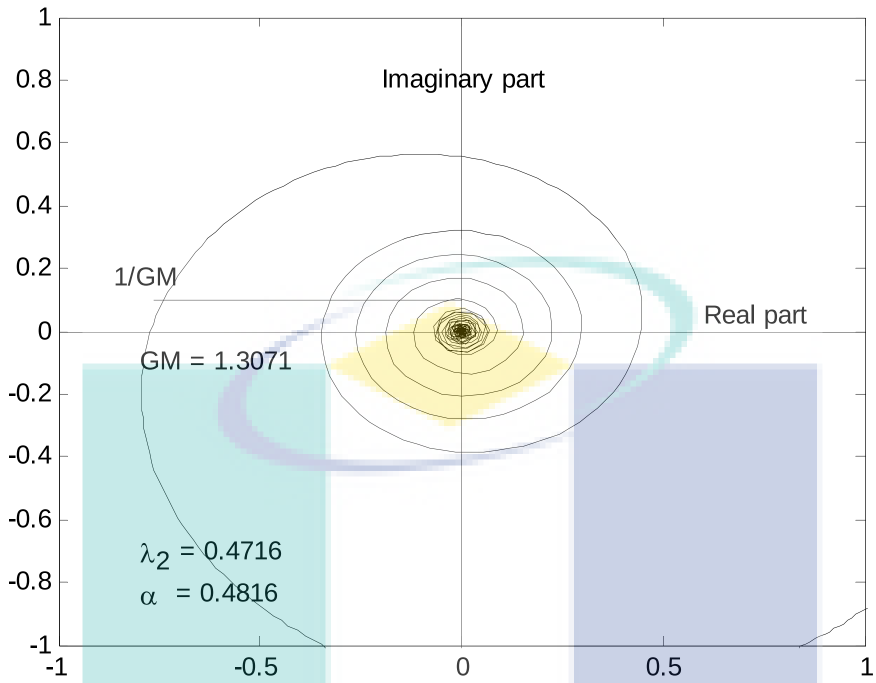


Figure 3.11 Interpretation gain margin of FOPDT process on Nyquist plot of Kaya 2DOF-IMC

The time responses of the three structures with Mp-GM tuning method are shown in Figure 3.12. The time responses are for the set point tracking (at time 1) and the disturbance rejection when a magnitude of 0.5 disturbance with transfer function of $Gd = \frac{1}{s+1}$ is introduced to the system at time 10. From these figures and integral absolute error (IAE) values, it can be seen that with the same criteria (Mp and GM), standard and proposed feedback 2DOF-IMC controller structures yield almost the same time responses. The same result is indicated in all cases that studied in this research. Therefore in the next section the comparison standard 2DOF-IMC with Mp GM tuning is not done anymore. Comparison is done by standard 2DOF-IMC with IMCTUNE.

The result shows that Kaya 2DOF-IMC gives oscillatory response or sensitive controller. This is because, the GM value can not be set to 2.4 as in the requirement of MP-GM method. To determine overall performance, the three controllers need to be tested in a different cases i.e. nominal and slowest case. Figure 3.13 and 3.14 show the output responses of nominal and slowest case.

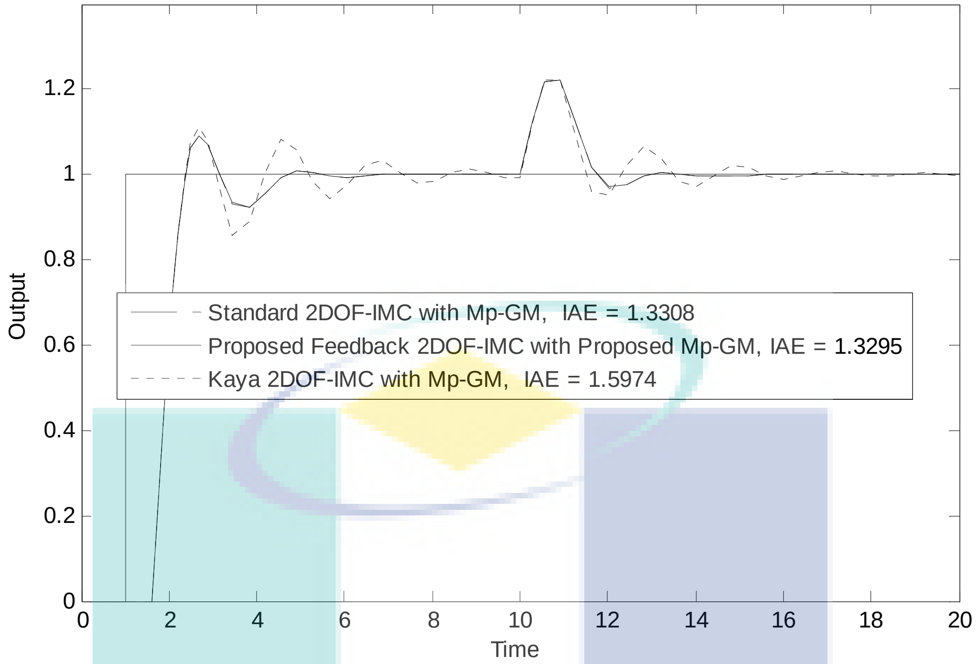


Figure 3.12 Time response of the feedback 2DOF-IMC and standard 2DOF-IMC, FOPDT with θ/τ > 1.

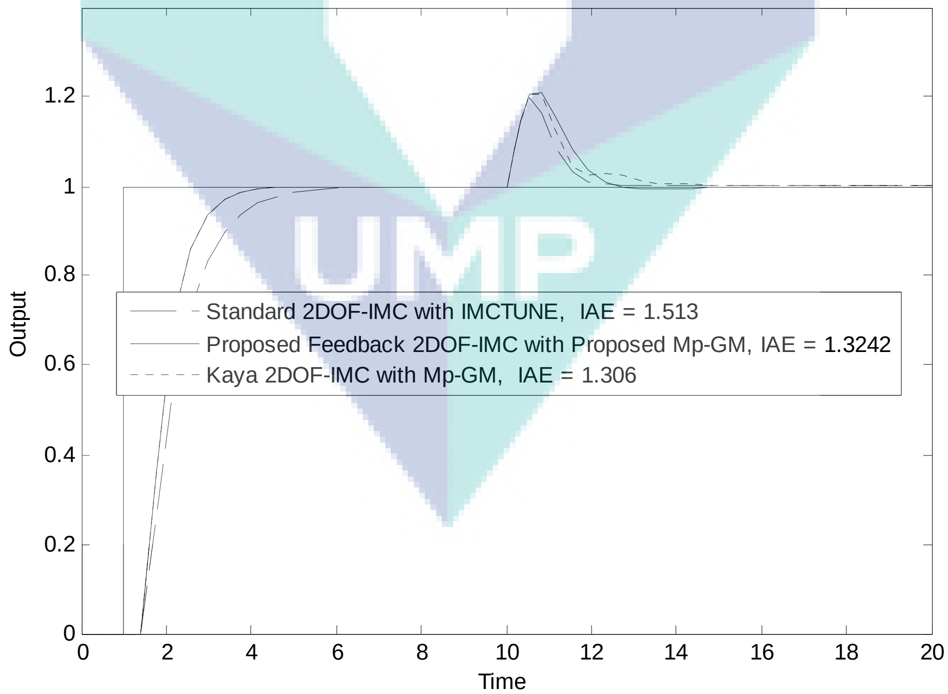


Figure 3.13 The output response for no-error in the model are imposed, FOPDT with θ/τ > 1.

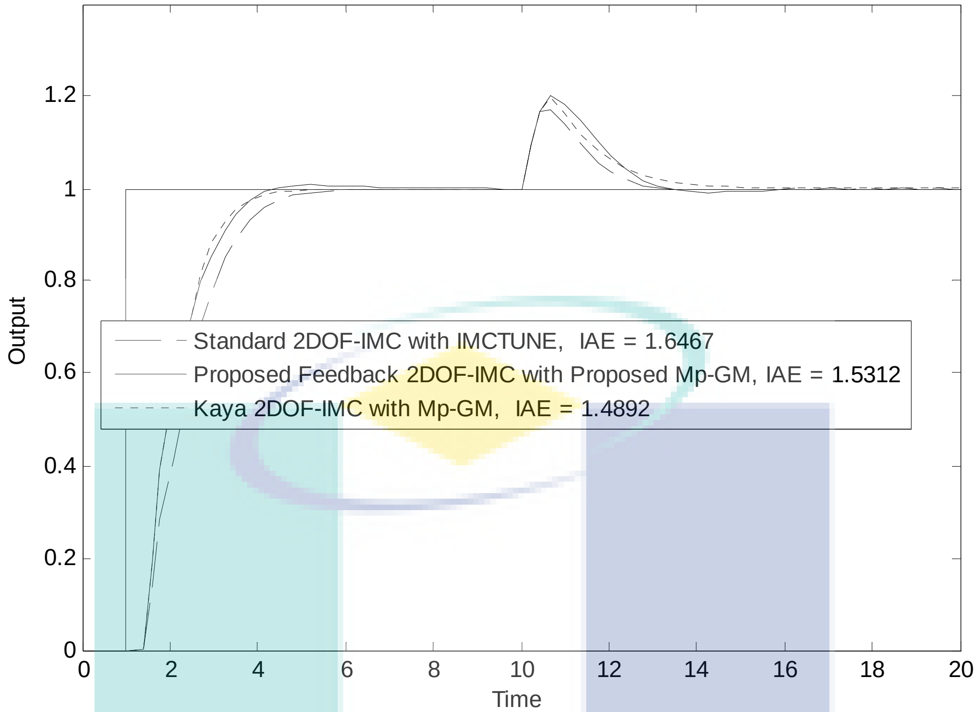


Figure 3.14 The output response for slowest case, FOPDT with θ/τ > 1.

Table 3.2 shows the IAE values of the three controllers for each case and mean of IAE for each controller. From the mean value of IAE, it can be seen that proposed feedback with Mp-GM tuning method gives the smallest IAE.

Table 3.2 The IAE value of FOPDT process with θ/τ > 1.

Controller	IAE			
	Worst	Nominal	Slowest	Mean
Standard 2DOF-IMC	1.3308	1.513	1.6467	1.4969
Proposed 2DOF-IMC	1.3295	1.3242	1.5312	1.3950
Kaya 2DOF-IMC	1.5974	1.306	1.4892	1.4642

3.4.4 Effects of Mp value to output responses.

Mp value has strong correlation with overshoot (section 3.2). From Figure 3.12 to 3.14 show that overshoot occurred in the worst case only, while the nominal and the slowest case does not cause overshoot. Therefore the determination of Mp value is based on the overshoot when the set point is introduced in worst case. To keep the process remains stable in the worst conditions overshoot is specified does not exceed 10%. Table 3.3 below presented proposed feedback 2DOF-IMC controller parameter using Mp-GM tuning for various values of Mp and its percentage overshoot. Percentage overshoot is based on output response in Figure 3.15.

Table 3.3 Controller parameters and its percentage overshoot

Mp	λ_1	λ_2	α	% OS
1	0.6880	0.6192	2.8492	0.26
1.05	0.5240	0.4716	1.5616	8.10
1.1	0.4570	0.4113	1.1513	12.35

The smaller Mp, it will give sluggish control action for nominal and slowest case. On the other hand, the bigger Mp produces the higher overshoot. It may results unstable response for worst case problem. From the Table 3.3 and Figure 3.15 the appropriate Mp value is 1.05.

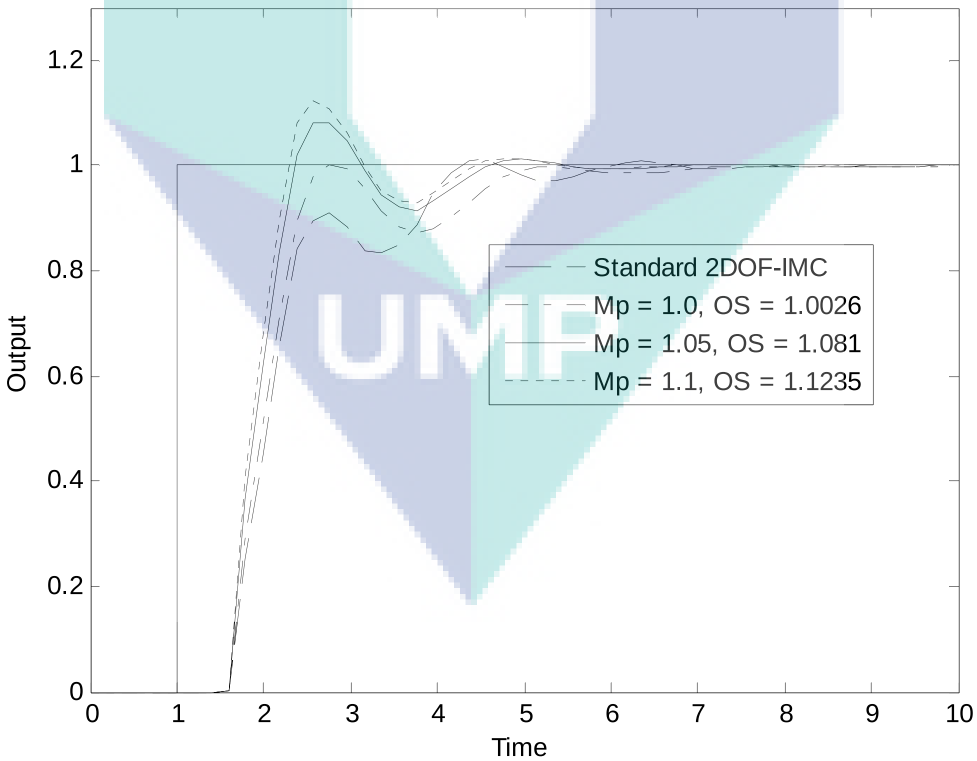


Figure 3.15 Effects of Mp value to output response of FOPDT $\theta/\tau > 1$

3.4.5 Effect of ratio λ_2 to λ_1

Brosilow (2001) stated that for better disturbance rejection, the value of λ_2 is always less than λ_1. A case study below shows how the ratio of λ_2 to λ_1 affects the output responses. The FOPDT model with $\theta/\tau <1$ is adopted from Vilanova et al. (2008). The uncertainty model is assumed $\pm$ 20%.

Consider the FOPDT model with $\theta/\tau <1$ is described as below

$$Gp = \frac{ke^{-\theta s}}{\tau s + 1}, \quad 0.8 \le k \le 1.2, 2.4 \le \tau \le 3.6 \text{ and } 1.2 \le \theta \le 1.8 \tag{3.20}$$

$$Gp_m = \frac{e^{-1.5s}}{3s+1} \tag{3.21}$$

$$Gd = \frac{0.5}{2s+1} \tag{3.22}$$

The worst case is at plant with k = 1.2, τ = 2.4 and θ = 1.8. Using the Mp-GM tuning, the value of λ_1 is 1.8510. The values of λ_2 and α for the corresponding ratio of λ_2 to λ_1 are presented in Table 3.3 below. For comparison, the controller parameters of the standard 2DOF-IMC with IMCTUNE are presented in Figure 3.16. From the figure, λ_1, λ_2, and α is 0.70304, 0.46536 and 1.4438 respectively. The Kaya 2DOF-IMC with Mp-GM tuning obtain parameters λ_1, λ_2 and α are 1.8510, 0.9255 and 0.9355 respectively.

Table 3.4 The value of λ2 and α for the corresponding λ_2/λ_1

λ_2 / λ_1	λ_2	α
0.7	1.2957	3.6957
0.9	1.6659	4.4159
1.1	2.0361	5.1661

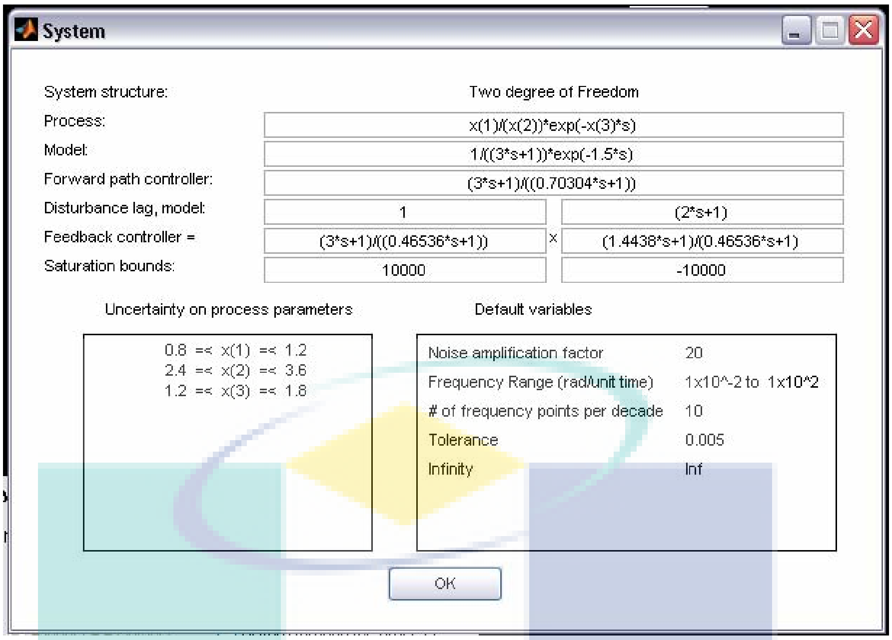


Figure 3.16 Controller parameters of the standard 2DOF-IMC with IMCTUNE, FOPDT $\theta/\tau < 1$

The responses of the worst case, no error in the model and slowest case are presented in Figure 3.17 – 3.19. In these figures, the time responses of specification (λ_2/λ_1) of Mp-GM tuning method are compared with standard 2DOF-IMC with IMCTUNE and Kaya 2DOF-IMC with Mp-GM as a base case. A unit set point is introduced at time 1 and at time 20 a 0.3 magnitude of disturbance is entered to the system. From Figures 3.17 to 3.19 show that IMCTUNE gives unstable response for worst and slowest case, but it produces very good response (smallest IAE) for nominal case. The Kaya 2DOF-IMC gives oscillatory response on worst case, but good responses on nominal and slowest case. Table 3.4 shows IAE value of several λ_2/λ_1 of proposed feedback 2DOF-IMC for worst, nominal and slowest case. The smallest mean of IAE is at $\lambda_2/\lambda_1 = 0.9$, then $\lambda_2/\lambda_1 = 0.9$ is selected as parameter specification of Mp GM tuning method.

Table 3.5 Effect of λ_2/λ_1 to output response.

	IAE			
λ_2/λ_1	Worst	Nominal	Slowest	Mean
0.7	3.4570	3.7072	4.3450	3.8364
0.9	3.4635	3.7110	4.3161	3.8302
1.1	3.5324	3.7158	4.2919	3.8467

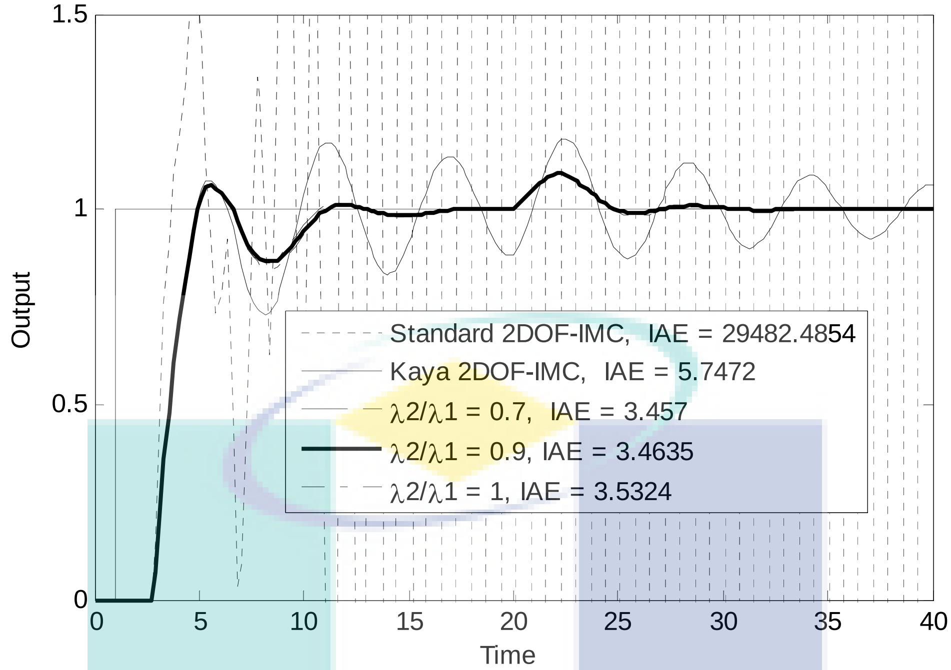


Figure 3.17 The worst case responses for the case FOPDT with θ/τ < 1.

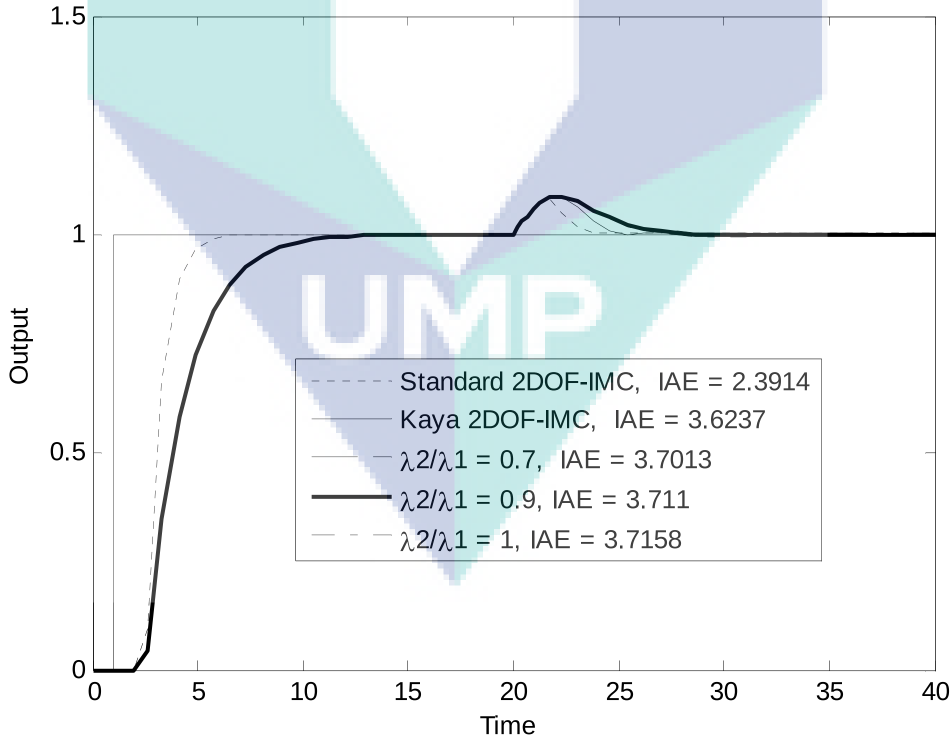


Figure 3.18 The responses of the case FOPDT with θ/τ < 1 with no error in the model.

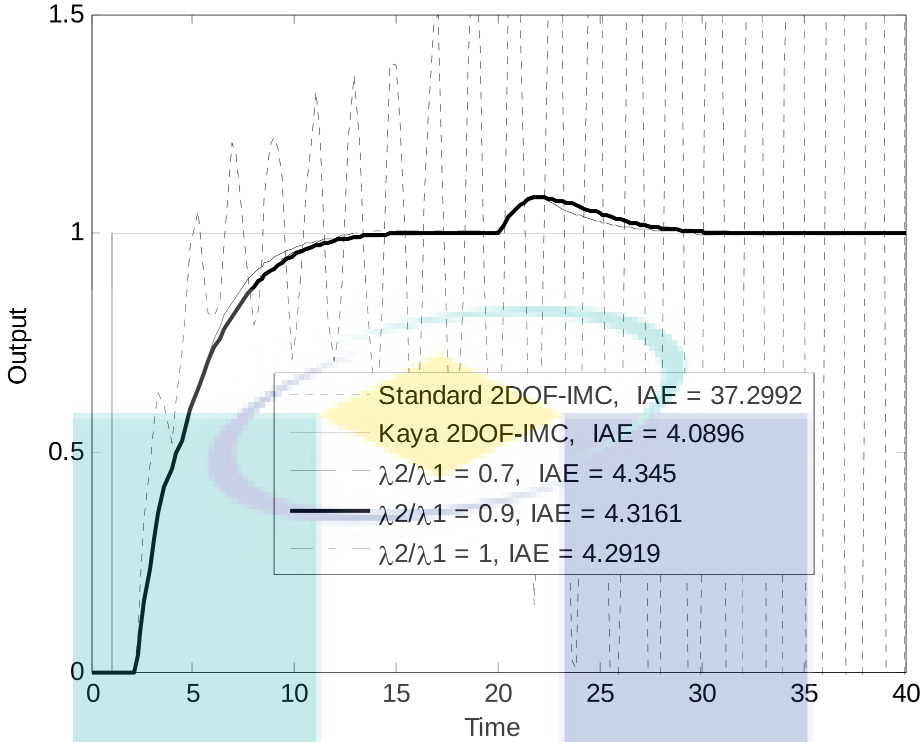


Figure 3.19 The worst case responses for the case FOPDT with $\theta/\tau < 1$.

3.4.6 Effect of GM to output response

The effect of GM criteria to the process responses is shown through the case study below. Suppose a FOPDT with $\theta/\tau \cong 1$ (Brosilow and Joseph, 2001)

$$Gp = \frac{ke^{-\theta s}}{s+1}, \qquad 0.8 \le k, \theta \le 1.2 \tag{3.23}$$

$$Gp_m = \frac{e^{-s}}{s+1} \tag{3.24}$$

The worst case is at plant with k = 1.2, and θ = 1.2. The slowest case is at plant with k = 0.8, and θ = 0.8. The Mp-GM tuning method gives λ_1= 1.047 and λ_2 = 0.9423. For GM criteria 1.7, 2.4 and 3.1, the value of α is 4.7723, 3.1023 and 2.1823 respectively. As a base case, IMCTUNE for standard 2DOF-IMC and Kaya 2DOF-IMC are also presented.

In this process, IMCTUNE produces λ_1= 1.0352, λ_2 = 0.6022 and α = 0.9418 and Kaya 2DOF-IMC obtains λ_1= 1.047, λ_2 = 0.9423 and α = 0.9523.

Figure 3.20 – 3.22 show the responses of the system for the worst, no-error in the model and slowest case. A unit set point is entered at time 1 and a disturbance magnitude of 0.3 with transfer function of $\frac{1}{s+1}$ is introduced to the system at time 20. IMCTUNE gives a smaller IAE than Mp GM for the worst and no error in the model cases.

The smaller GM values produces more sensitive controller (Figure 3.20 to 3.22). It is because from the Nyquist plot (Figure 3.23 and 3.24), the smaller GM will yields the graph closer to critical point (-1, 0). And vice versa, the bigger GM will produce the graph at a longer distance from critical point; it will give more sluggish controller. The performance of the effect of GM on output response is described in IAE value. The corresponding GM at the smallest IAE value will be selected. The values of IAE for the worst, nominal and the slowest case are described in Table 3.6. From this table show that the smallest mean of IAE value at GM = 2.4, then the GM 2.4 is selected for the best GM specification.

Table 3.6 IAE values at difference GM specification

	IAE			
GM	Worst	Nominal	Slowest	Mean
1.7	3.0224	2.6187	2.9863	2.8758
2.4	2.6274	2.5186	2.8537	2.6666
3.1	2.5224	2.5472	2.9827	2.6841

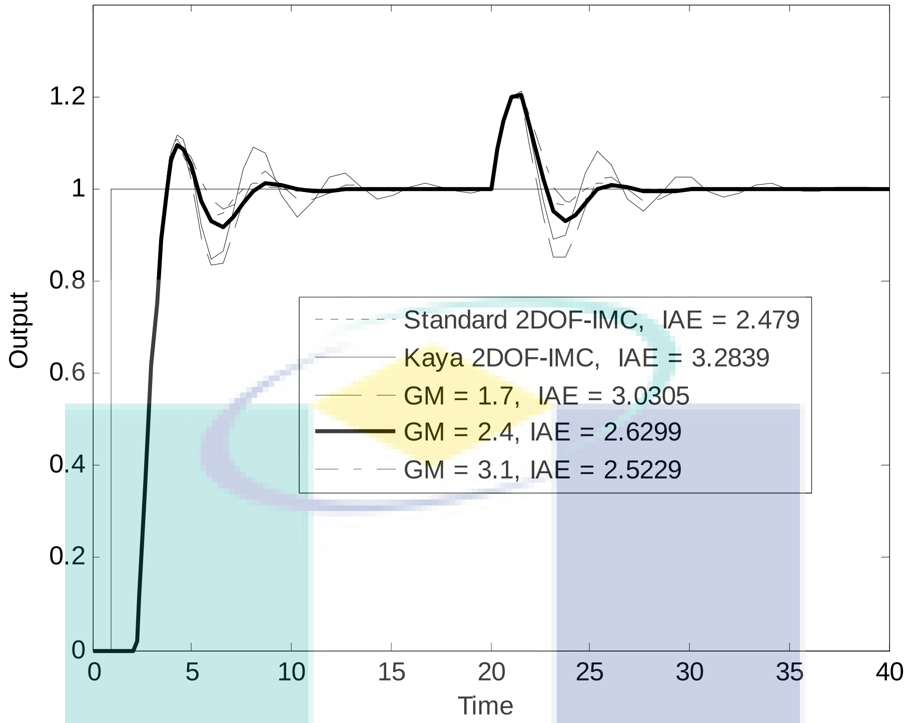


Figure 3.20 The worst case responses of FOPDT with $\theta/\tau \cong 1$.

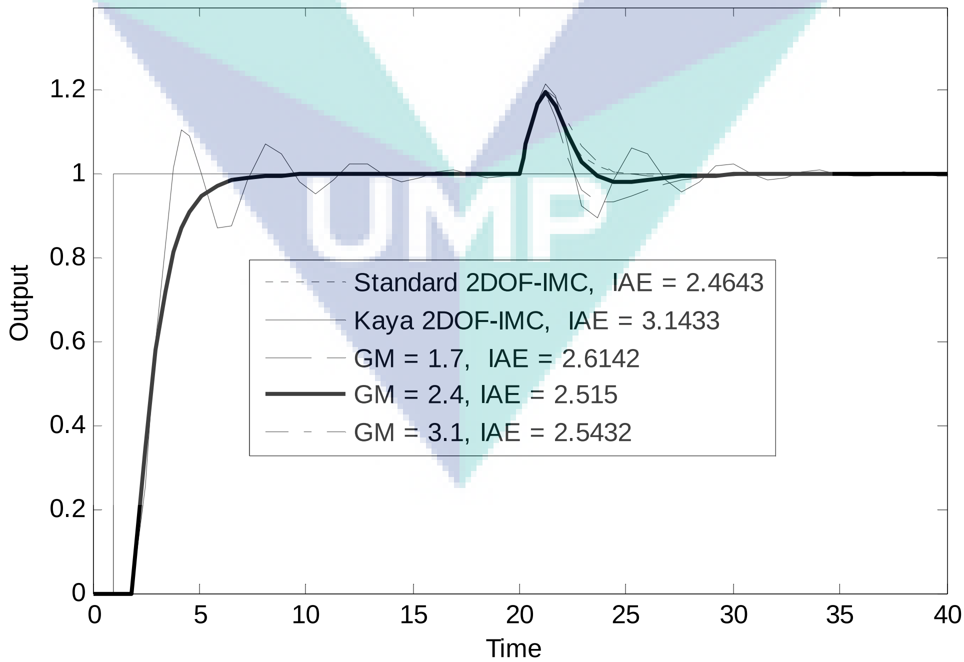


Figure 3.21 The responses of FOPDT with $\theta/\tau \cong 1$ with no error in the model.

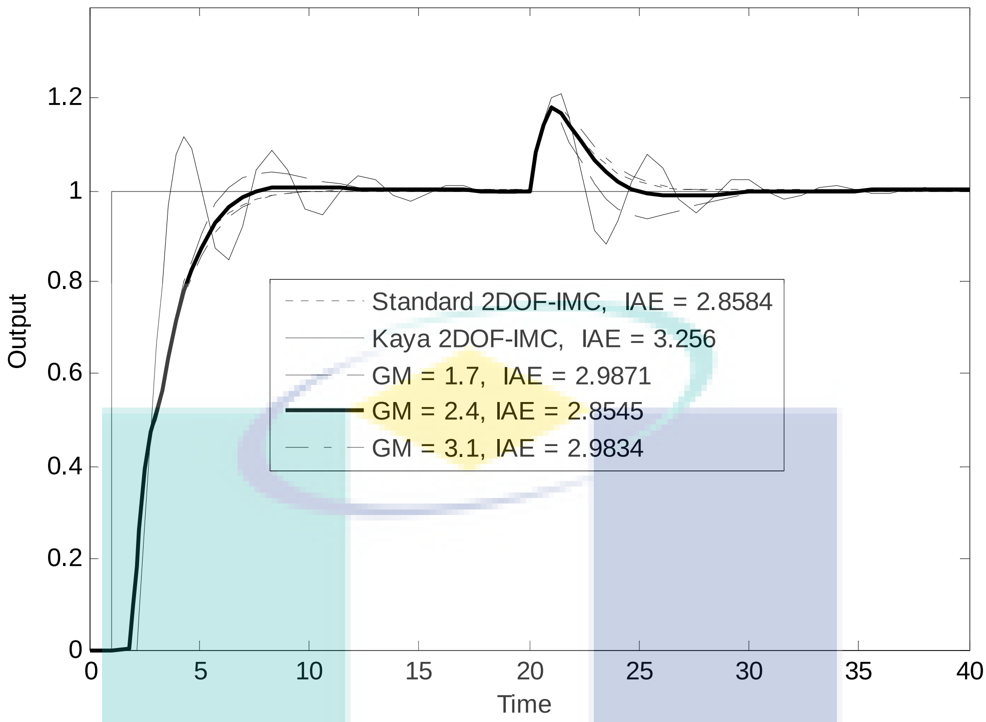


Figure 3.22 The output responses of FOPDT with θ/τ ≅ 1 for the slowest case.

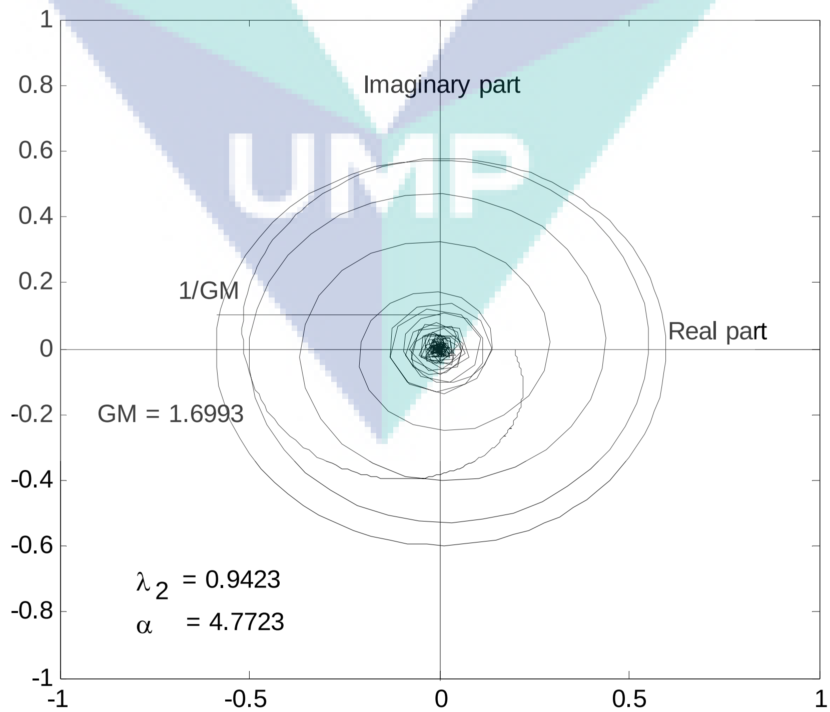


Figure 3.23 Nyquist plot of FOPDT with θ/τ ≅ 1, GM = 1.7

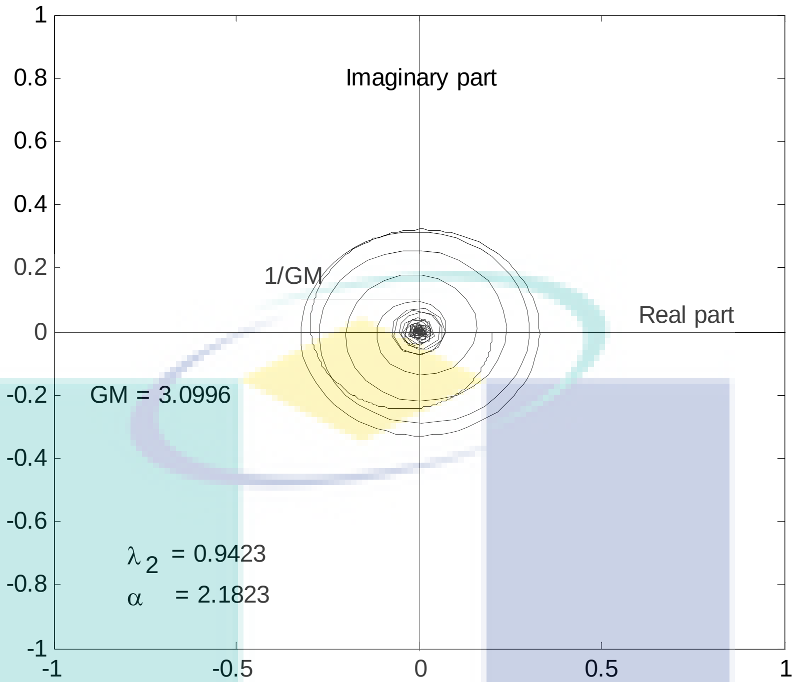


Figure 3.24 Nyquist plot of FOPDT with θ/τ ≅ 1, GM = 3.1

3.4.7 Effect of simplification model (Gp_m) and controller form

3.4.7.1. Second order with underdamped process

The performance of the proposed Mp-GM tuning method is tested on higher-order process i.e a second order underdamped process. Second order with underdamped can be found in the nonisothermal of continuous stirred tank reactor (CSTR) process. A dynamic model of nonisothermal of CSTR was developed by Marlin (2000). A transfer function of temperature to coolant flow is expressed as:

$$Gp = \frac{(-6.07s - 45.83)}{s^2 + 1.79s + 35.80} \tag{3.25}$$

Approximation of the above transfer function to FOPDT can be performed with a combination of approaches by Skogestad (2003) and Panda et al. (2004). Skogestad approach produces the transfer function as follows;

$$Gp = -\frac{e^{-0.13}}{0.02s^2 + 0.04s + 0.78} = -\frac{1.28e^{-0.13}}{0.03s^2 + 0.05s + 1} \tag{3.26}$$

Eq. (3.26) is then simplified by Panda et al. (2004), it gives transfer function as follows;

$$Gp \cong -\frac{1.28e^{-0.15}}{0.05s + 1} \tag{3.27}$$

Figure 3.25 shows open loop responses of the original second order underdamped process and FOPDT approximation.

Process uncertainty of the second order process in Eq. (3.25) is performed by Eq. (3.28). The value of a and b in Eq. (3.28) are varies $\pm$ 20% from nominal values i.e $-7.28 \le a \le -4.86$ and $-55.00 \le b \le -36.67$

$$Gp = \frac{(as + b)}{s^2 + 1.79s + 35.80} \tag{3.28}$$

Two strategies are imposed to design the controller;

(i) Gc and Gm are in FOPDT form

(ii) Gc is in FOPDT form and Gm is in the original second order process.

The Mp-GM tuning method produces the worst case plant at $a = -4.86$ and $b = -55.00$. For the first strategy (Gc and Gm are in the form FOPDT) the proposed Mp-GM tuning method results λ_1 = 0.9715, λ_2 = 0.8744 and α = 1.9713. For the second strategy (Gc is in FOPDT form and Gm is in the original second order process) the proposed Mp-GM tuning method results λ_1 = 0.9045, λ_2 = 0.8141 and α = 3.4851.

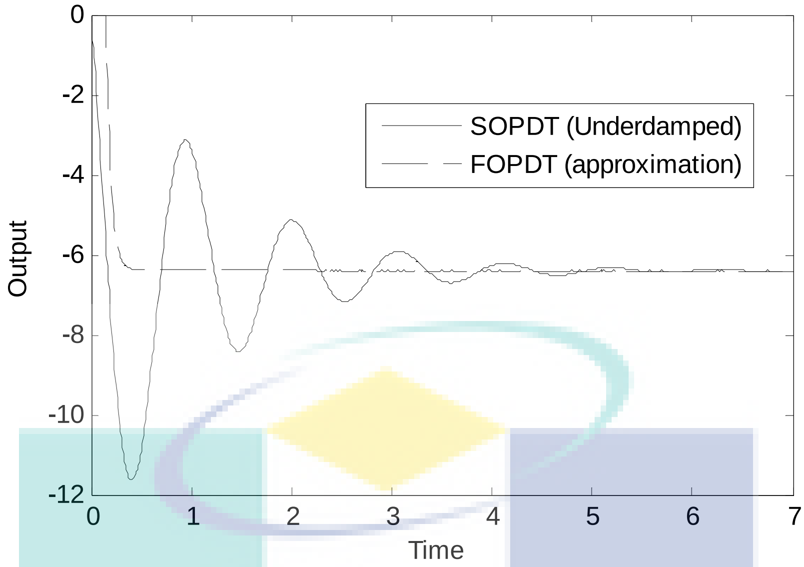


Figure 3.25 FOPDT approximation of second order underdamped process.

Figure 3.26 and 3.27 show the Nyquist plot of two strategies. From these figures, the first strategy (Gc and Gp_m are in FOPDT form) has lower degree of stability than second strategy (Gc is in FOPDT and Gp_m in original form). This is because the Nyquist plot for the first strategy may easily be altered to enclose the (-1, j0) (Kuo, 1995). However, the above situation occurs when the Mp value is not restricted. In Mp GM tuning method, the Mp value has been appointed 1.05. Then the stability can be guaranteed.

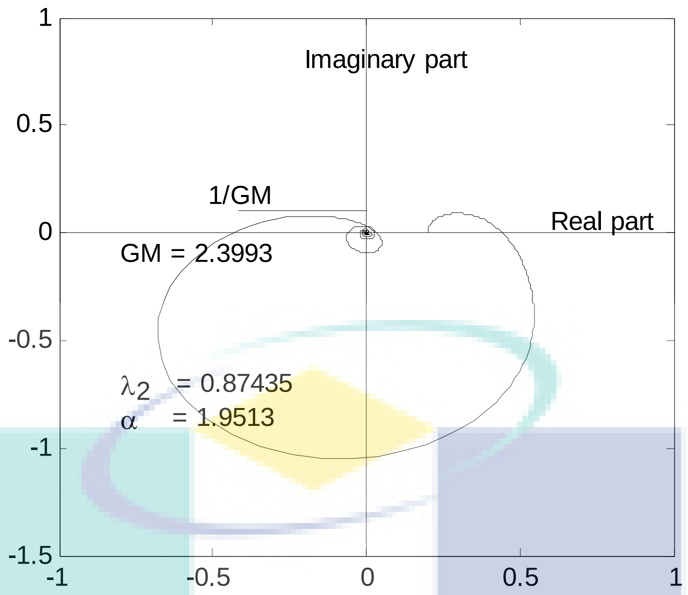


Figure 3.26 Nyquist plot of Mp GM tuning for underdamp SOPDT system with controller transfer functions are FOPDT form.

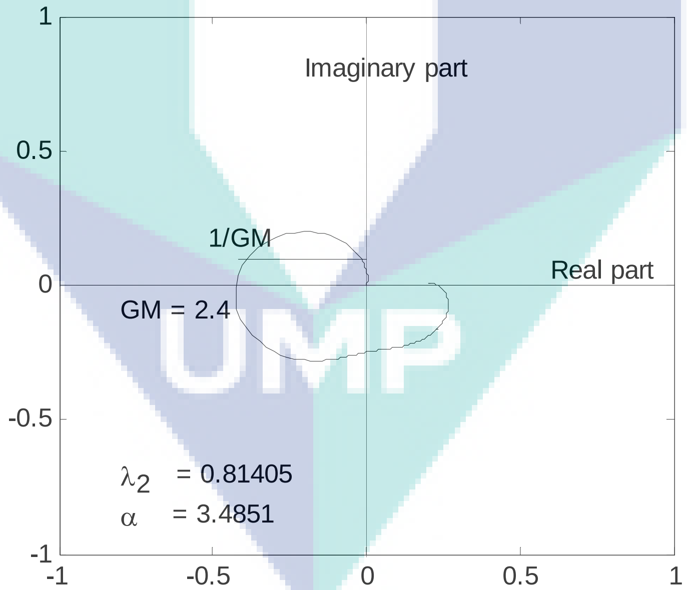


Figure 3.27 Nyquist plot of Mp GM tuning for underdamp SOPDT system with Gc_1 is FOPDT form and Gc_2 is SOPDT form.

Comparison of closed-loop responses of the both strategies with standard 2DOF-IMC can not be conducted. It is because in 2DOF-IMC system, IMCTUNE produces the λ_2 as initial value (any number that is entered to the input). Here, comparison with

1DOF-IMC and Kaya 2DOF-IMC with Mp-GM tuning performance are presented. The filter time constant of 1DOF-IMC (λ_1) for first and second strategy is 1.001 and 0.9159 respectively and the Kaya 2DOF-IMC controller parameters are λ_1 = 0.9045, λ_2 = 0.8141 and α = 0.8456. Figure 3.28 shows the time response when a disturbance magnitude of 0.5 with transfer function of $\frac{1}{0.5s+1}$ is introduced to the system at time 10.

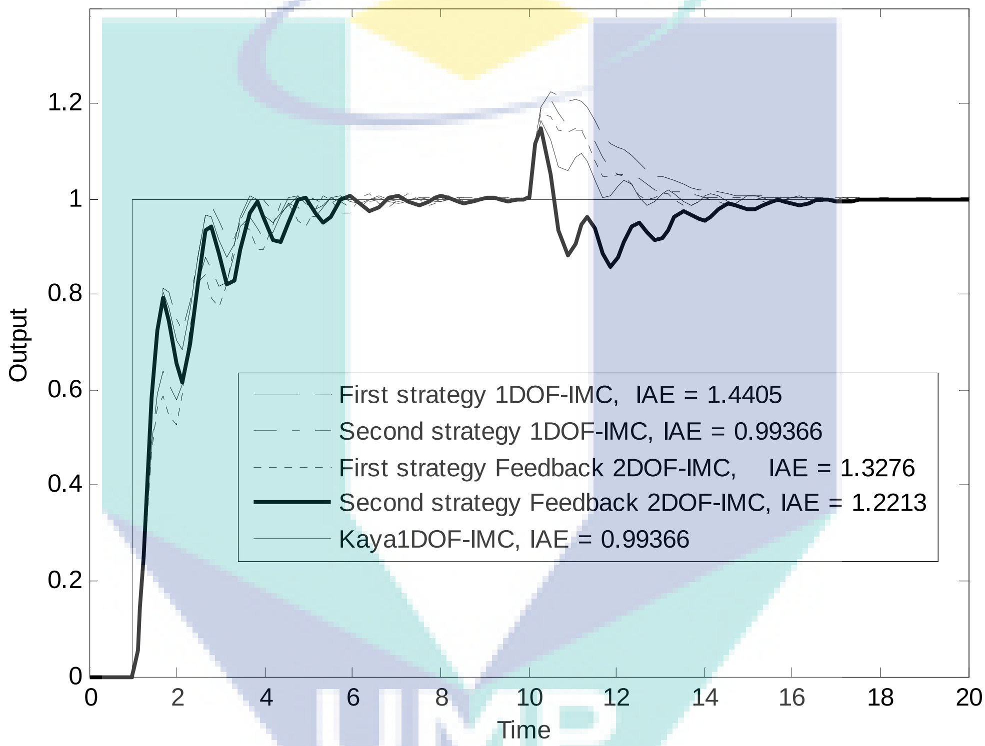


Figure 3.28 Time response of second order with underdamped process using two form controller strategies.

Figure 3.28 shows that the second strategy gives smaller IAE than first strategy both in proposed 2DOF-IMC and 1DOF-IMC. However, the proposed Mp GM yields bigger IAE than standard 1DOF-IMC and Kaya 2DOF-IMC. Here, Kaya 2DOF-IMC produces GM = 2.4 as in the requirement of Mp-GM tuning. It does not like in previous cases that Kaya 2DOF-IMC gives GM value less than 2.4.

3.4.7.2 Third order with non minimum phase process

The proposed method can be imposed to non minimum phase (inverse response) with high order process as described in the case study below. The uncertainty of model parameter is assumed $\pm$ 20%. The simplification of plant model to FOPDT model is based on Skogestad half rule (Skogestad, 2003).

Consider non-minimum phase with high order process below (Skogestad, 2003);

$$Gp = \frac{(-as+1)}{(s+1)^3}, \quad \text{assumed that} \quad 1.6 \le a \le 2.4 \tag{3.29}$$

$$Gp_m = \frac{(-2s+1)}{(s+1)^3} \quad with \;\; FOPDT \;\; Gp_m = \frac{e^{-3.5s}}{(1.5s+1)} \tag{3.30}$$

By using a strategy that Gc is in the FOPDT form and Gm in the original third order with nonminimum phase process, the proposed Mp-GM tuning method generates λ_1 = 4.865, λ_2= 4.3785 and α = 12.1695. The worst case is at plant with zero = 2.4. Figure 3.23 shows the GM criteria of third order with nonminimum phase process on the Niquist plot.

IMCTUNE obtains very large filter time constants (λ_1) for both 1DOF-IMC and 2DOF-IMC. Then the 1DOF-IMC tuning based on Mp criteria is used as comparison with proposed feedback 2DOF-IMC. 1DOF-IMC tuning by using Mp criteria is first step of proposed Mp-GM tuning method. As calculated above, the filter time constant for 1DOF-IMC is 4.865.

Figure 3.29 shows Nyquist plot for the GM criteria of third order with nonminimum phase process on the Nyquist plot. This figure shows that for the minimum case, it has more positive phase shift as ω varies (Kuo, 1995). The closed loop stability criteria is also imposed to the system i.e the Nyquist path does not enclose the (-1,j0). Figure 3.30shows the time response of proposed feedback 2DOF-IMC using proposed Mp-GM tuning method ,1DOF-IMC using IMCTUNE and Kaya 2DOF-IMC..

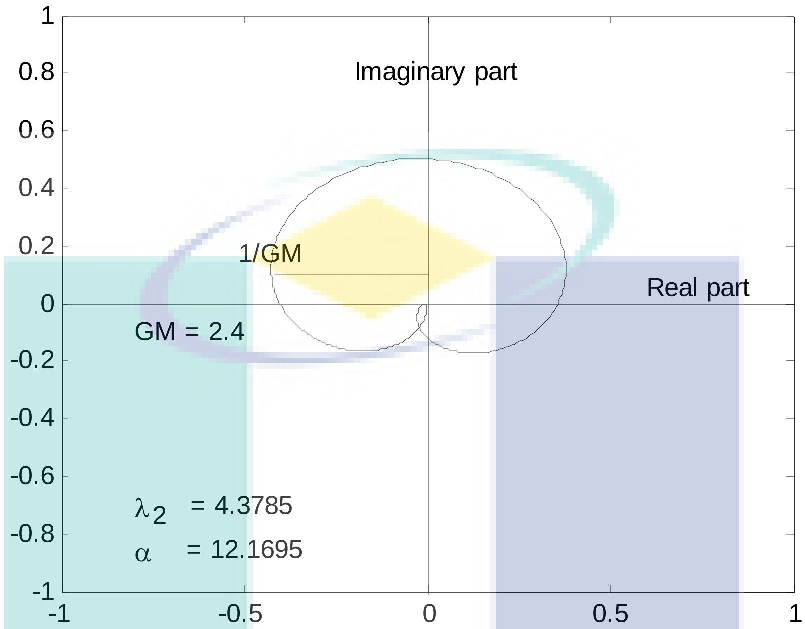


Figure 3.29 GM criteria of third order with nonminimum phase process on the Niquist plot.

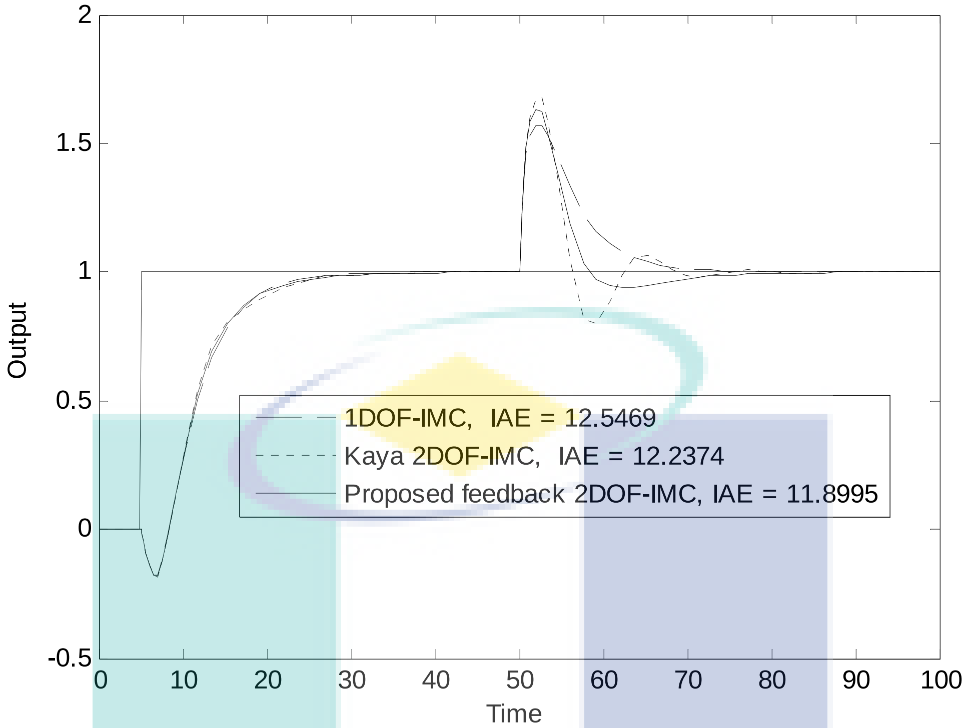


Figure 3.30 Time response of controller design for non minimum phase with high order process.

Figure 3.30 shows that the proposed feedback 2DOF-IMC with proposed Mp-GM tuning obtains the better controller. The proposed feedback 2DOF-IMC yields smaller IAE than 1DOF-IMC with Mp tuning and Kaya 2DOF-IMC. These results prove the superiority of the proposed tuning for difficult process (third order process with nonminimum phase). In this type of process, the IMCTUNE does not give realistic parameters value because it produces very large filter time constant or a value as initial input.

3.5 SUMMARY

A 2DOF-IMC controller based on feedback/feedforward control structure a robust and simple tuning method based on new structure have been proposed. The proposed structure then called as feedback 2DOF-IMC while the proposed tuning method is called Mp-GM tuning method. The parameters were calculated based on frequency response i.e. maximum peak / resonant peak (Mp) and gain margin (GM) criteria. The calculation based on worst case in an uncertainty system.

The proposed method was compared and analyzed with standard 2DOF-IMC with IMCTUNE (Stryczek et al., 2002) and Mp-GM and Kaya 2DOF-IMC with Mp-GM. The proposed method has been successfully implemented to FOPDT and higher order processes. The FOPDT process are varies controllability ratio i.e.; $\theta/\tau \leq 1$, $\theta/\tau \cong 1$ and $\theta/\tau \geq 1$. The higher processes are second order with underdamped and third order with nonminimum phase process. Although the two of higher order process are difficult processes, the proposed feedback 2DOF-IMC and Mp-GM tuning method able to obtain controller parameter under uncertainty system. In the contrast, IMCTUNE did not give robust result for studied system with results for underdamped and nonminimum phase system.

There are several specifications that can be specified in this Mp-GM tuning method i.e. the value of Mp, λ_2/λ_1, and GM. The best value of Mp is 1.05, λ_2/λ_1 is 0.9, and GM is 2.4. The Mp value is determined from the overshoot response when set point is introduced to the system. The best Mp value is selected when the overshoot response is no more than 10%. While the λ_2/λ_1 and GM specifications are determined from the smallest mean of IAE output response of FOPDT process for the worst, nominal and slowest case. The inputs of the output response are set point and disturbance rejection. FOPDT system is used to determine the specification values, because the chemical process model commonly can be simplified to FOPDT transfer function. However, the specifications can be used for higher order difficult process such as underdamped and nonminimum process.

Although Mp-GM tuning is derived from proposed feedback 2DOF-IMC structure, but it can be used for other structures such as the standard 2DOF-IMC and Kaya 2DOF-IMC structure. From the value of IAE, the Mp-GM does not always give the smallest value of IAE as in second order with underdamp process. However, Mp-GM gives smaller IAE values for other studied cases.

CHAPTER 4

EXPERIMENTAL IMPLEMENTATION OF PROPOSED Mp-GM TUNING METHOD

4.1 INTRODUCTION

This chapter describes the practical aspect of the research through the implementation of proposed Mp-GM tuning of 2DOF-IMC on proposed feedback 2DOF-IMC and standard 2DOF-IMC as studied in Chapter 3. An experimental test rig has been developed by modification of existing air flow pressure and temperature (AFPT) process control pilot plant. A hardware-in-the-loop setting was developed using MATLAB and simulink through the use of specific data acquisition card and Data Acquisition Toolbox facilities. The controller was evaluated and compared with standard 2DOF-IMC and IMC control scheme tuned by IMCTUNE (Stryczek et al., 2002) as benchmarking.

4.2 PLANT DESCRIPTIONS

This work adopts the pilot plant AFPT (Air Flow Pressure Temperature) control system, containing three control loops for flow, temperature and pressure control. For simplicity, the pilot plant diagram is described in Figure 4.1. A heater consists of heating element that is spooled on asbestos cement as shown in Figure 4.2. The asbestos cement is assembled inside of galvanize iron pipe (Figure 4.3). The plant can be operated either manually or using Distributed Control System (DCS) in the control room. Temperature (TE91) is manipulated by the electric power. The pressure is manipulated by the compressed air inlet to the system. Under normal operation, the air pressure is 55 psia. The flow rate is manipulated using control valve (FCV91). The maximum flow rate is 50 kg/hr. The heater is installed in the 6 m pipe. The temperature sensor is installed about 1 m from heater outlet. For safety reason, the maximum air temperature is 200°C (Sintech.SDN.BHD, 2003).

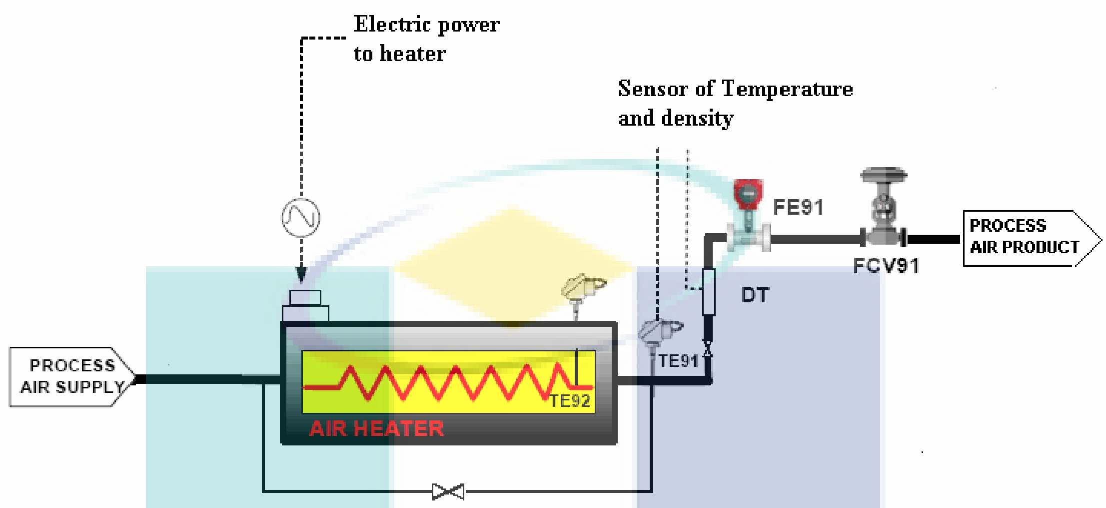


Figure 4.1 Air heater system.

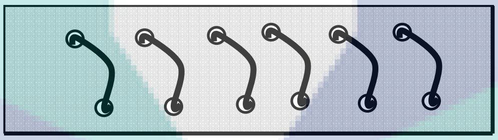


Figure 4.2 Installation of heating element in asbestos cement board.

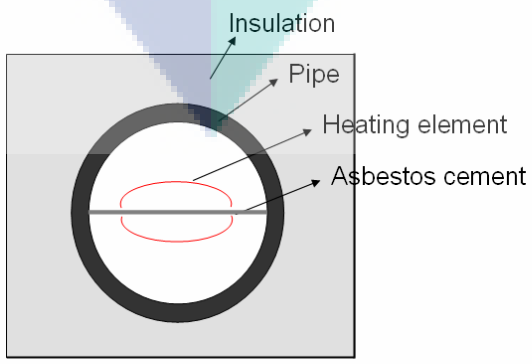


Figure 4.3 Installation of heating element and asbestos cement in galvanized pipe.

4.3 EXPERIMENTAL SETUP

This study was conducted by modifying the equipment of existing pilot plant. Block diagram of field signals to the DCS of AFPT pilot plant shown in Figure 4.4. While the process flow diagram of AFPT pilot plant shown in Figure 4.5. Modifications are made by tapping the input signal i.e flow, pressure, temperature and density. While the output signal is tapped to manipulate the flow and heater power supply. Wiretapping conducted in the Marshalling rack (see Figure 4.4). Signals are forwarded and then inserted into Advantech I/O card via the I/O connector (Figure 4.6). Here, the safety action is carried out in the DeltaV workstation. For example, if the temperature of air is more than 200^{o}C or the air flow is fail then the heater will shut off.

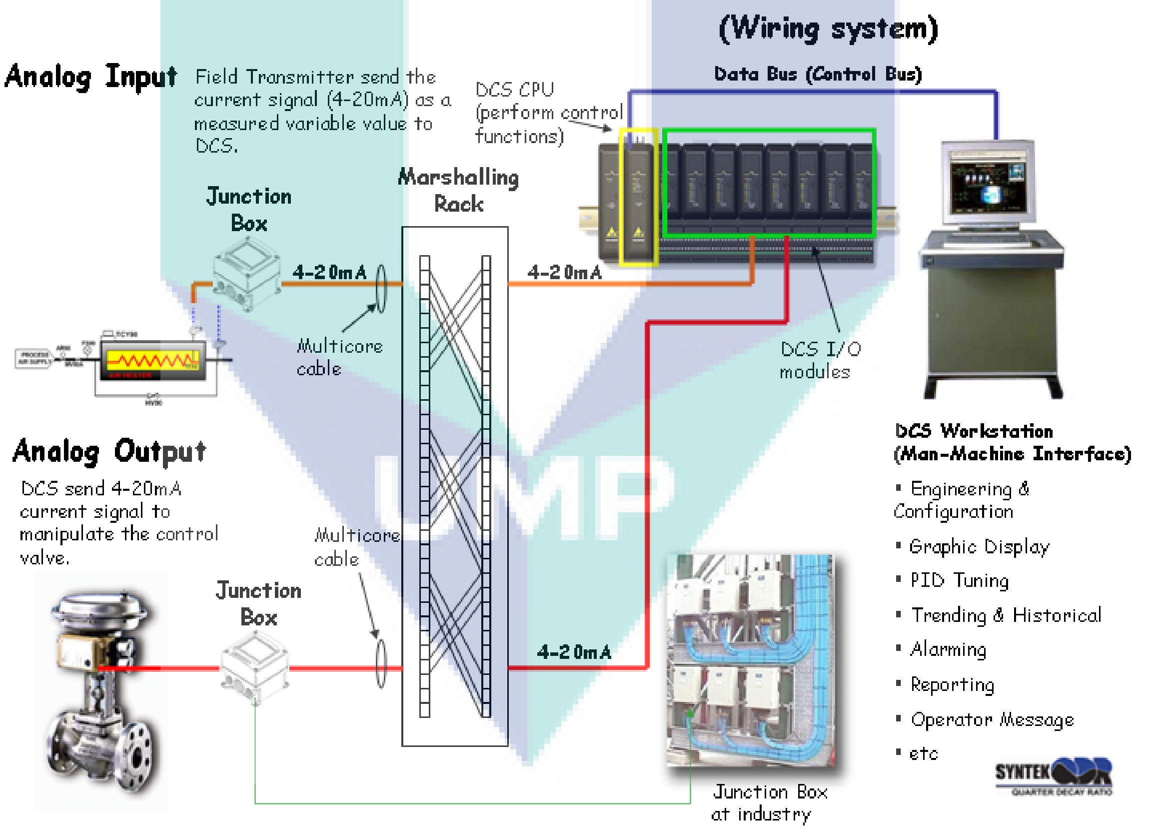


Figure 4.4 The field signal connected to DCS.

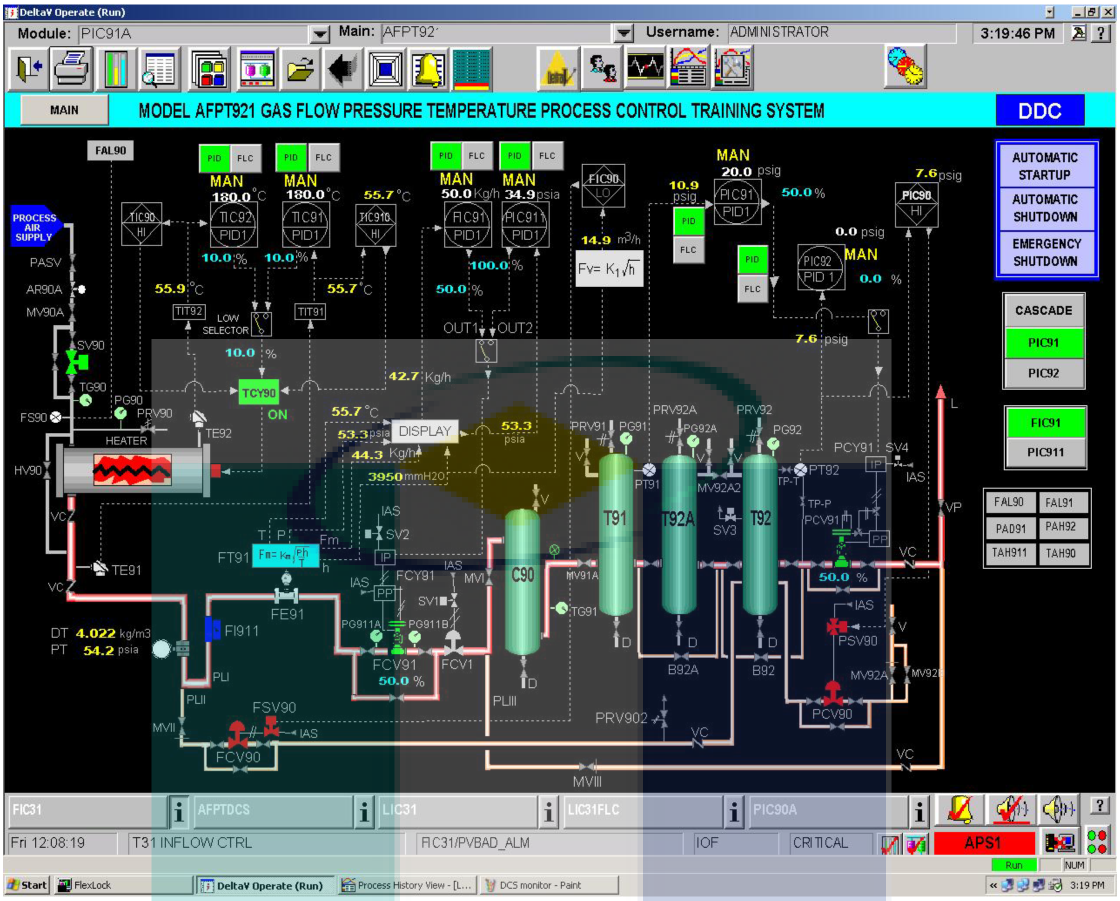


Figure 4.5 Human interface of AFPT pilot plant of deltaV workstation.

Figure 4.6 I/O connector.

This study uses matlab simulink R2009a as human interface software. The software uses data acquisition toolbox to communicate with hardware. Figure 4.7a shows the human interface in simulink program. Figure 4.7b and 4.7c show output and Input data acquisition toolbox (DAT). The hardware uses Advantech PCI-1713 as analog input and advantech PCI-1720U as analog output.

The Advantech PCI-1713 analog input provides 32 analog input channels with a sampling rate up to 100 kS/s, 12-bit resolution and isolation protection of 2,500 V_{DC}. The Advantech PCI-1720U provides four 12-bit isolated digital-to-analog outputs for the universal PCI bus. With isolation protection of 2,500 V_{DC} between the outputs and the PCI bus, the PCI-1720U is ideal for industrial applications where high-voltage protection is required. The I/O cards were mounted in expansion slot of Pentium 4 PC, with RAM (Read Access Memory) 512MB.

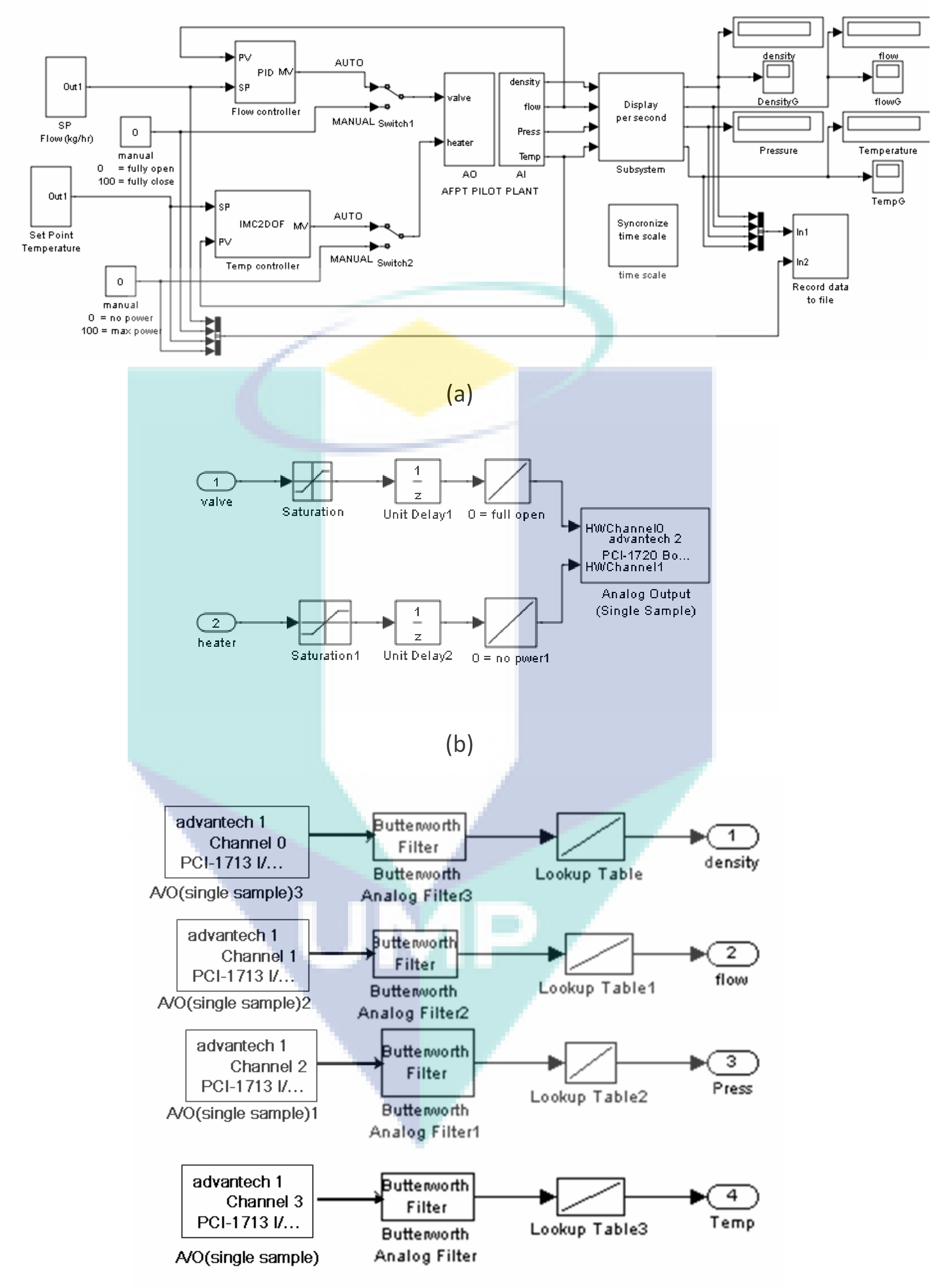
The input signals were filtered by Butterworth lowpass filter (Butterworth, 1930). This filter is approximated by the property that its magnitude response is flat in both passband and stopband. The magnitude-squared function of an Nth-order lowpass filter is given by Parks and Burrus (1987):

$$|H(i\omega)|^2 = \frac{1}{1+(\omega/\omega_c)^{2N}} \tag{4.1}$$

The laplace transform of the Butterworth filter can be derived by the following equation;

$$H(s)H(-s) = |H(i\omega)|^2\Big|_{\omega=s/i} = \frac{1}{1+\left(\frac{s}{i\omega_c}\right)^{2N}} = \frac{(i\omega_c)^{2N}}{s^{2N}+(i\omega_c)^{2N}} \tag{4.2}$$

$$H(s) = \frac{\omega_c^N}{\prod_{k=1}^{N}(s-s_k)} \tag{4.3}$$



(c)

Figure 4.7 (a) Human interface in matlab simulink program, (b) Analog ouput Data acquisition toolbox in simulink, and (c) Analog input data acquisition toolbox.

Where $s_k = (-1)^{\frac{1}{2N}}(i\omega_c) = \omega_c e^{i\pi\left(\frac{1}{2}+\frac{2k-1}{2N}\right)}, k = 1,2,..., N$ (4.4)

Where is cut off frequency (bandwidth), ω is frequency and N is N^{th} filter order. From Eq. (4.2) shows that two parameters (ω_c and N) are specified to get laplace transform. The parameters are set by trial and error, so that output signal has same in trend and magnitude with input signal. The Matlab code of Butterworth filter is presented in Appendix D.

Lookup table is used to convert the measurement signal to the real unit such as flow (kg/hr), temperature (°C) and pressure (psia). The value of the lower and upper are calibrated. As an instance, lower and upper temperature is 0 – 200°C. These values are corresponding to lower and upper signal of 1 – 5 volt. Here, the lower and upper values are captured from the existing pilot plant as in Deltav Workstation.

4.4 MODEL IDENTIFICATION AND CONTROLLER TUNING

4.4.1 Model identification using step response model

Step response is conducted by manual mode controller. At a certain time a step change of power of electrical heater is introduced. Figure 4.8 to 4.11 are the step responses of the process. Based on these Figures, FOPDT model identification are determined. Gain process (k) is deviation final and initial temperature divide by magnitude of the step. Process time constant (τ) is the time required to reach 63.2%. Dead time is response time delay after the step is given. The model identification method can be seen in Figure 4.12. The FOPDT step response models are presented in Table 4.1

Table 4.1 shows the value of FOPDT parameters, τ is ranged from 596-870, and θ is ranged 36-60, and gain values (k) is ranged from 4.1 - 4.9 (data no 1-7). Data no 9 and 10 has k value equal to1.7. Based on the gain (k) values of the process models, the uncertainty model is divided into two regions. Region 1 is data no.1-8 (temperature more than 50^{o}C) and region 2 is data no. 8-10 (temperatures less than 55^{o}C). Maximum, minimum and nominal values of the process model are presented in Table 4.2.

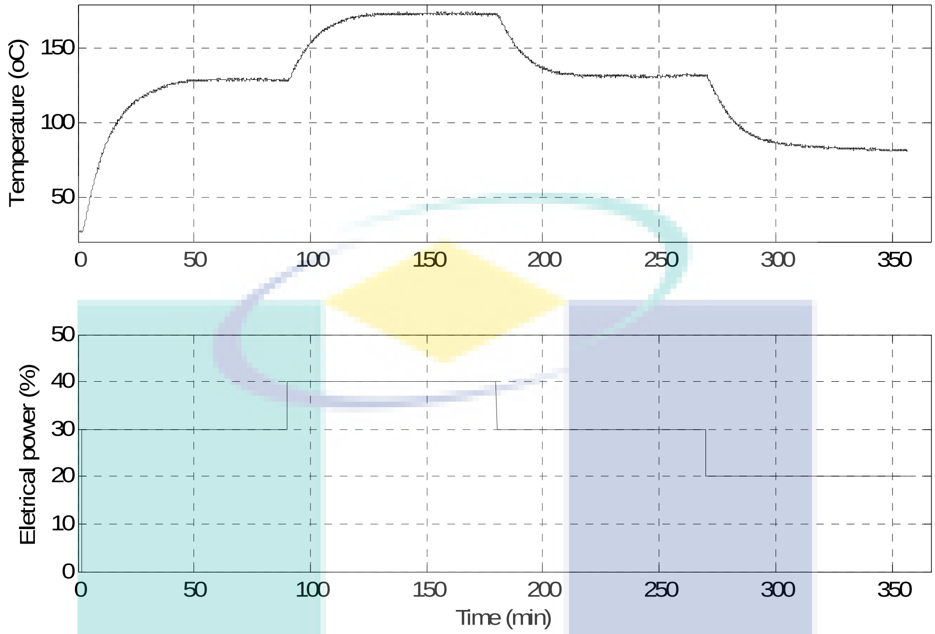


Figure 4.8 Step responses of the plant from 30% to 40%, 40% to 30%, and 30% to 20 %

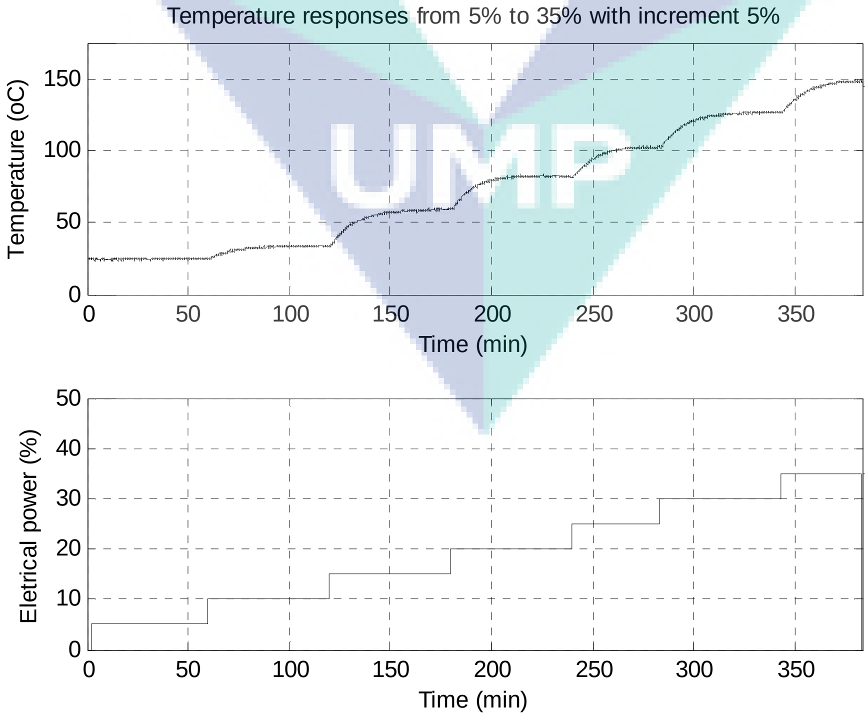


Figure 4.9 Step responses of the plant from 5% to 30% with increment 5%

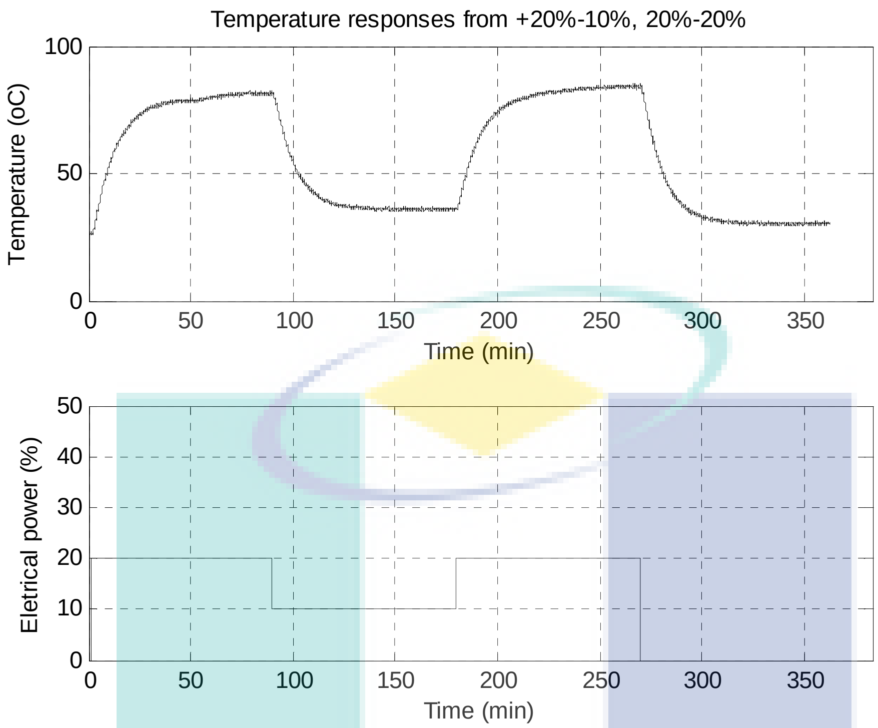


Figure 4.10 Step responses of the plant from 20% to 10% and 10% to 20%

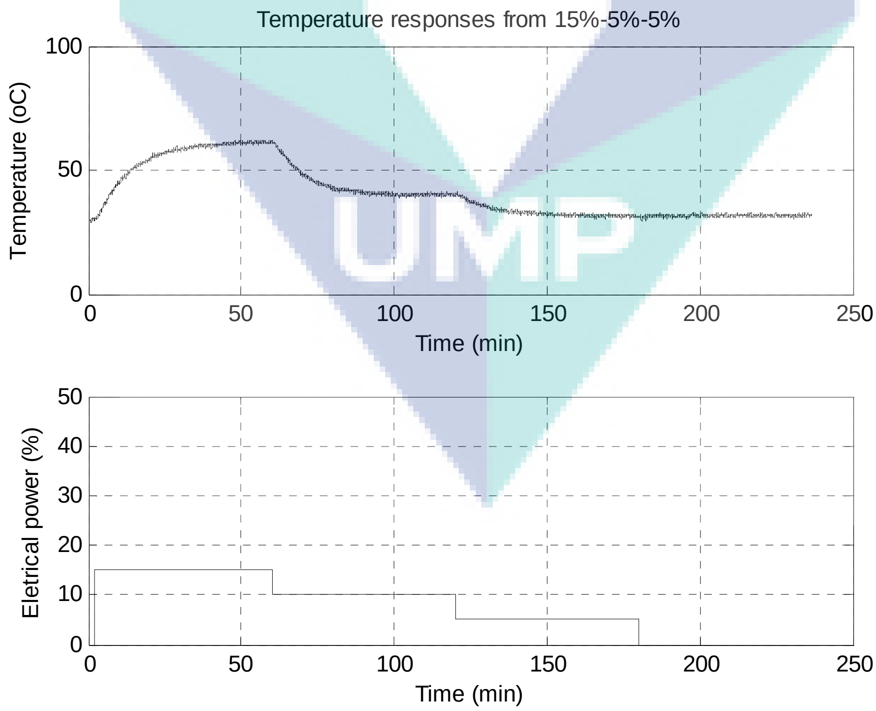


Figure 4.11 Step responses of the plant from 15% to 10% to 5%

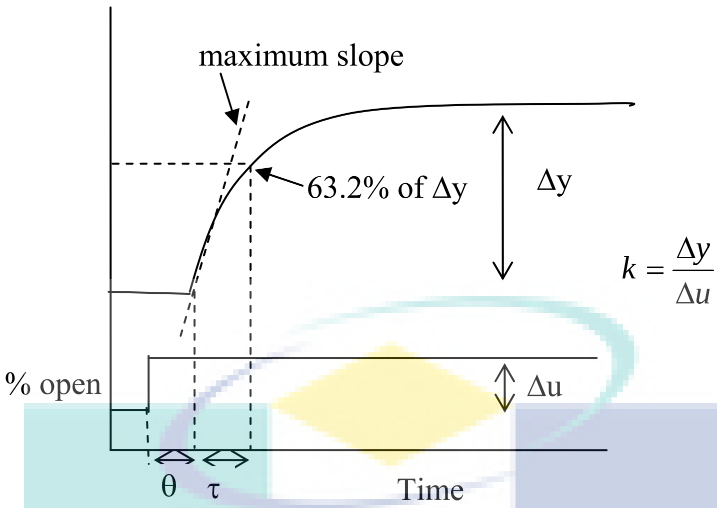


Figure 4.12 Identification of FOPDT model

Data no.10 shows step response from 5-10% and gives temperature from 25^{o}C to 33.8^{o}C. The ambient temperature is about 25^{o}C, it means that step response from 0-5% produces zero gain value or electrical power does not give temperature change for step less than 5%.

Table 4.1 The FOPDT step response models of the plant

No	Step change [%]	Init temp [^{o}C]	New temp [^{o}C]	k, gain	τ [sec]	θ [sec]
1	40 – 43	170.5	184	4.5	726	50
2	40 – 37	170.5	156	4.8	870	60
3	40 – 30	173	132	4.1	605	45
4	30 – 40	130	174	4.4	693	36
5	20 - 10	82	37	4.5	596	45
6	15 - 10	60.5	40	4.1	682	50
7	10 - 20	37	85	4.8	720	50
8	10 - 15	34	58.5	4.9	644	50
9	10 – 5	40.5	31.5	1.7	707	51
10	5 -10	25	33.8	1.7	653	55

Table 4.2 Two regions of process model of AFPT pilot plant.

Region	k	τ, [sec/min]	θ, [sec/min]
Region 1			
Max :	4.8	870/14.5	60/1
Min :	4.1	596/9.9	36/0.6
Nominal (mean):	4.5	733/12.2	48/0.8
Region 2			
Max :	4.9	707/11.8	55/0.917
Min :	1.7	653/10.9	50/0.833
Nominal (mean):	3.3	680/11.3	52.5/0.875

4.4.2 The controller tuning and time responses of AFPT pilot plant

The Mp-GM tuning method of proposed feedback 2DOF-IMC is applied to the AFPT pilot plant. The Mp-tuning method of standard 2DOF-IMC and IMC (IMCTUNE) is designed as benchmarking. In IMCTUNE, the time unit of the transfer function should be converted to minutes and converted to second again in implementation of controller. However, IMCTUNE for 2DOF-IMC suggested the Gc_2 controller as a first order. The Gc_2 controller transfer functions are presented in Table 4.3.

The three controller parameters for both regions are shown in Table 4.3. The responses of the three controllers system change to set point and disturbance are compared. The step of the disturbance is flow rate from 40 kg/hr to 20 kg/hr entered at time 100 (min). The responses on operating condition region 1 are shown in Figure 4.13. Meanwhile, the responses of control system on region 2 are presented in Figure 4.14.

Table 4.3 The three controller parameters for both of regions

Controller type and region	**Gc_1**	**Gc_2**
1DOF-IMC		
Region 1 :	$\frac{1}{4.5}\left(\frac{733s+1}{163.548s+1}\right)$	-
Region 2 :	$\frac{1}{3.3}\left(\frac{680s+1}{183.054s+1}\right)$	-
Standard 2DOF-IMC		
Region 1 :	$\frac{1}{4.5}\left(\frac{733s+1}{163.458s+1}\right)$	$\frac{1}{4.5}\left(\frac{733s+1}{163.482s+1}\right)$
Region 2 :	$\frac{1}{3.3}\left(\frac{680s+1}{413.784s+1}\right)$	$\frac{1}{3.3}\left(\frac{680s+1}{120.624s+1}\right)$
Feedback 2DOF-IMC		
Region 1 :	$\frac{1}{4.5}\left(\frac{733s+1}{64.534s+1}\right)$	$\frac{1}{4.5}\left(\frac{733s+1}{64.534s+1}\right)\left(\frac{174.0506s+1}{58.0806s+1}\right)$
Region 2 :	$\frac{1}{3.3}\left(\frac{680s+1}{68.367s+1}\right)$	$\frac{1}{3.3}\left(\frac{680s+1}{68.367s+1}\right)\left(\frac{206.0703s+1}{61.5303s+1}\right)$

Figure 4.13 shows the proposed feedback 2DOF-IMC tuned by proposed Mp-GM tuning yields the fastest response to reach the new set point and the fastest response to reject the disturbance. It shows that IMCTUNE can not determine the optimal parameters in the air heater system. Even, standard 2DOF-IMC produces larger IAE than 1DOF-IMC. It is because IMCTUNE suggests that the Gc_2 is first order that has filter time constant similar to Gc_1 time constant.

The disturbance rejection responses of the three of controllers system are still very slow to return to the initial set point may take up to 30 minutes (Figure 4.12). This is because a change in flow rate is significant from 40kg/hr to 20kg/hr. At a high temperature the heater is very hot, so if there is a significant decrease in flow rate so the temperature will be increase quickly and then decrease slowly even though the percentage of electrical power is 0%. The saturation lower limit of the control system is

0%, it could not be worth the negative as in simulation. It is because the real plant has the minimum value of control action is 0% (saturation) and maximum value is 100%.

Figure 4.13 shows when the disturbance entered to the system at time 100 min, the inverse response were detected for about 2 min. The temperature decreases for a short while due to the increase of pressure in the chamber. The pressure increase is because the control valve for flow is installed after air heater chamber.

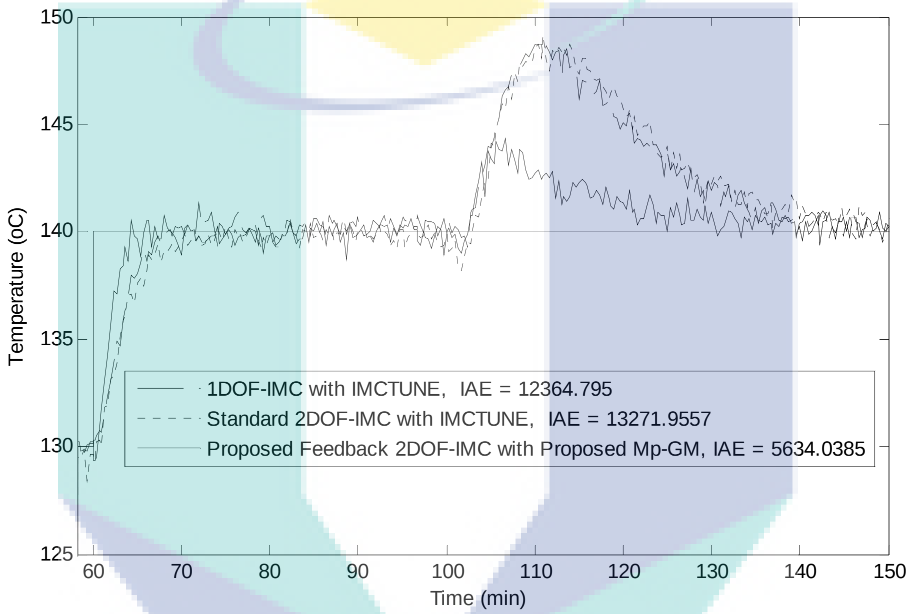
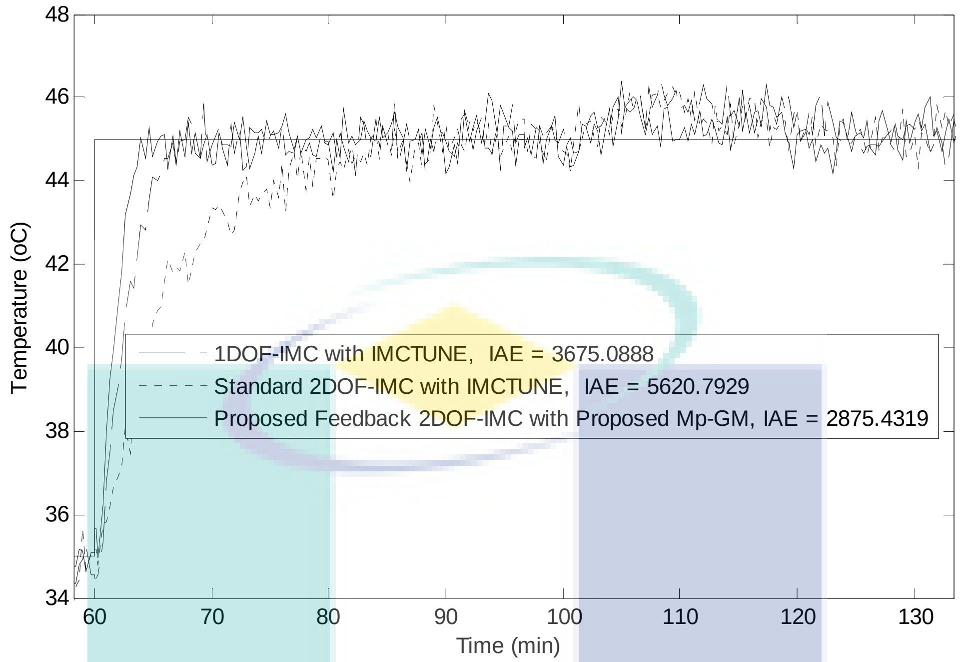


Figure 4.13 The responses of the three controllers system on region 1.

In region 2, Figure 4.14 shows the proposed feedback 2DOF-IMC with Mp-GM tuning produces the fastest set point tracking and disturbance rejection. The disturbance entered at 100 min. On this region 2, the disturbance can be rejected quickly by all the three controller system. Since at low temperature range, the heater is not too hot then the rising temperature due to changes in flow from 40kg/hr to 20kg/hr could still be overcome easily.

Data from Figure 4.13 and 4.14 proved that the proposed feedback 2DOF-IMC with Mp-GM tuning gives the better results both for set point tracking and disturbance rejection for both of the regions.



(a)

Figure 4.14 The time responses of the three controllers system on region 2.

4.5 SUMMARY

The air heater process has two regions that are very different characteristic from the parameters of the process transfer function. Then the use of one controller may not be appropriate. From the close loop response it can be seen that the disturbance in region 2 can be rejected easily. While in the region 1 the disturbance rejection is very slow.

IMCTUNE method encountered problem when the value of τ and θ are too large. The unit (sec) of τ and θ then should be converted to unit (min) to make its parameters are smaller. However, IMCTUNE method can not generate the good controller parameters of 2DOF-IMC in all regions as it suggested first order transfer function in Gc_2 controller.

In region 1, the controller still can not reject of disturbance quickly because there are a few things; heater has a high temperature so that in addition to conduction and convection heat transfer process occurs radiation (radiation occurs when the surface temperature over 500^{o}C). The occurrence of radiation process causes the pipe to be more heat than the air. So the pipe is also a heat source when the heater power is reduced. This is the reason that the disturbance response is very slow. This is evident in region 2, where the process is running at low temperatures. In this range, heater temperature is not too hot so that the radiation has not yet occurred. So the response to this disturbance may be faster.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In overall this research is to overcome the weaknesses of IMC controller which giving very sluggish response to disturbance rejection. The problem could be eliminated using 2DOF-IMC. However, the existing tuning method derivation under model uncertainty using structure of standard 2DOF-IMC is mathematically complicated and has its limitation. Therefore it is needed to develop a tuning method which will simplify the tuning of 2DOF-IMC under model uncertainty.

This research proposed a new structure and a new tuning method for 2DOF-IMC. The new structure is derived based on feedback/feedforward IMC schema and it is called as feedback 2DOF-IMC. The feedback loops is presented with Gc_1 and feedforward controller is presented with Gc_2. The Gc_1 then is set as set point controller and Gc_2 is set as disturbance rejection controller. With the principle of classical feedback structure, frequency response tuning such as Mp and GM can be implemented easily. Mp is used for tuning of Gc_1 while GM is used for tuning of Gc_2. The tuning is determined based on worst case of an uncertainty process. The proposed tuning method is then called as Mp-GM tuning.

There are several specifications should be set to obtain the optimal controller parameters. The values of these specifications are determined based on time response and IAE value on the worst case, the nominal case and the slowest case of FOPDT processes. FOPDT with $\theta / \tau \geq 1$ was used to prove that the time response was identical when feedback 2DOF-IMC and standard 2DOF-IMC were tuned by Mp-GM method. The FOPDT $\theta/\tau \geq 1$ also used to determine the Mp value. FOPDT with $\theta/\tau \leq 1$ was used to find the best ratio of λ_2/λ_1. Meanwhile, FOPDT with $\theta/\tau \cong 1$ was used to get the best value of GM. Mp value is selected when the overshot of step response is less than 10%. The ratio of λ_2/λ_1 and GM are selected based on the minimum mean of IAE values on worst, nominal and slowest case. The specifications were obtained as follows.

(i) Mp is set to 1.05.

(ii) λ_2 is set to 0.9 λ_1

(iii) GM is set to 2.4

The effectiveness of the proposed feedback 2DOF-IMC and Mp-GM tuning method is also simulated and compared through higher processes include second order with underdamped and third order with nonminimum phase processes. The comparison are conducted with standard 2DOF-IMC using IMCTUNE tuning and Kaya 2DOF-IMC using Mp-GM tuning. Although the two of higher order process are considered difficult processes, the proposed feedback 2DOF-IMC and Mp-GM tuning method were able to obtain the better controller even under process uncertainties. Effects of model and controller form simplification were studied. The results show that Gc in FOPDT form and Gm in the original high order form gave smaller IAE (better time response).

The proposed feedback 2DOF-IMC and the proposed Mp-GM tuning are also successfully implemented in real-time on a laboratory scale air heater pilot plant. The process model is divided into two regions. The time responses show that the proposed feedback 2DOF-IMC and the proposed Mp-GM tuning gave faster set point tracking and disturbance rejection responses than 1DOF-IMC or standard 2DOF-IMC in both regions.

5.2 RECOMMENDATIONS FOR THE FUTURE WORKS

A number of recommendations for future work that may enhance the superiority of the proposed Mp-GM method are outlined as follows:

a. Implementation to auto tuning is a challenge for the Mp-GM tuning method.
   Parametric uncertainty model of a process can be identified in some range of operating conditions with the relay feedback test. The 2DOF-IMC controller parameters can be easily calculated with Mp-GM tuning method after identifying the model of the process.

b. Experimental study to various types of chemical processes should be performed.
   Further ensure the benefit of the proposed method. It is necessary to test on other chemical processes that have different characteristics from those have been exemplified in the present study.

c. Future research is needed to formulate Mp-GM method for multi input multi output (MIMO) system.
   Operating conditions such as temperature, pressure and flow should be maintained simultaneously to maintain the product quality. Operating conditions may be maintained at several different points. So the interaction between process variables can not be avoided. Process control in such cases is very difficult to resolve with SISO control system and it is necessary to apply MIMO control system. Feedback 2DOF-IMC and Mp-GM tuning is possible applied to the structure of MIMO control system. The main loop transfer function and interaction can be identified with a step response. Sensitivity, complementary sensitivity, open-loop and closed loop transfer function can be stated in a matrix. Mp-GM tuning criteria can be applied to these matrices.

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Appendix A

LIST OF PUBLICATIONS

A.1. Journal

1. Juwari, R.Mamat, S.Y Chin and B.B.Abdul Aziz. A robust and simple tuning method for two-degree-of-freedom internal model control under model uncertainty. *International Journal of Control, Automation and Systems. (submitted)*

A.2 International Conference

1. Juwari, S. Y. Chin., B. B. Abdul Aziz and N. A. F. Abdul Samad. A Structure of Two-Degree-of-Freedom Internal Model Control from Feedback/Feedforward Scheme. *10^{th} International Conference on Automation, Robotics and Computer Vision (ICARCV)*, 17-20 Desember 2008, Hanoi, Vietnam.

2. Juwari, R.Mohd Yunus, S. Y. Chin., B. B. Abdul Aziz and N. A. F. Abdul Samad. Two-Degree-of-Freedom Internal Model Control for Paralell Cascade Scheme. *International Symposium on Information Technology (ITSIM)* 26-29 August 2008, Kuala Lumpur, Malaysia

3. Juwari, S.Y. Chin, R. Mamat. Open loop responses of air heater system. *3^{th} International Conference on Chemical and Bioprocess Engineering (ICCBPE 2009)*, 12-14 August 2009, Universiti Malaysia Sabah.

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A.3 National Conference

1. Juwari, B.B. Abdul Aziz and M.Y. Mohd Yunus. Gas Density Control Based on Inferential Cascade PID Strategy. *Malaysian Science and Technology Congress (MSTC)* 4-6 September 2007 Subang Jaya, Malaysia.

2. Juwari, B.B. Abdul Aziz and M.Y. Mohd Yunus. Soft Gas Densitometer Using Semi-Empirical Model. *21^{st} Symposium of Malaysian Chemical Engineers (SOMChE)* 12-14 December 2007 Kuala Lumpur, Malaysia.

3. Juwari, S. Y. Chin., B. B. Abdul Aziz and N. A. F. Abdul Samad. Internal Model Control for Parallel Cascade Control System. *Malaysian Technical Universities Conference on Engineering and Technology (MUCET)* 8-10 March 2008 Perlis, Malaysia.

APPENDIX B

MATLAB CODE OF PROPOSED Mp-GM TUNING FOR 2DOF-IMC

```
clear all
clc
%this program designed for SOPDT process
% input lower and upper bound of plant model parameters (Gp)
ap=[-7.28 -4.86];
bp=[-55 -36.66];

%input fix model parameters (Gpm)
km=-1.28;
taum=0.05;
tetam=0.15;

iter=0;
w=logspace(-3,3,200);
s=1i*w;
hold off
disp('    ')
disp(' This program is designed by Juwari ...')
disp(' Please wait.... ')
disp('    ')
for f1=1:2
    a=ap(f1);
    for f2=1:2
        b=bp(f2);
            lamda1=tetam;
            pm=(km*exp(-tetam*s))./(taum*s+1);
            pw=(a*s+b)./(s.^2+1.79*s+35.8);
            iter=iter+1;
            Cimc=(taum*s+1)./(km*(lamda1*s+1));
            T=abs((pw.*Cimc)./(1+ (Cimc.*(pw-pm))));
            CSm=max(T);
            disp(sprintf('Case(%2.0f) a=%4.4f,b=%4.4f, max|T
(jw)|=%4.4f',iter,a,b,CSm));
            figure(1)
            loglog(w,T);
            ylabel ('|T (j\omega)|')
            xlabel('\omega (frequency)')
            hold on
            drawnow;
            para(iter,:)=[a b CSm];
    end
end

m=max(para(:,3));
iter=0;
for i=1:size(para)
    iter=iter+1;
    if para(i,3)==m
        param=para(i,:);
        break
    end
end
```

```
%IMC
disp('    ')
disp (sprintf('The wosrt case is case (%2.0f)',iter));
disp('    ')
app   =param(1);
bpp   =param(2);

fac=taum/20;
Mp=3;
while Mp >=1.05
    fac= fac+0.001;
    lamda1=fac;
    w2=logspace(-3,3,201);
    s=1i*w2;
    pm=(km*exp(-tetam*s))./(taum*s+1);
    pw=(app*s+bpp)./(s.^2+1.79*s+35.8);

    C1=(taum*s+1)./(km*(lamda1*s+1));
    CS=abs((pw.*C1)./(1+C1.*(pw-pm)));
    Mp=max(CS);

end

figure(2)
loglog(w2,CS);
ylabel ('|T (j\omega)|')
xlabel('\omega (frequency)')
text(1,2,['max = ',num2str(Mp)])
text(.1,.1,['\lambda 1 = ',num2str(lamda1)])
%2dof
faklamd2=0.7;
lamda2=faklamd2*lamda1;
alpa=lamda2;
GM=1;

while GM<=1.7
    alpa=alpa+0.0001;
    w3=logspace(-3,3,1000);

    s=1i*w3;
    pm=(km*exp(-tetam*s))./(taum*s+1);
    pwp=(app*s+bpp)./(s.^2+1.79*s+35.8);

    C1=(taum*s+1)./(km*(lamda1*s+1));
    C2=C1.*(alpa*s+1)./(lamda2*s+1);
    Cd=(C1+C2)/2;
    S=abs((1-pm.*Cd)./(1+Cd.*(pwp-pm)));
    T=abs((pwp.*C1)./(1+Cd.*(pwp-pm)));
    OL=Cd.*(pwp-pm);
    reg=real(OL);
    img=imag(OL);
    %cari GM pada axis real negatif
    sudut=angle(OL);
    err=0.1;
    a=find(sudut<pi+err & sudut>pi-err);
    b=OL(a) ;

    re=real(b);
```

```
    im=imag(b);
    g=abs(min(re));
    GM=1/g;

end
disp('.:              Robust and Simple Tuning of              :.')
disp('.:       The Proposed Feedback 2DOF-IMC Controller      :.')
disp('.:====================By Juwari===================== :.')
disp('     ')
disp        (' 1. The wosrt case plant model     ')
disp(sprintf('     Gp  = (%4.4f*s+%4.4f)/(s^2+1.79*s+35.8)',app,bpp))
disp(sprintf('     Gpm = %4.4f*exp(-
%4.4f*s)/(%4.4f*s+1)',km,tetam,taum))
disp ('      ')
disp        (' 2. Controller paramaters')
disp(sprintf('     Gc1 = (1/%4.4f) *
(%4.4f*s+1)/(%4.4f*s+1)',km,taum,lamda1))
disp(sprintf('     Gc2 = Gc1 * (%4.4f*s+1)/(%4.4f*s+1)',alpa,lamda2))
disp ('  ')
disp         (' 3. Additional informations')
disp         ('    See the figures ');
disp(sprintf ('          lamda2=%4.4f *lamda1', faklamd2));
disp(sprintf ('          max|T (jw)| = %4.4f', Mp));
disp(sprintf ('          GM          = %4.4f', GM));

xya=-1.2:0.01:1.2;
gx=min(re):0.01:0;

figure (3)
plot(reg,img,xya,0,0,xya,gx,0.1,'r','linewidth',1.4)
axis([-1 1  -1.5 1])
text(0.6,0.05,'Real part')
text(-0.2,.8,'Imaginary part')
text(min(re)-0.1,0.17,'1/GM')
text(-.8,-.7,['\lambda 2 = ',num2str(lamda2)])
text(-.8,-.8,['\alpha     = ',num2str(alpa)])
text(-.8,-.1,['GM = ',num2str(GM)])
hold off
```

APPENDIX C

TUNING PROCEDURE OF IMCTUNE

The Mp-tuning software is adopted from website of prentice hall publisher http://www.phptr.com/brosilow/ . The software is copyright by Karel Stryzek, Jiawen Dong, Tinnakom Kunsen, and Coloman B Brosilow (2002). Figure C.1 shows the primary IMCTUNE interface for 2DOF-IMC control system for the case where disturbance passes through the process. The controller is split into two parts: forward path and a feedback part. While the menu bar for 1DOF-IMC and 2DOF-IMC systems are the same, but contain of view and compute tab are different.

Several input data are needed i.e.; disturbance model (Pd), the process-bound uncertainty, the nominal model, the feedback path controller (qqd or Gc_2), and the forward path controller (qr or Gc_1). After all the data are inserted then the tuning can be done by click **compute|2 degree of freedom tuning | inner loop tuning | partial sensitivity function** (see Figure C.2)

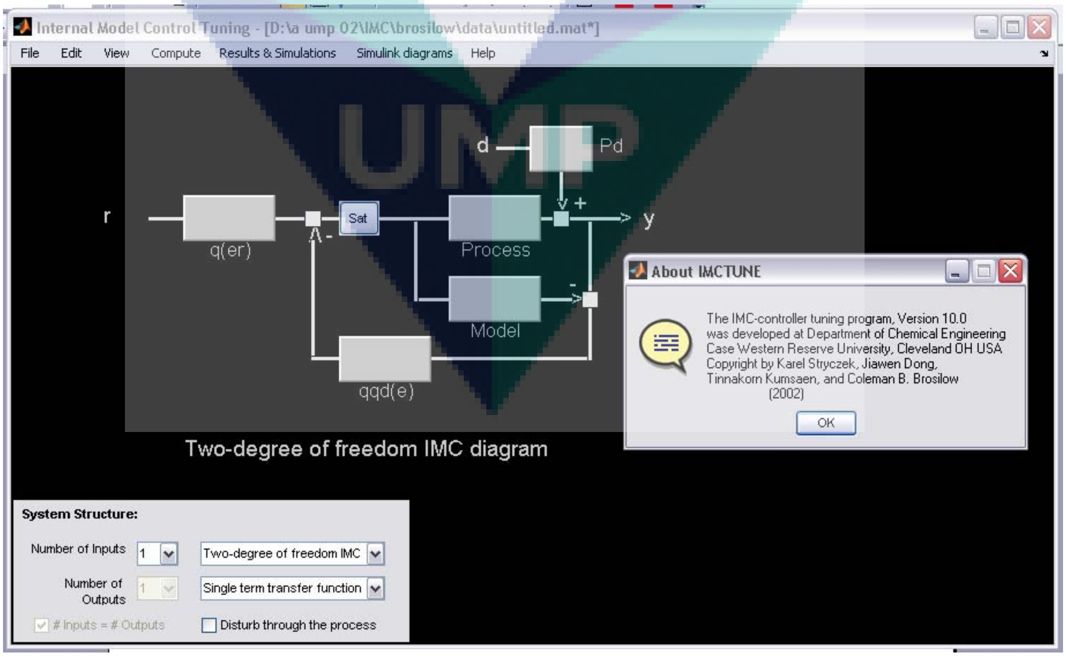

Figure C.1 Primary interface of IMCTUNE 2DOF-IMC

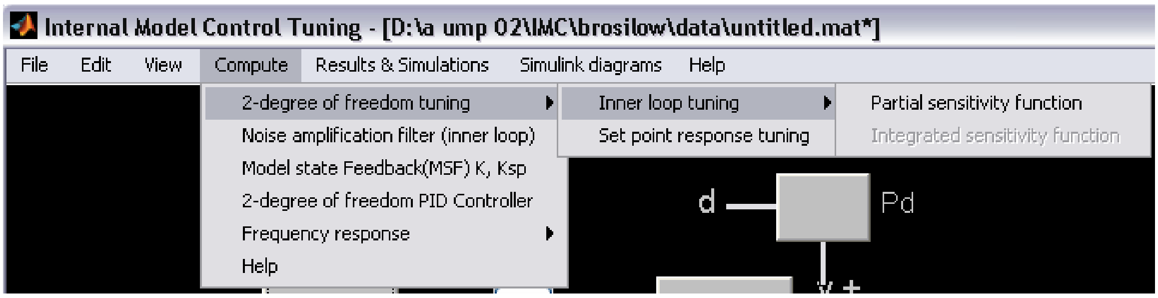

Figure C.2. Tuning 2DOF-IMC

Figure C.3 shows the result of the Mp-tuning of 2DOF-IMC. The main results are model of feedback controller (Gc_2) and forward path controller (Gc_1). The others are input and default variables.

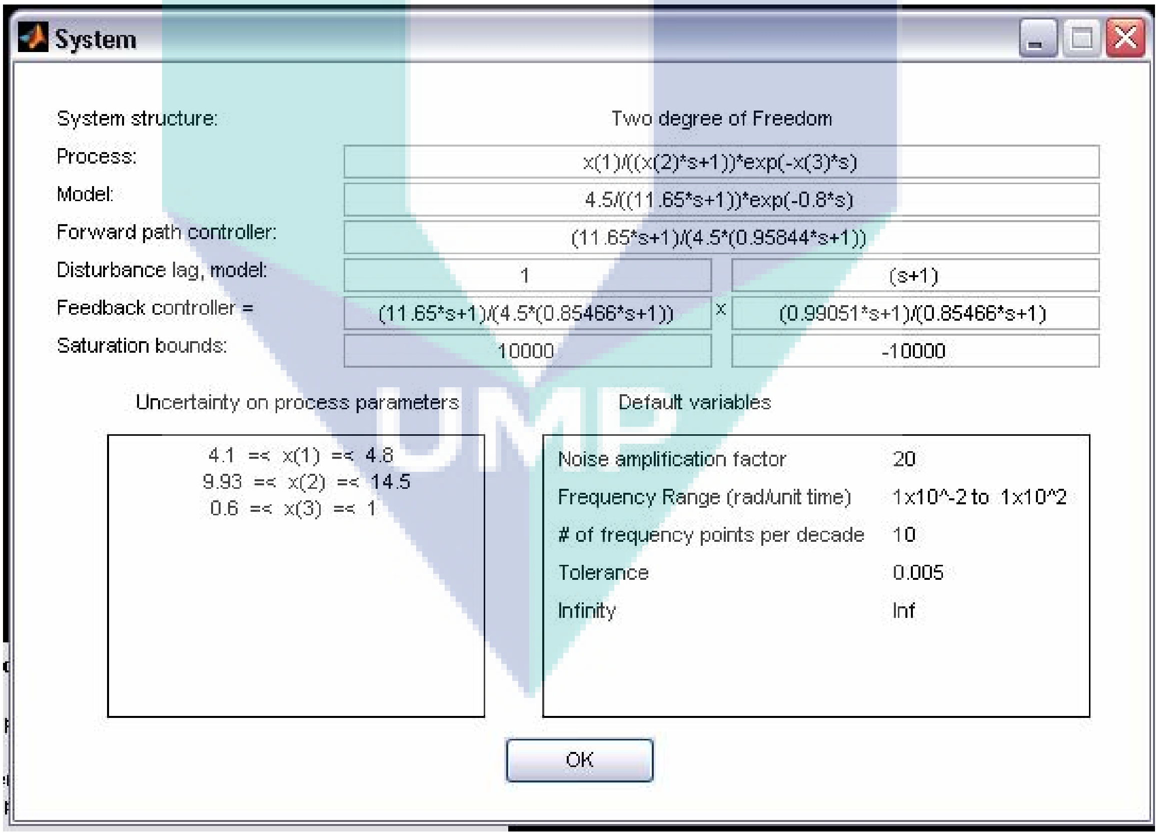

Figure C.3 Result of Mp-Tuning for 2DOF-IMC

APPENDIX D

BUTTERWORTH FILTER CODE USING MATLAB S-FUNCTION

```
function [B,A] = butterdesign(N,Wc)
%BUTTERDESIGN Butterworth adopted by William Spinelli %
p = Wc*exp(i*(pi*(1:2:N-1)/(2*N) + pi/2));
p = [p; conj(p)];
p = p(:);
if rem(N,2)==1, p = [p; -Wc]; end
A = poly(p);
B = real(prod(-p));
```