

# **Optimization of Pseudo Random Binary Sequence (PRBS) combination for Online Modeling of MIMO Ill-conditioned System**

by

Khor Wooi Kin  
14930

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UNIVERSITI TEKNOLOGI PETRONAS  
32610, BANDAR SERI ISKANDAR,  
PERAK DARUL RIDZUAN

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## **Abstract**

This paper aims to improve the performance of system identification based on optimization of Pseudo Random Binary Sequence (PRBS) excitation signal combination for Multiple-Input Multiple Output (MIMO) Ill-Conditioned system. Ill-conditioned system is defined as system that is formed by various variables and the level of interaction between all the variables is high. It is found that in the case of ill-conditioned system, the design of PRBS combination as excitation signal will affect the performance of system identification. The experimental subject of this paper is the air pilot plant that is located in Universiti Teknologi PETRONAS (UTP). Empirical modeling method is first used to obtain the steady gain matrix of the system, followed by the transfer function based on the time constant of the system. A process will be created on simulation based on the transfer function obtained. High correlated, moderate correlated and un-correlated set of PRBS will be used as excitation signal for system identification. The test signal combination will also be tested in the real plant implementation. The performance of different combination of PRBS will be examined by using Bode plot and fit percentage. The result shows that the lower the correlation, the better the modeling performance for the operation in both simulated and real process environment.

## **Chapter1: Introduction**

### **1.1 Background of Studies**

Controller design is the key feature in control system, the design can only be good if enough information about the process or system is available. This is where the system identification works, in order to know the plant characteristic and behavior in details by using input-output data of the plant. However, according to Pajonk (2009) and Kumar et.al (1986), normal steady routine of input-output data is not critical enough to actually approximate the plant behavior, an application of excitations signal as an input to the system is needed [1] [2]. Pseudo Random Binary Sequence (PRBS) is one of the most common test signal used in the industry.

There are many types of process system in the industries and the requirement for excitation signal is different for each type of process system. In this paper, our focus is put on the Multiple-Input Multiple-output (MIMO) ill conditioned plant. Ill-conditioned process plant is defined as the process plant that has high level of interaction between all the variables (inputs and outputs). The performance of system identification is not stable by using random sets of input test signal, it is interesting to investigate the relationship between excitation signals that can affect the performance of system identification.

Our main task in this paper is to design a set of input test signal that is able to carry out the best performance of system identification. The result will then be implemented in the real process plant, which is the air pilot plant that is located in Universiti Teknologi PETRONAS. This is one of the main motivation of this paper as many research have proved performance of test signals solely in simulation software platform, but not tested with the real plant design as the operator of plant rather not to disturb the daily operation.

With the principle of control engineering, reference of literature review and the case study of air pilot plant, conclusion about the type of combination of input signals that can improve system identification of ill-conditioned plant is expected.

## **1.2 Problem Statement**

System identification is crucial in the industry as it helps the operator to understand the behavior and the characteristic of the process plant. For a Multiple-Input Multiple-Output (MIMO) process, a set of excitation signal is required in order to carry out the system identification. Often, the excitation signals are designed individually and randomly selected to form a set of excitation signal. However, researches show that certain undefined combination of excitation signals can affect the performance of system identification. It is interesting to investigate and define the actual relationship between excitation signals so that the performance of system identification can be improved and the controller becomes more reliable.

## **1.3 Objective**

By referring to the previous section of background and problem statement, the objectives of this paper are summarized and listed as below:

- To define and design the best combination of excitation test signals that can improve and stabilize the performance of system identification in MIMO ill-conditioned system. Virtual Process is built on MATLAB Simulink based on Air Pilot Plant Model and the performance of excitation test signal sets are examined based on their real time response and frequency response.
- To implement and validate the result from simulation into real process plant that has MIMO and ill-conditioned properties which is the air pilot plant located in Universiti Teknologi PETRONAS. Similar to the simulation procedure, performance of excitation test signal sets are examined based on their real time response and frequency response.

## **1.4 Scope of Study**

It is important to limit the scope of study as the knowledge of System Identification is too huge. This project will cover just the system identification based on excitation signal, more specifically PRBS. The objective is to determine how the test signal combination affects the performance of identifying a MIMO ill-conditioned process. If there is extra time, the experiment will be repeated but in closed-loop operation.

## Chapter 2: Literature Review

According to Grevers (2005), almost 75% of the budget for control related project is used to develop the plant model [3]. Thus, it is vital to improve the effectiveness of system identification for modeling the plant in order to be cost effective. System identification is first found in 1960s, and becoming more and more popular in the last 2 decades [2] [4]. This chapter aims to analysis the past research and experiments, learn from the past experience in conducting relevant system identification. A brief introduction of different type of system identification will first be introduced, followed by two approaches to define the interaction of multi-variable in the system, the next section will present the analysis and comparison of few past researches and experiment, and ends with a brief conclusion of the chapter.

According to Prof. Bemporad A. (2010), there are three types of system identification models which are white box, grey box and black box [5]. Further reference to Ljung (1987), white-box model refers to model which the structure is fully based on first principle, while the structure of grey-box is partially known from first principle and the structure as well as parameters and last, the black-box model is completely unknown and solely based on the input-output data [6]. In this paper, the model is defined as black-box as the estimation of structure and parameters depends purely on the input-output data.

Our main focus is about Multiple-Input Multiple-Output (MIMO) system, the research direction is different with Single-Input Single-output (SISO) system as the MIMO system has multiple interactions [7]. Often, the MIMO system is related to the condition number of the system, condition number is parameter to measure the degree of interaction between the multi-variables of the system. High condition number indicates high degree of interaction between variables, if the system has condition number larger than 1, it is then defined as ill-conditioned system [8] [9] [10] [11] [12] [13]. The physical or specific explanation of ill-conditioned is simply that it is very difficult to alter or control any output from one input, as the outputs are dependent to more than one input [9]. According to Haggblom (2014) and Sadabadi and Poshtan (2009), Singular Value Decomposition (SVD) is employed to determine the condition number of a process system [11] [12] [13]. Given the MIMO system with  $M \times M$  inputs and outputs as follows:

$$Y(s) = G(s)u(s) \quad (1)$$

Where  $Y(s)$  is the output of the system,  $u(s)$  is the input of the system and  $G(s)$  is the transfer function of the system, yields SVD of:

$$G(s) = W\Sigma V^T \quad 2$$

Where  $\Sigma$  is the diagonal matrix when  $W$  and  $V$  are the orthogonal matrices of the transfer function. The ratio of diagonal matrix defines the condition number of the system [11] [12] [13]. Another interesting parameter that we can get from the SVD is the gain directionality of the system from the value of  $V$ . According to Skogestad *et. al.* (1988), the gain direction of the system indicates the degree of sensitivity of the system response toward the direction of input signal. The physical explanation would be how the input affects the outputs in term of direction (positive or negative) [14].

With reference to Marlin T. E. (1995), another parameter that can measure the degree of interaction between multiple variables in a MIMO system is Relative Gain Array (RGA) [15]. RGA is first proposed by Bristol (1966), it is matrix with element formed by the ratio of open-loop gain to close-loop gain, the equation of RGA is as shown [16]:

$$\lambda_{ij} = \frac{\left(\frac{\partial CV_i}{\partial MV_j}\right)_{MV_k=const, k \neq j}}{\left(\frac{\partial CV_i}{\partial MV_j}\right)_{CV_k=const, k \neq i}} = \frac{\left(\frac{\partial CV_i}{\partial MV_j}\right)_{Other\ loops\ open}}{\left(\frac{\partial CV_i}{\partial MV_j}\right)_{Other\ loops\ Close}} \quad 3$$

With reference to the equation 3, for a 2 x 2 MIMO system, the RGA can be defined as

$$\lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} \quad 4$$

Different range of  $\lambda$  indicates different level of interaction between multi variables and are summarized in the table 1 below [17]:

Table 1: Level of interaction for different value of  $\lambda$

$\lambda_{ij}$	Level of Interaction	Pairing Possibility
$\lambda_{ij} = 0$	Low interaction	Do not pair $U_i$ and $Y_j$
$\lambda_{ij} = 1$	High interaction	Pair $U_i$ with $Y_j$
$\lambda_{ij} < 0$	Low Interaction	Do not Pair $U_i$ and $Y_j$
$\lambda_{ij} \leq 0.5$	Moderate Interaction	Do not Pair $U_i$ and $Y_j$
$\lambda_{ij} > 1$	Very high Interaction	Pair $U_i$ with $Y_j$

Where  $U$  is the input with  $i= 1, 2, 3, \dots, M$  and  $Y$  is the output with  $j= 1, 2, 3, \dots, M$ .

Take the example study case by Caret *et. al.* (2006), the RGA value of a 3 x 3 blending unit used to stabilize the product steam temperature is [18]:

$$RGA = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} \\ \lambda_{21} & \lambda_{22} & \lambda_{23} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} \end{bmatrix} = \begin{bmatrix} \frac{2}{13} & \frac{4}{13} & \frac{7}{13} \\ \frac{11}{13} & \frac{5}{13} & -\frac{3}{13} \\ \mathbf{0} & \frac{4}{13} & \frac{9}{13} \end{bmatrix} \quad 5$$

From the RGA matrix, Caret *et. al.* concludes that  $U_1$  is used to control  $Y_2$  as the value is nearest to 1 which is 11/13, indicating the strongest pairing interaction. The second step the author takes is to pair  $U_3$  and  $Y_3$ , as they have second highest RGA which is 9/13. In order to control  $Y_1$ , the best option will be  $U_3$ . However, it was used to control  $U_3$  earlier, thus, the best choice is to pair  $U_3$  with  $Y_2$  [18]. Note that the main difference between ill-conditioned process and strongly interactive process (RGA) is that the process with strong interaction will always be ill-conditioned but not vice versa [19].

The next section will discuss and analysis about few experiments or researches that are done by other researcher in the related field. The conclusion of each experiments and researches are summarized in the table 2 below:

Table 2: Conclusion of each experiment on system identification

Author	Conclusion	References
Ghosh R., Haggblom K.E. and Boling J. M. (2014)	<ul style="list-style-type: none"> <li>• All gain directions are needed to be excited properly in order to identify an ill-conditioned system.</li> </ul>	[10]
Sadabadi M.S. and Postan J. (2009)	<ul style="list-style-type: none"> <li>• Low gain direction of process system is estimated poorly by uncorrelated test signals</li> <li>• Modification of test signal to be rotated input based on SVD can improve the performance of test signal.</li> </ul>	[11]
Kuramoto A. S. R. <i>et. al.</i> (2012)	<ul style="list-style-type: none"> <li>• Direction of output excitation affect the performance of the test signal.</li> </ul>	[12]
Haggblom K. E. (2014)	<ul style="list-style-type: none"> <li>• Gain direction has affected the process dynamics.</li> </ul>	[13]
Skogestad, Morari and Doyle (1988)	<ul style="list-style-type: none"> <li>• Ill-conditioned plant is the plant that the gain is strongly dependent on the direction of input.</li> </ul>	[14]
Lee H. and Rivera D. E. (2005)	<ul style="list-style-type: none"> <li>• Direction and power amplitude of test signal can affect the performance in highly interactive system.</li> </ul>	[20]
Boling J. (2001)	<ul style="list-style-type: none"> <li>• Proper excitation in low-gain direction of input signal is required by Ill-conditioned system.</li> </ul>	[21]

Note that all the reference researches and experiments have extracted the steady state gain matrix and transfer function from the real plant and tested the performance of test signals only by using the simulation software, but never implement in the real plant process. However the conclusion they have drawn from the simulation are worth for reference as the explanation is based on scientific theory but not randomly made. The main conclusion after the analysis of literature review is that in an ill-conditioned plant, the performance of test-signal is strongly affected by the gain direction, if the weak gain direction can be excited, the performance of system identification can be improved drastically.

## Chapter 3: Methodology and Project Work

### 3.1 Methodology and Project Activities

This chapter will explain and discuss about the methodology that is used to determine how the combination of excitation test signal set affect the performance of system identification. As mentioned in the previous section, the experiment will be carried out by using real plant model.

#### 3.1.1 Plant Setup and Understanding of Manual

The chosen plant model is air pilot plant which is located in Block 23 of Universiti Teknologi PETRONAS. This is a real plant model with MATLAB interfacing which enable us to implement the test signal and extract input-output data. The figure 1 shows the plant structure for this experiment.



Figure 1: Air Pilot Plant that is used for system identification

There are two Process Control Valves (PCV) which are tagged as PCV 202 and PCV 212 together with two Pressure Transmitters (PT) which are tagged as PT 202 and PT 212. The valves and pressure transmitter are as shown in the figures below.



Figure 2: PCV 212



Figure 3: PCV 202



Figure 4: PT 212

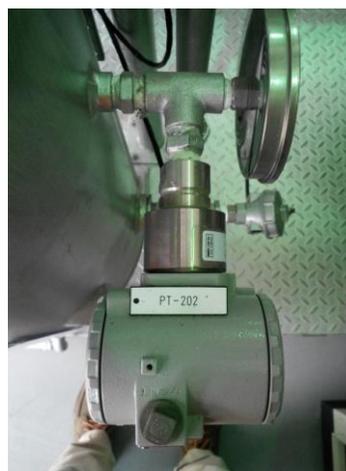


Figure 5: PT 202

The Process Control Valve (PCV) will be the input to the process while the Pressure Transmitter (PT) will display the output of the process. Since there are two PCV and two PT in this plant, it is determined as a 2x2 Multiple Input Multiple Output (MIMO) system. The block diagram of the system is illustrated in the figure 6 below, where  $U_1$  and  $U_2$  are the input (Process Control Valve),  $Y_1$  and  $Y_2$  are the output (Pressure Transmitter) and  $H$  is the transfer function of each process.

### 3.1.2 MATLAB Simulink Interfacing with Process Plant

Since the plant model is controlled by MATLAB interfacing, all the input-output data implementation and extraction are programmed through the MATLAB Simulink software. The MATLAB Simulink configuration is designed and drawn as shown in the figure 7 below. It is noted that the input signal block is where we will input our excitation signal and the PT 202 and PT 212 are the output data that we need in order to model the system identification. The noise of the output is filtered by using Gaussian's filter right after they are read from the PT, and before they are displayed as value in the MATLAB Simulink software.

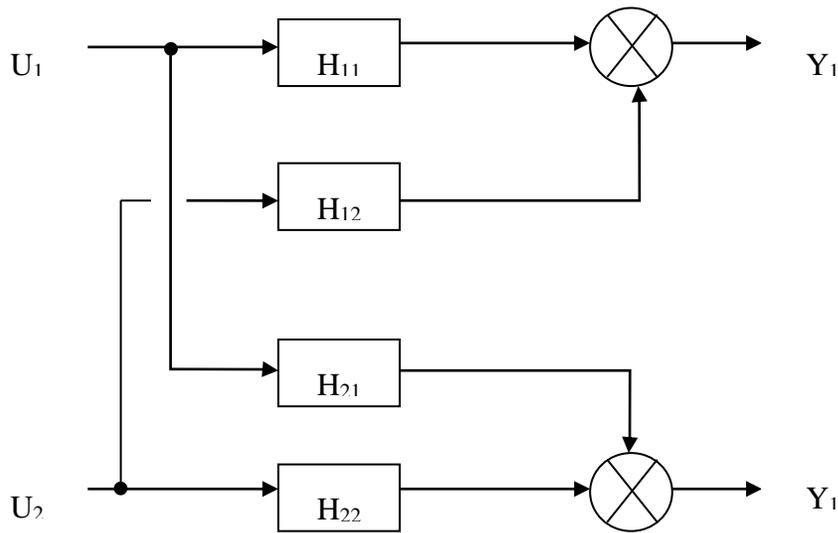


Figure 6: Control Diagram of 2 x 2 MIMO process

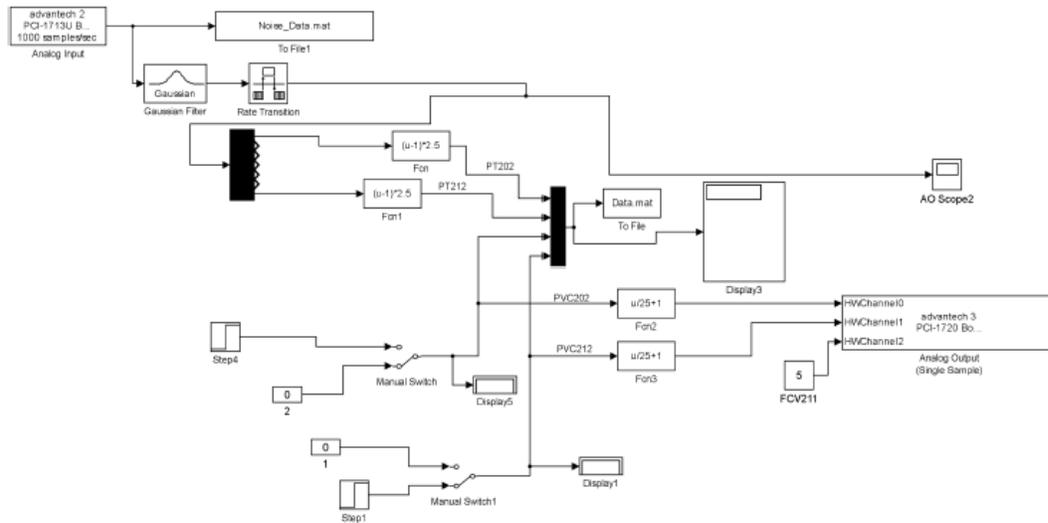


Figure 7: MATLAB Simulink interference with the plant process

### 3.1.3 Determination of Steady-State Gain Matrix and Transfer function of Plant

After the plant is chosen and software interfacing setup configuration is ready, the next step is to determine the transfer function of the plant from the steady-state gain matrix, which is found by using the input-output data from the plant process. The equation used to obtain the steady state gain matrix is as shown below:

$$K = \begin{bmatrix} \frac{\Delta y_1}{\Delta u_1} & \frac{\Delta y_1}{\Delta u_2} \\ \frac{\Delta y_2}{\Delta u_1} & \frac{\Delta y_2}{\Delta u_2} \end{bmatrix} \quad 6$$

Where  $y$  = output and  $u$  = input.

The Process Control Valve (PCV) and Pressure Transmitter (PT) are related to the formula above by matching the input and output where:

$$u_1 = \text{PCV 202}; u_2 = \text{PCV 212}; y_1 = \text{PT 202}; y_2 = \text{PT 212}$$

In order to obtain the steady-state gain matrix, two experiments are conducted. First step of experiment is to set PCV 202 to be 30% open, and PCV 212 is 45% open. The process is run for 10 minutes, when the steady-state is obtained. After 10 minutes, PCV 202 is changed from 30% to 60% opening, but PCV 212 is kept constant as 45%, this process will last for 15 minutes. Output values PT 202 and PT 212 are recorded throughout the whole experiment for 25 minutes. The second experiment is similar to the first experiment except that the role of PCV 202 and PCV 212 are exchanged with each other. The setup configuration is drawn in MATLAB Simulink interface and is shown in the figure 6. The steady state gain matrix is obtained by using equation 6 with utilization of the input-output data from the both experiment mentioned. After the steady-state gain matrix is obtained, the next step will be to determine the transfer function of the plant process. By plotting the graph for PT 202 and PT 212 values versus time, the time constant is determined at 63% of the transient state. The transfer function is then obtained by using the equation 7.

$$K = \begin{bmatrix} \frac{K_{11}}{1+\tau_{y11}S} & \frac{K_{12}}{1+\tau_{y12}S} \\ \frac{K_{21}}{1+\tau_{y21}S} & \frac{K_{22}}{1+\tau_{y22}S} \end{bmatrix} \quad 6$$

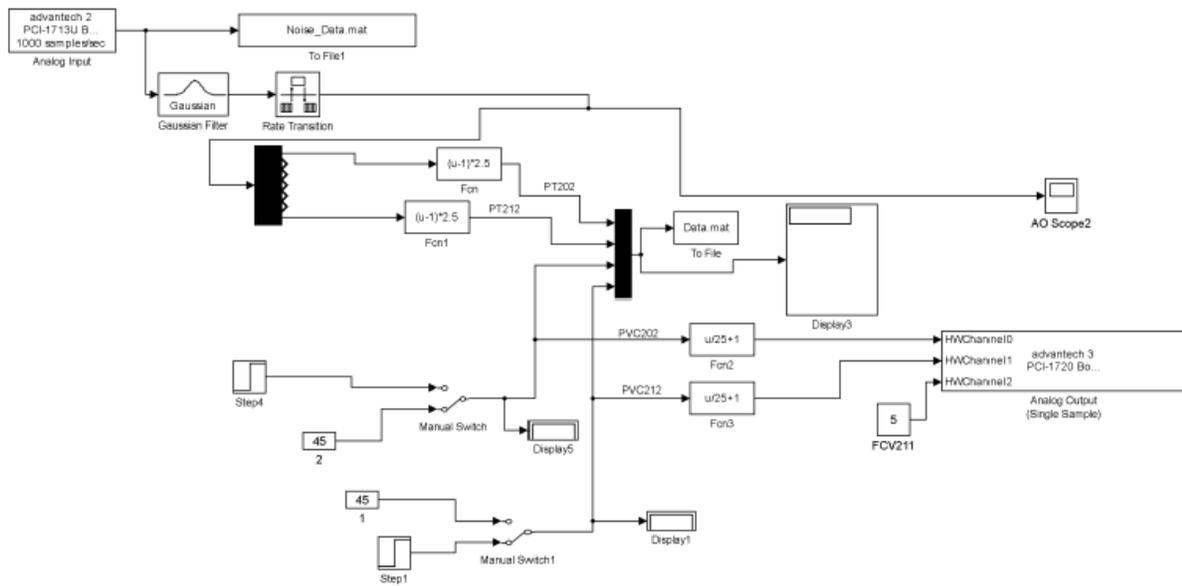


Figure 8: Experiment 1 (PCV 202: 30%  $\rightarrow$ 60% and PCV 212: 45%)

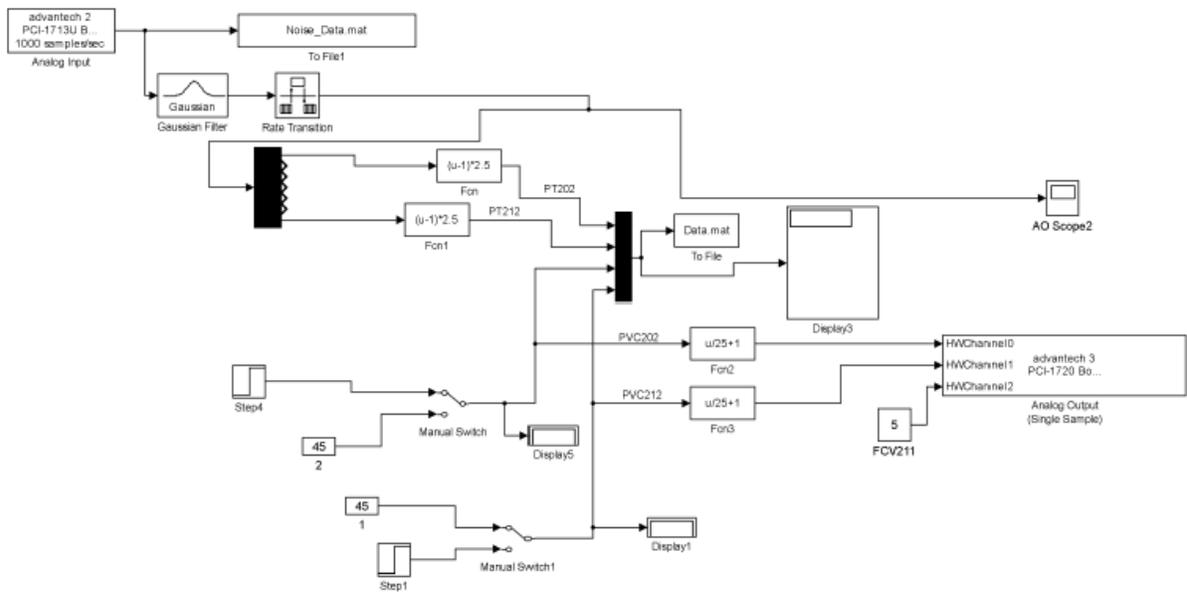


Figure 9: Experiment 2 (PCV 202: 45% and PCV 212: 30%  $\rightarrow$ 60%)

### 3.1.4 Verification of ill-Condition properties

After the transfer function is obtained, the next step is to determine the ill-conditioned properties of the system. By using equation as mentioned in the literature review section, the condition number is the ratio of the system diagonal matrix. Now the plant characteristic is fully understood and verified, the focus should then be put on the excitation test signal.

### 3.1.5 Design of Input excitation signal

In the design of excitation test signal, Pseudo Random Binary Sequence (PRBS) is first designed individually. According to Kuramoto *et. al.* (2012), the bandwidth used to design the PRBS is calculated from the system by using the equation below:

$$\omega_L = \frac{1}{B_s \tau_{Max}} \leq \omega \leq \frac{\alpha_s}{\tau_{Min}} = \omega_H \quad 7$$

Where the  $\tau_{Max}$  and  $\tau_{Min}$  are the maximum and minimum time constant from the MIMO system, and  $B_s$  is used to scope the amount of information at low frequency in the test signal and  $\alpha_s$  is used to ensure high frequency component is available [12]. According to Rivera *et. al* (1994),  $B_s$  and  $\alpha_s$  are chosen to be 3 and 2 respectively [22], and as for the switching time,  $T_{sw}$  can be designed by using the equation below [23].

$$T_{sw} \leq \frac{2.8 \tau_{dom}^L}{\alpha_s} \quad 9$$

where  $\tau_{dom}^L$  is the lowest dominant time constant in the process. Next, different sets of PRBS test signal combination will be produced in order to excite the process plant system respectively for system identification. 4 combinations of PRBS with significant difference of correlation coefficient value will be created by shifting of the original PRBS signal. This can ensure that the magnitude and duration of the input signal will remain unchanged.

### 3.1.6 Apply of excitation signal into simulation software

After 4 combinations of PRBS with significant difference of correlation coefficient are ready, they will be applied to the virtual process plant that is created in the MATLAB simulink software. The virtual plant, or in other term, plant in simulation is created based on the transfer function obtained from the earlier stage of the project. One combination of PRBS will be applied at one

time and the outputs will be recorded for further analysis in the later stage of the project. The experiment will then be repeated with another combination of PRBS that has different value of correlation coefficient until all 4 combinations are applied and tested. The setup of the virtual plant with input and output is as shown in the figure below.

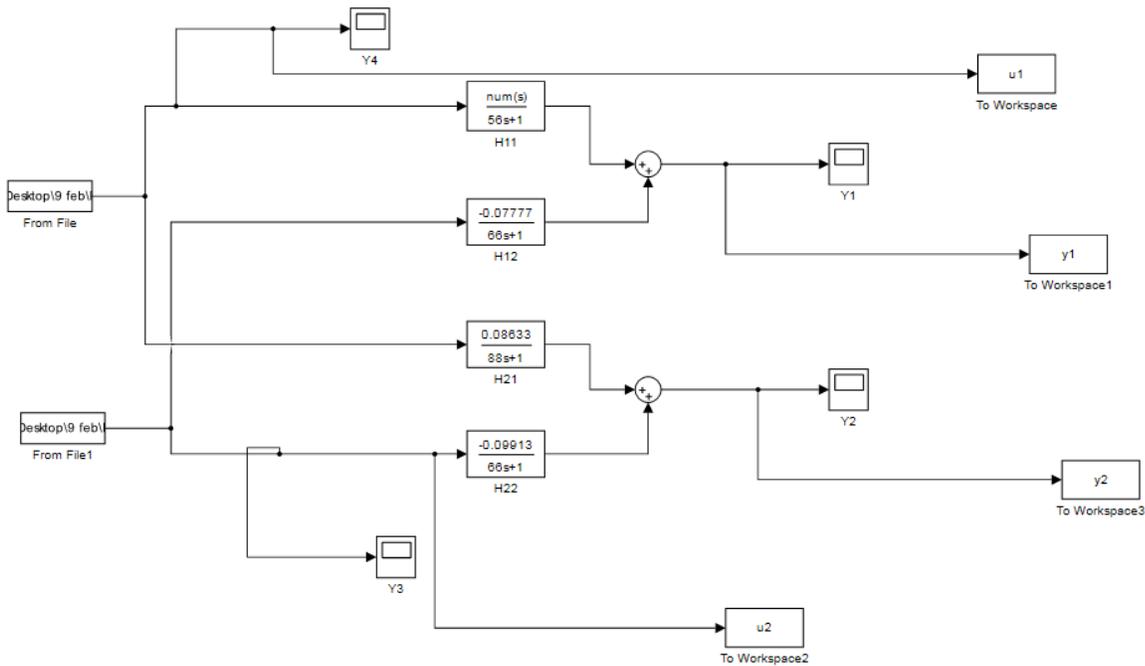


Figure 10: setup of virtual plant in MATLAB Simulink platform

### 3.1.7 Data process and performance analysis

After the data for different experiments are captured, they will be processed and examined by employing the **MATLAB System Identification Toolbox**. System Identification Toolbox is widely used to model non-linear or linear dynamic system purely based on the input-output data. It supports not only the data analysis and processing, but also the determination of suitable model structure and order, and estimate the model parameter.

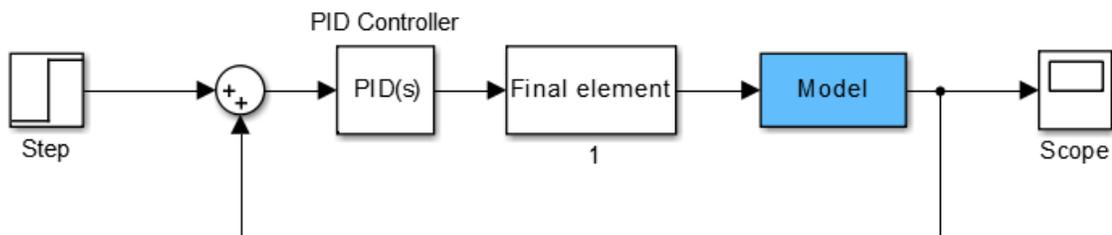


Figure 11: The role of modeling in complete loop of process

The build-in function 'iddata' is first used to package all the input-output data pairs into variables containing input and output in time-domain series. The complete package of data is then imported into system identification tool. The toolbox is then used to estimate the model order. After selecting the estimated order of the model, the modeling result will then be shown in the system identification tool and exported to the workspace for further display and analysis. The layouts of the toolbox are as shown in figure 12 in sequence.

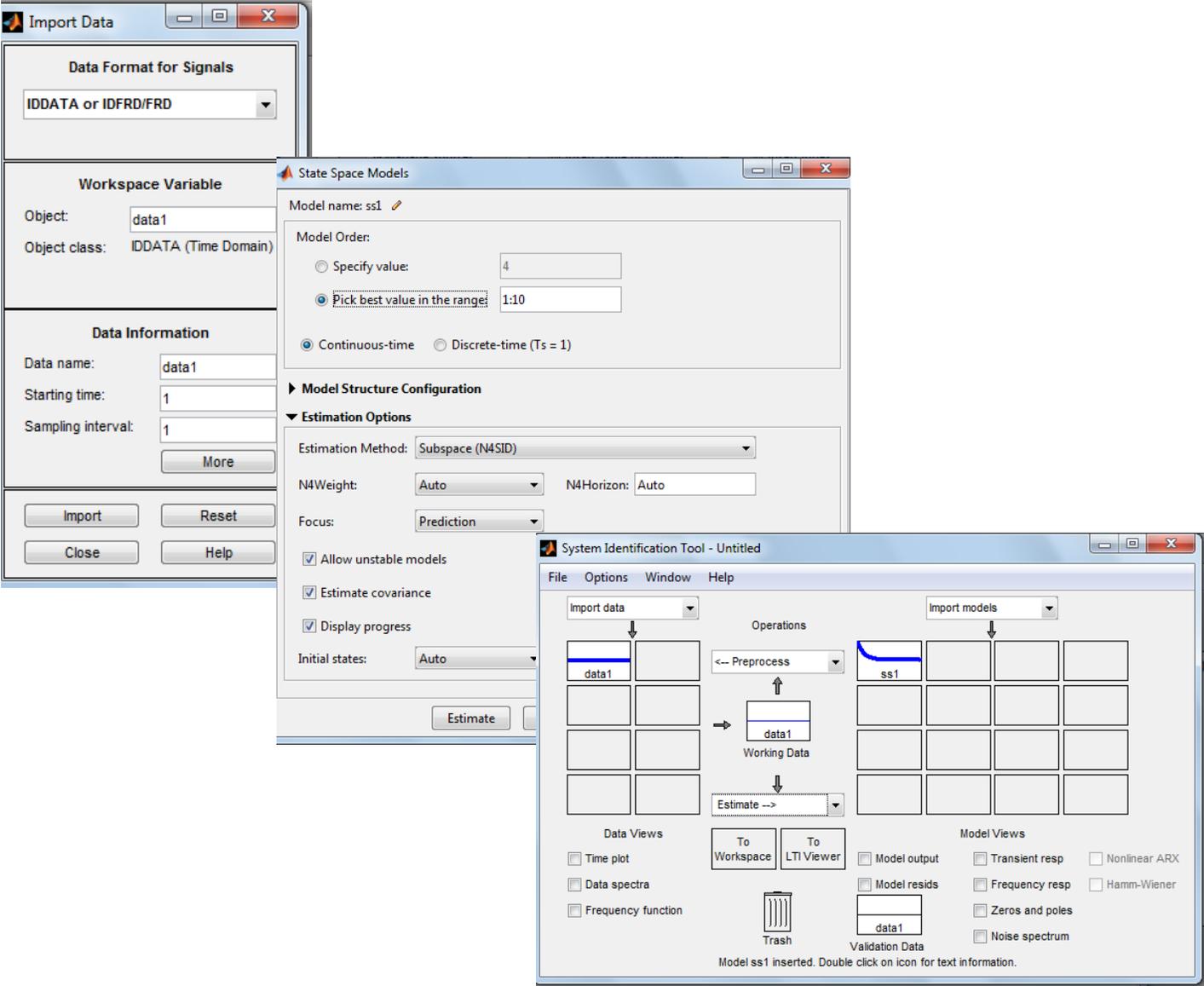


Figure 12: Modeling based on measured input-output data.

The performance of the models are evaluated by using **bode plot** and **fit percentage** of the model towards the actual parameter from transfer function obtained. By using bode plot and fit percentages, the models will be examined in both frequency domain and time domain. Bode plot represents the frequency response of the system including magnitude and phase shift by bode magnitude plot and bode phase plot [24]. On the other hand, the fit percentage is used to examine the percentage of similarity between the model and the actual transfer function, it can be employed by calling the 'compare' function in MATLAB software.

### **3.1.8 Implementation in real process plant**

The experiment is then implemented in the real plant where the different combinations of PRBS signals will be applied towards the actual plant process via MATLAB Simulink platform and the input-output data will be collected. The data processing procedure and concept as well as the method to examine the performance of system identification for different combinations of excitation input signals are similar to the method used in simulation stage presented in section 3.1.7.

### 3.2 Key Project Milestone

In this sub-chapter, we will first list the project key milestone and determine the targeted completion date for each milestone. The details gantt chart and submission of documents toward FYP committee will be involved in the appendices.

Table 3: Project Key milestone and the expected date of Completion

<b>Project Key Milestone</b>	<b>Expected Date of Completion</b>
Plant Setup and understanding of manual (Power Up, MIMO properties)	16/11/2014
MATLAB Simulink Interfacing with process plant (Noise filter, Scaling, Valve Control, Data display)	16/11/2014
Determination of Steady-State Gain Matrix of plant from step response of system	23/11/2014
Determination of Transfer function of plant based on the time constant of system	30/11/2014
Verification of Ill-condition properties of plant (Condition number, RGA, Gain direction)	7/12/2014
Design of single PRBS test signal based on plant properties (time constant, bandwidth, period, Amplitude)	14/12/2014
Design different combination of PRBS as test signal set (correlated, uncorrelated)	31/12/2014
Implementation in simulation platform and determination of result (based on transfer function from step response)	8/2/2015
Implementation in real process plant and determination of result (different combination of PRBS)	28/2/2015

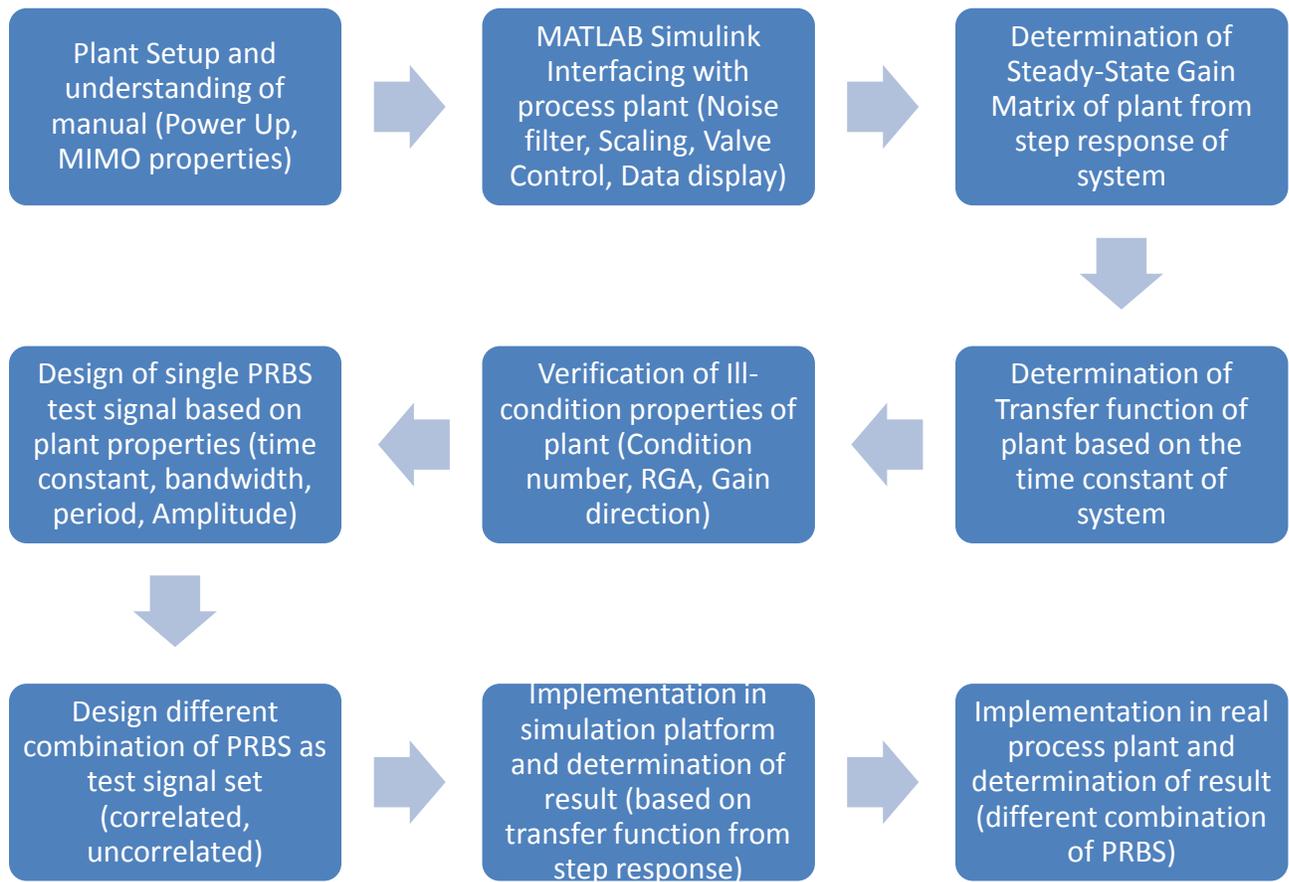


Figure 13: Project Key Milestone

## Chapter 4: Result and Discussion

### 4.1 Determination of Steady-state gain matrix

Two experiments are carried out and summarized as below:

Table 4: The design of step response experiment of the system

Exp	Variables	Event
Exp 1	PCV 202	Step input from 30% to 60%
	PCV 212	Steady gain input of 45%
Exp 2	PCV 202	Steady gain input of 45%
	PCV 212	Step input from 30% to 60%

The result of Experiment 1 is presented in graph of Pressure versus time for each pressure transmitter (PT 202 and PT 212) as shown in the figure 11-14.

#### Experiment 1:

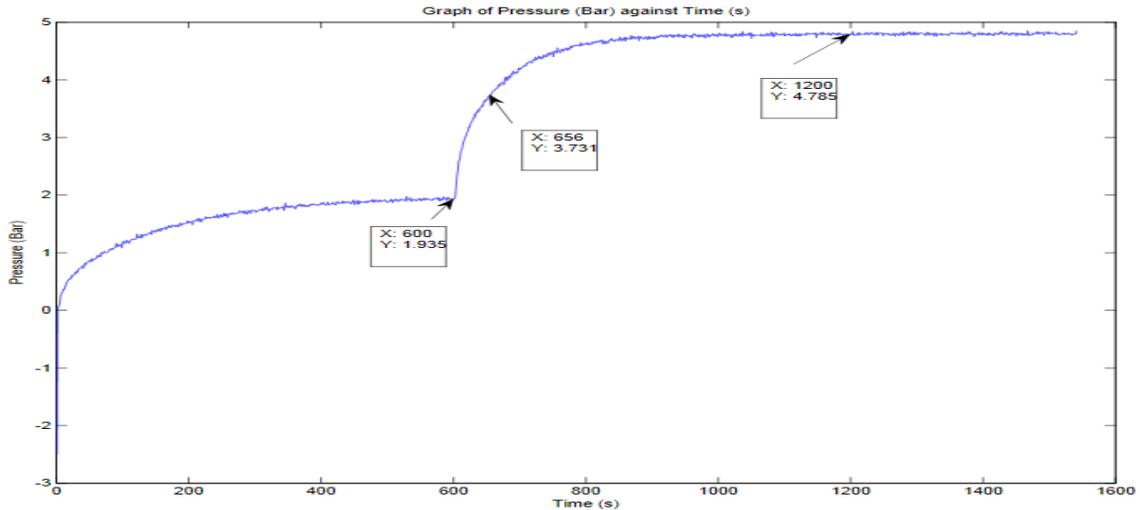


Figure 14: PT202: Graph of Pressure (kPa) versus Time (s)

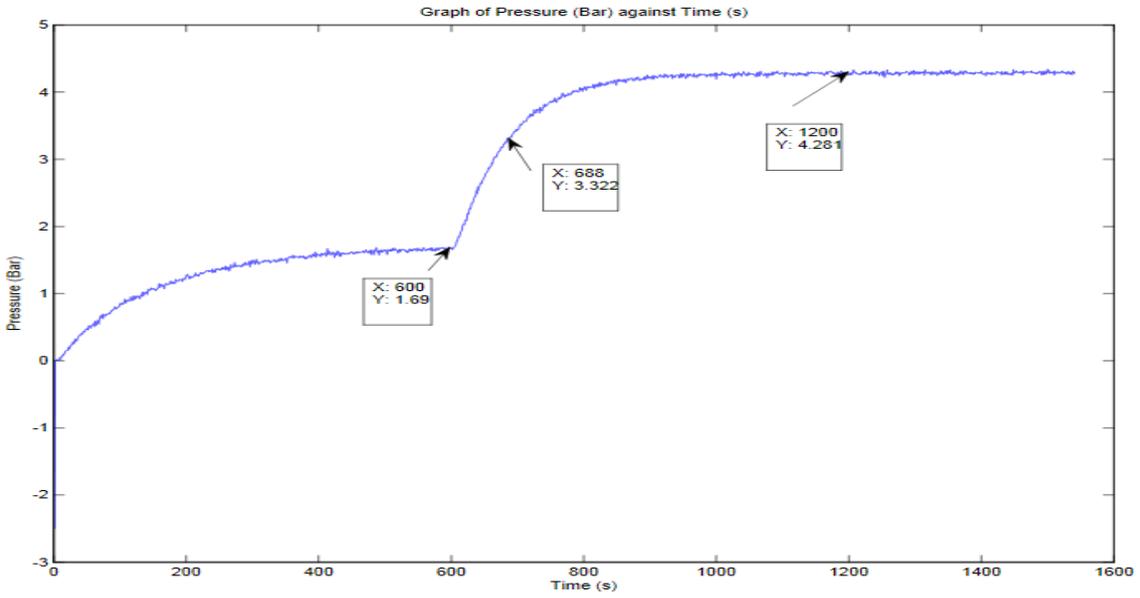


Figure 15 : PT212: Graph of Pressure (kPa) versus Time (s)

## Experiment 2

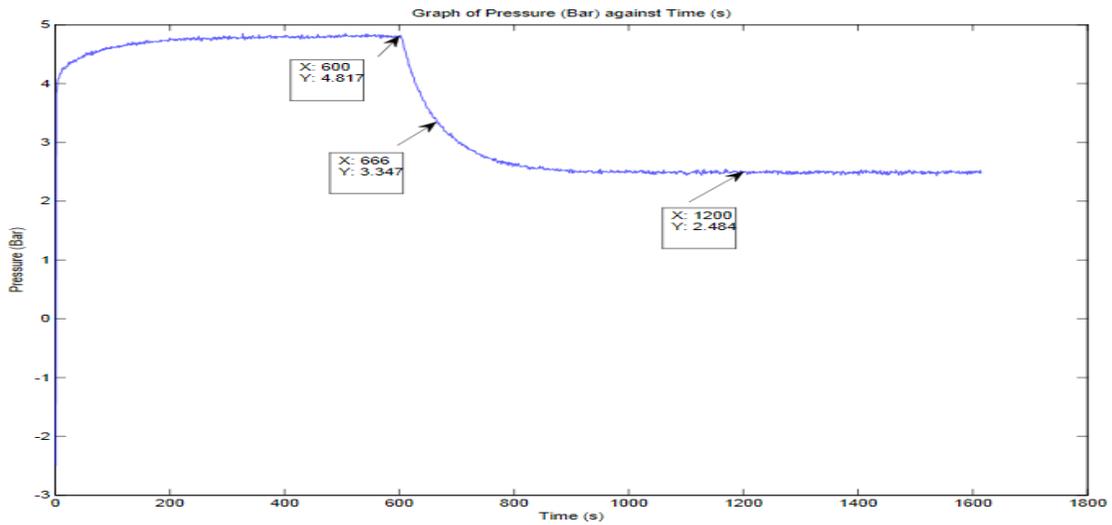


Figure 16: PT202: Graph of Pressure (kPa) versus Time (s)

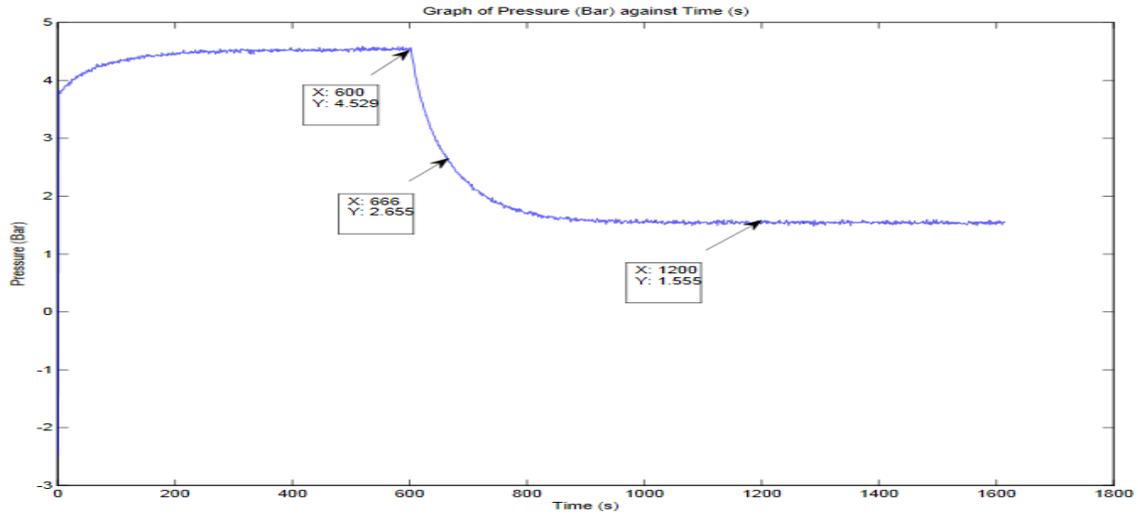


Figure 17: PT212: Graph of Pressure (kPa) versus Time (s)

From the graph we can calculate the difference between pressure changes when the input is applied. By letting

$$U_1 = \text{PCV 202}; U_2 = \text{PCV 212}; Y_1 = \text{PT 202}; Y_2 = \text{PT 212}$$

With reference to equation 6, the steady-state gain matrix, K is yield:

$$K = \begin{bmatrix} \frac{\Delta y_1}{\Delta u_1} & \frac{\Delta y_1}{\Delta u_2} \\ \frac{\Delta y_2}{\Delta u_1} & \frac{\Delta y_2}{\Delta u_2} \end{bmatrix} = \begin{bmatrix} \frac{2.85}{30} & \frac{-2.33}{30} \\ \frac{2.59}{30} & \frac{-2.97}{30} \end{bmatrix} = \begin{bmatrix} 0.09500 & -0.07777 \\ 0.08633 & -0.09913 \end{bmatrix}$$

The singular value decomposition for the system is calculated by using equation 2 and yields:

$$W = \begin{bmatrix} -0.1187 & -0.9929 \\ -0.9929 & 0.1187 \end{bmatrix}, \quad E = \begin{bmatrix} 0.8751 & 0 \\ 0 & 0.0660 \end{bmatrix}, \quad V = \begin{bmatrix} -0.9924 & 0.1230 \\ 0.1230 & 0.9924 \end{bmatrix}$$

By referring to the diagonal matrix E of the system, the condition number is defined as:

$$\text{Condition Number} = \frac{0.8751}{0.0660} = 13.25$$

Which is more than 1 and thus the system is defined as ill-conditioned system. The transfer function requires the value of time constant which is defined as 63% of the total pressure difference between the applications of input signal as shown in the equation 10.

$$K = \begin{bmatrix} \frac{K_{11}}{1 + \tau_{y11}S} & \frac{K_{12}}{1 + \tau_{y12}S} \\ \frac{K_{21}}{1 + \tau_{y21}S} & \frac{K_{22}}{1 + \tau_{y22}S} \end{bmatrix} \quad 10$$

By referring to the graph and data that are collected from the step response:

$$\tau_{y11} = (0.63 \times 2.85) + 1.935 = 3.731$$

$$\tau_{y12} = 4.817 - (2.333 \times 0.63) = 3.347$$

$$\tau_{y21} = (0.63 \times 2.591) + 1.69 = 3.322$$

$$\tau_{y22} = 4.529 - (2.974 \times 0.63) = 2.655$$

With the help of the graph and some calculation, the transfer function is equal to:

$$K = \begin{bmatrix} \frac{0.09500}{1 + 56S} & \frac{-0.07777}{1 + 66S} \\ \frac{0.08633}{1 + 88S} & \frac{-0.09915}{1 + 66S} \end{bmatrix}$$

## 4.2 Design of input excitation signal formed by different combination of PRBS

In order to design an individual PRBS as excitation signal to the process, a few parameters are needed including length of signal, the switching time and the amplitude. The length of signal and amplitude are designed to be more than the signal that are used to extract the transfer function of the plant process which are 2000 seconds, this is to ensure more data for analysis. The amplitude is set as 30% which is the same with the opening of valve for transfer function obtaining. As for the switching time, it is designed according to equation 9 in the earlier section. The first individual PRBS signal is as shown in the figure below. By applying shifting to the original PRBS signal, 5 combinations with different correlation coefficient value compare to the original PRBS signal are created as shown in the figure.

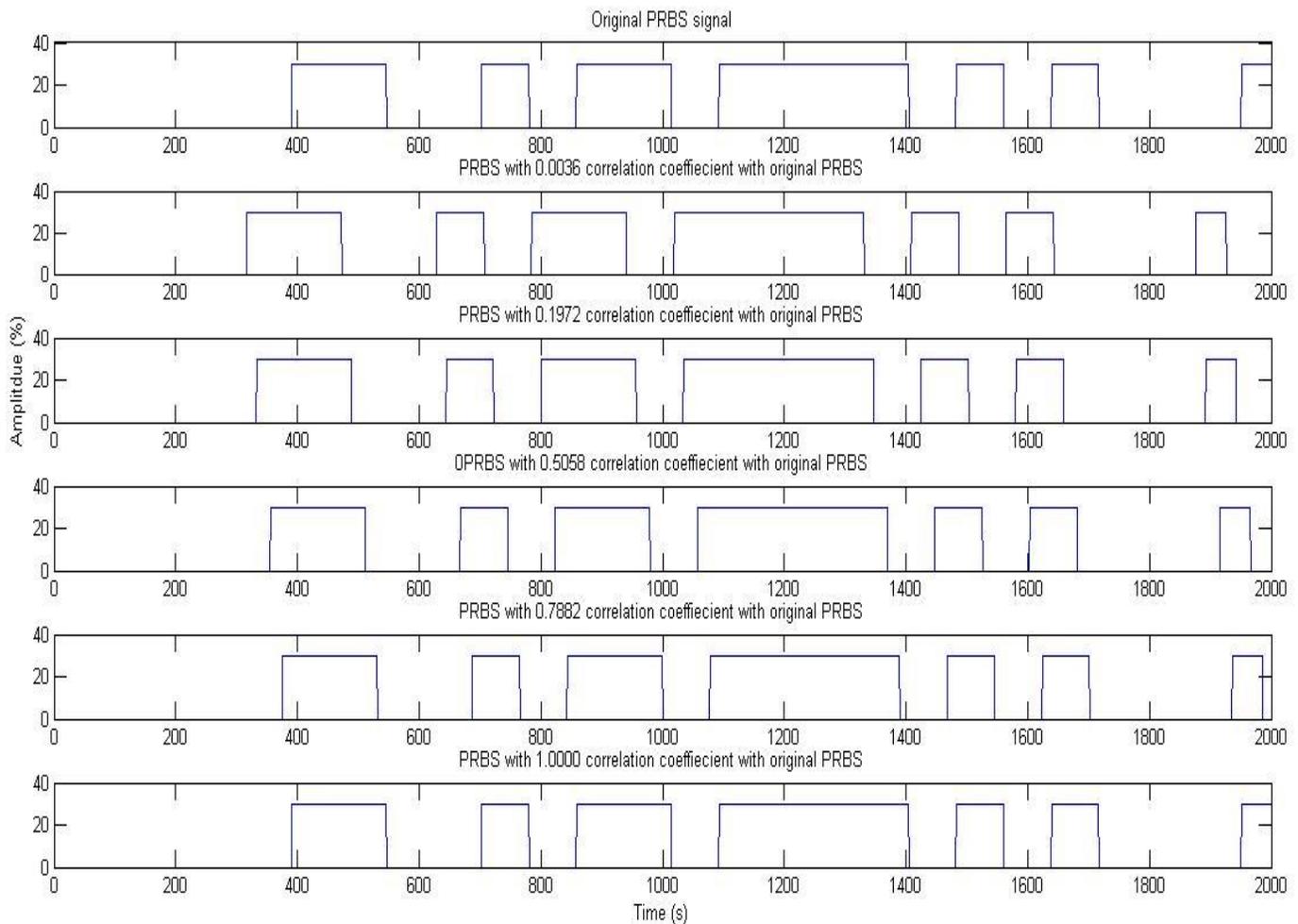


Figure 18: original PRBS signal and generated PRBS signal with different correlation coefficient value.

### 4.3 Application and Performance analysis of input excitation signal

Different combinations of PRBS signals are applied to the process plant transfer function with the combination below.

Table 5: Labeling for Application of PRBS combinations with different correlation coefficient

Combination	Modeling label	Correlation coefficient value
1	ss1	0.0036
2	ss2	0.1972
3	ss3	0.5058
4	ss4	0.7882
5	ss5	1.0000

The modeling results are tested with frequency response and time response as shown below.

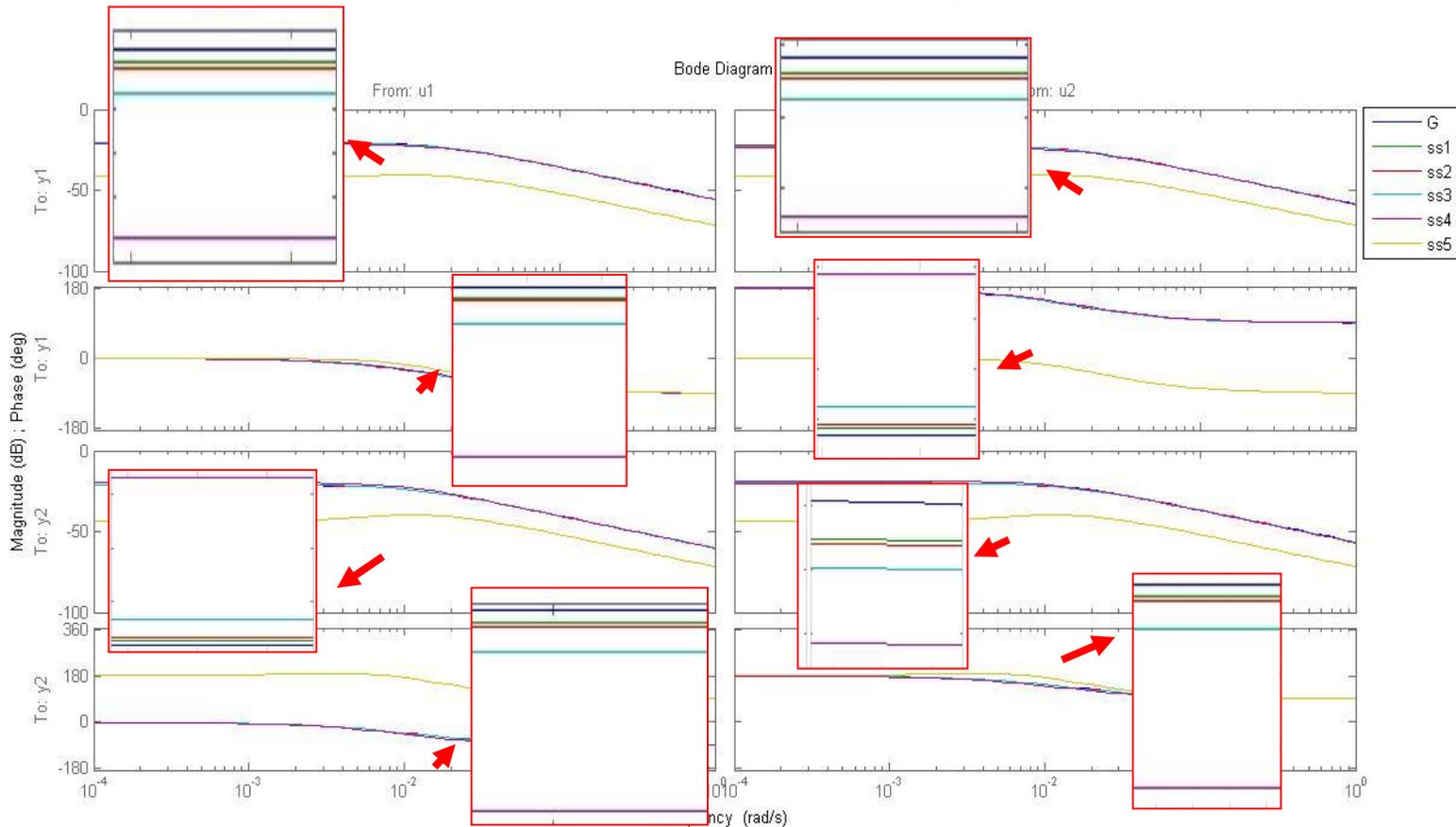


Figure 19: The Bode plot analysis of different models for simulated open loop operation

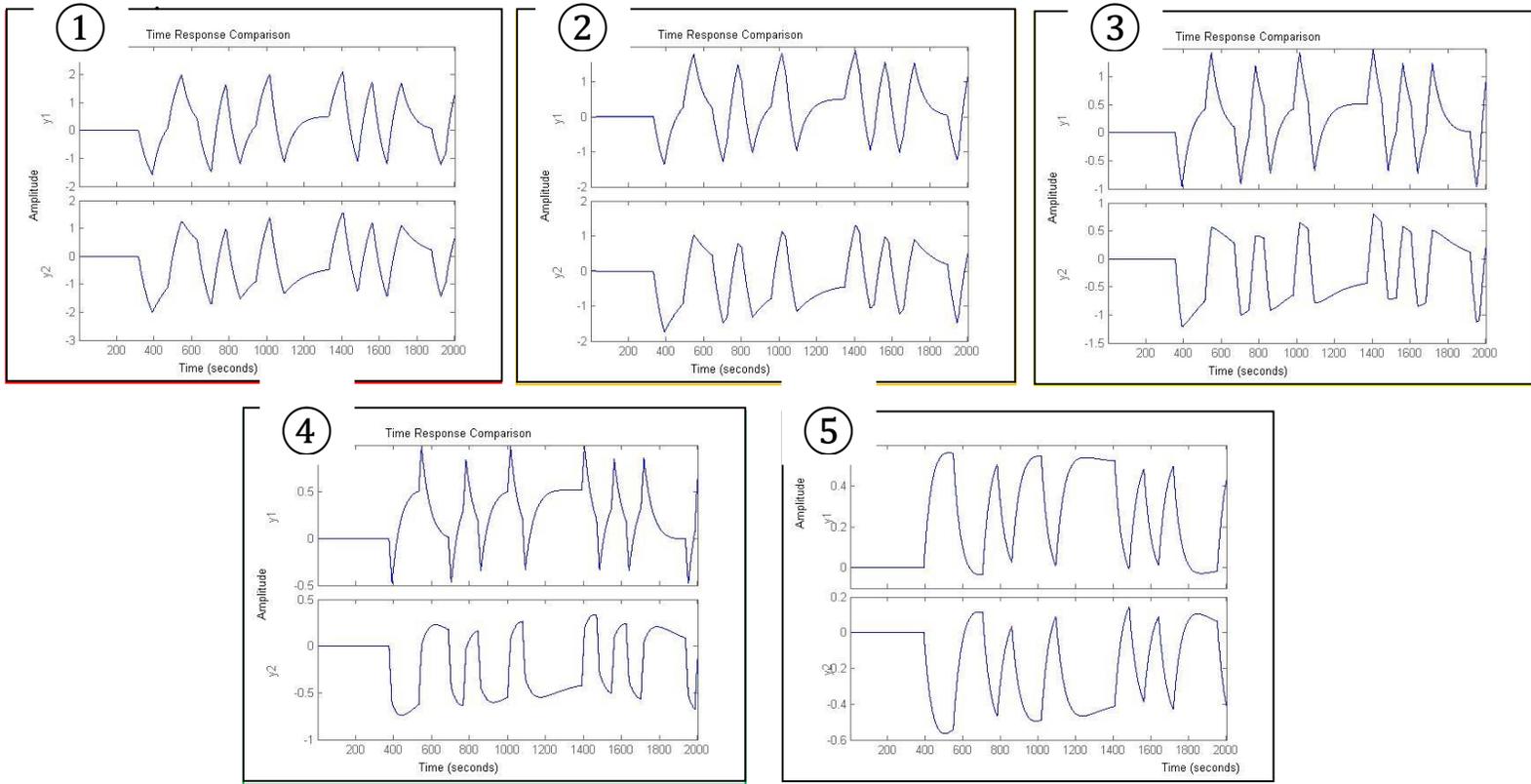


Figure 20: Fit percentage analysis for combination 1 – combination 5 for simulated open loop operation.

Table 6: fit percentage analysis for all combinations of test signal for simulated open loop operation.

Combination	Percentage difference with original process(%)	
	y1	y2
1	1.63	1.51
2	1.71	1.58
3	1.98	1.78
4	2.39	2.03
5	1.20	1.17

It is noticed that the time-domain performance (fit percentage) are equally good. However, the frequency-domain performance (Bode Plot) varies for each combination.

#### 4.4 Implementation in real Air Pilot Plant Process

The different combination of input signals are then implemented into the real air pilot plant and the modeling results are as expected, where the lower the correlation level between excitation signals, the better the performance of the system identification in open loop operation. The results are as shown.

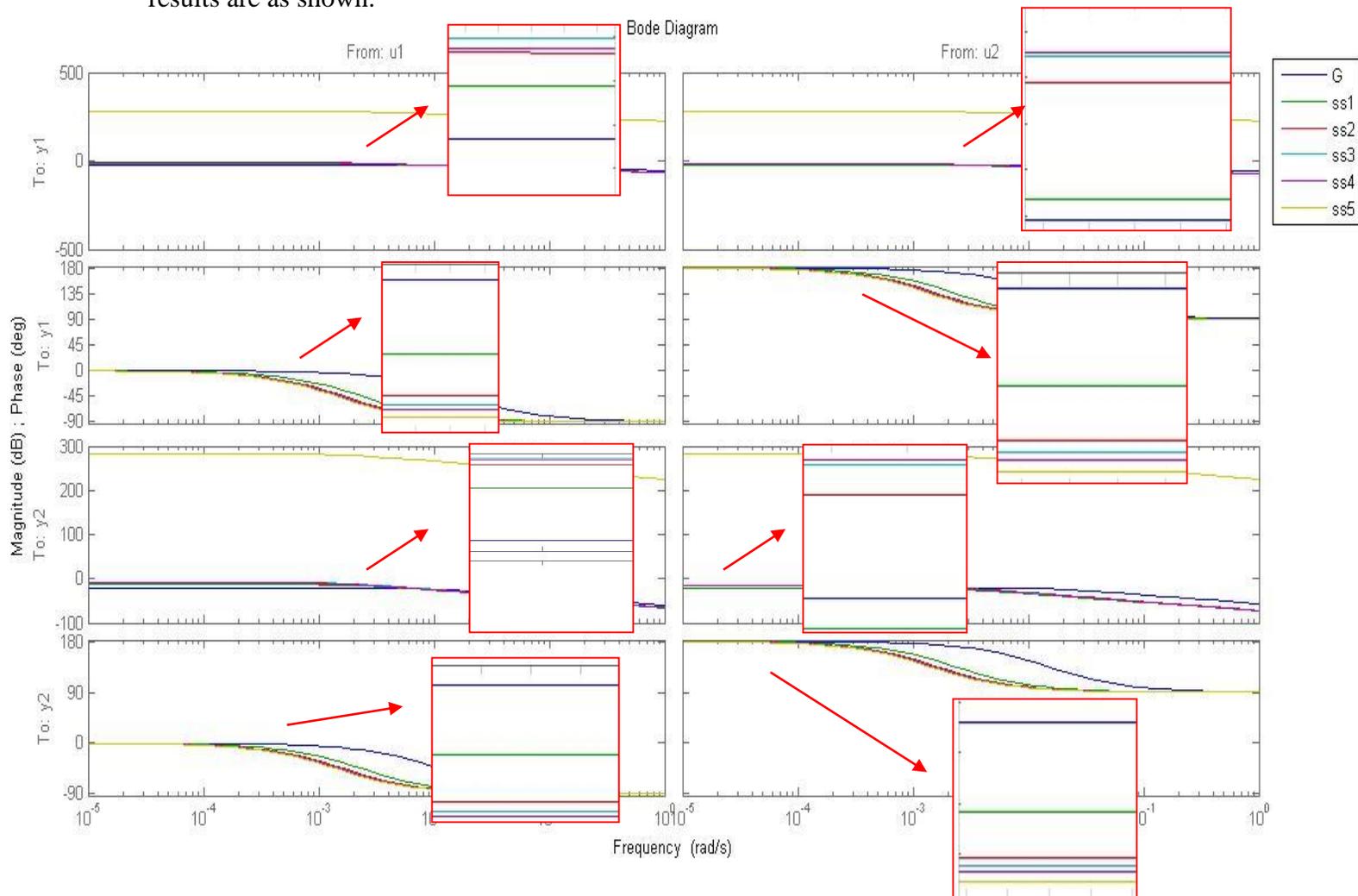


Figure 21: The Bode plot analysis of different models after implementation into real process plant.

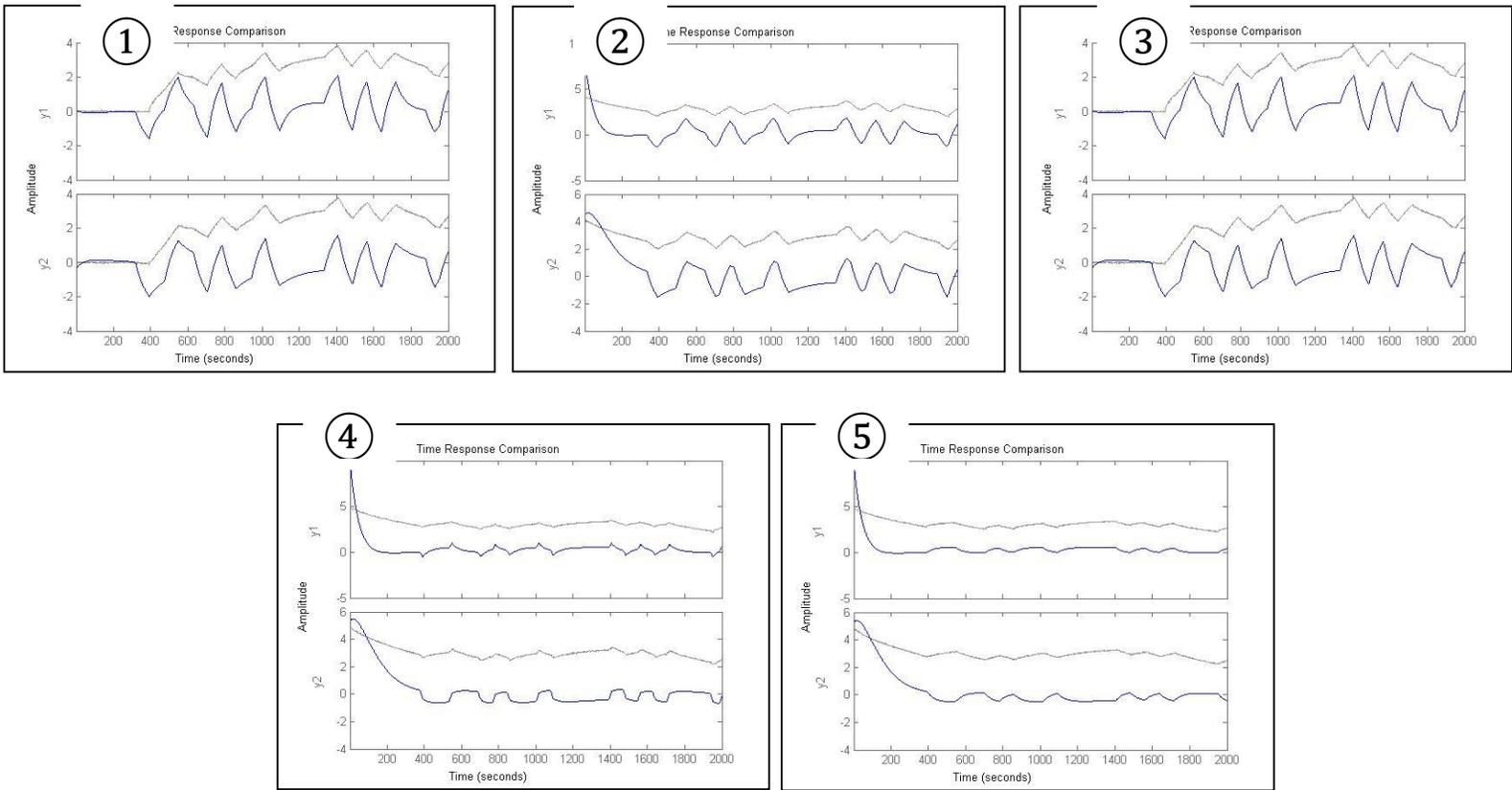


Figure 22: Fit percentage analysis for combination 1 – combination 5 after implementation into real plant process.

Table 7: fit percentage analysis for all combinations of test signal for simulated open loop operation.

Combination	Percentage difference with original process(%)	
	y1	y2
1	17.79	13.60
2	202.80	194.35
3	303.50	293.10
4	409.80	410.70
5	415.50	427.90

According to the result above, for an ill-conditioned Multiple-Input-Multiple-Output (MIMO) process, the lower the correlation level between test signals, the better the performance of system identification in both simulated and real process environment.

The results obey the literature review where specific designed of test input signals can affect the performance of system identification. Both the positive and negative gain direction should be excited completely in order to extract the actual behavior of the plant process.

If the plant process can be modeled precisely, it will bring big positive impact to the controller design, which will further bring cost cut down, safe plant environment and less accident occurrence.



The PID controller is tuned based on Ziegler-Nicholas closed-loop coefficient and some trials and errors. The performance of controller is tested with a step input and the controller coefficients are fixed when the output for step input is satisfactory. The controller coefficient is implemented throughout the experiment of closed-loop operation. The controller coefficient and is as shown below:

Table 8: the PID controller's coefficient value for closed loop operation.

Controller	Coefficient	
	Input 1	Input 2
<b>Proportional (P)</b>	0.5	-0.2
<b>Integral (I)</b>	0.5	-0.1
<b>Derivatives (D)</b>	0	0

The performance of closed-loop system identification is tested in frequency response and as shown in figure below.

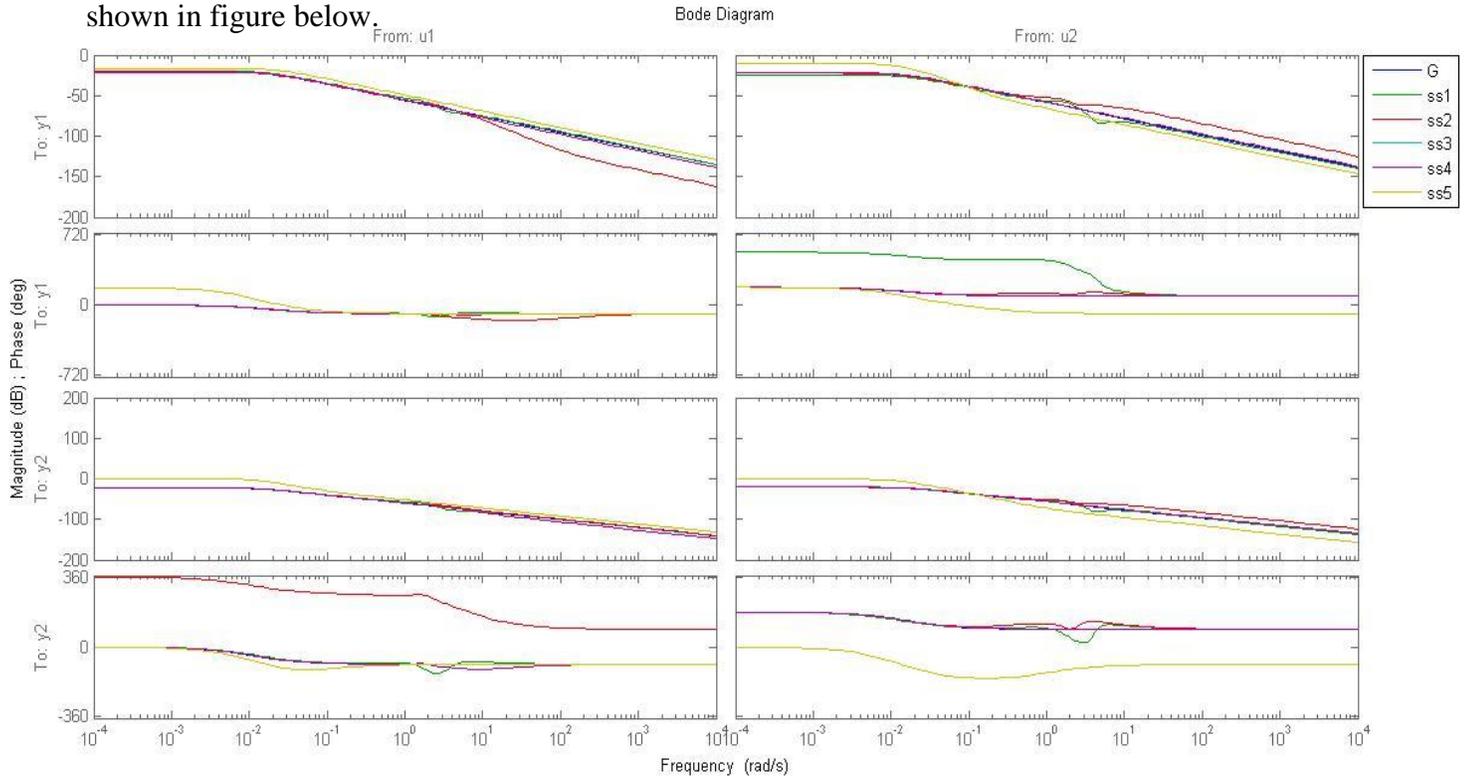


Figure 24: The Bode plot analysis of different models after implementation into real process plant.

From the graph above, it is showed that the system identification in closed-loop operation has the best performance when the correlation level of input signals is high but not equal to 1. This is an interesting founding and if time is permitted, the reason and theory behind the performance of system identification closed-loop operation shall be investigated.

## **Chapter 5: Conclusion and Recommendation**

This paper aims to improve the performance of system identification based on optimization of Pseudo Random Binary Sequence (PRBS) excitation signal combination for Multiple-Input Multiple Output (MIMO) Ill-Conditioned system. Ill-conditioned system is defined as system that is formed by various variables and the level of interaction between all the variables is high. It is found that in the case of ill-conditioned system, the design of PRBS combination as excitation signal will affect the performance of system identification. The experimental subject of this paper is the air pilot plant that is located in Universiti Teknologi PETRONAS (UTP). Empirical modeling method is first used to obtain the steady gain matrix of the system, followed by the transfer function based on the time constant of the system. A process will be created on simulation based on the transfer function obtained. High correlated, moderate correlated and un-correlated set of PRBS will be used as excitation signal for system identification. The test signal combination will also be tested in the real plant implementation. The performance of different combination of PRBS will be examined by using Bode plot and fit percentage. The result shows that the lower the correlation, the better the modeling performance for the operation in both simulated and real process environment. Both the objectives of to define and design the best combination of excitation test signals that can improve and stabilize the performance of system identification in MIMO ill-conditioned system and to implement and validate the result from real process plant that has MIMO and ill-conditioned properties which is the air pilot plant located in Universiti Teknologi PETRONAS are achieved. Future direction of investigating system identification in closed-loop operation is also involved in this paper.

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## Appendix

MATLAB code to generate different PRBS with certain correlation level:

```
% define Prbs
prbs1 = idinput ([2000 1], 'prbs', [1, 1/78.4], [0 30]);
prbs11= prbs1(1:1200,1);
prbs2 = circshift (prbs1, 1926 );%0.0036%
x1= corrcoef (prbs1, prbs2);
A1= x1(1,2)
prbs22= prbs2(1:1200,1);
prbs3 = circshift (prbs1, 1942 );%0.1972%
x2= corrcoef (prbs1, prbs3);
A2= x2(1,2)
prbs33= prbs3(1:1200,1);
prbs4 = circshift (prbs1, 1965 );%0.5058%
x3= corrcoef (prbs1, prbs4);
A3= x3(1,2)
prbs44= prbs4(1:1200,1);
prbs5 = circshift (prbs1, 1985 );%0.7882%
x4= corrcoef (prbs1, prbs5);
A4= x4(1,2)
prbs55= prbs5(1:1200,1);
prbs6 = circshift (prbs1, 2000 );%1%
x5= corrcoef (prbs1, prbs6);
A5= x5(1,2)
prbs66= prbs6(1:1200,1);

i= [1:2000];
i2= [1:1200];

PRBS1= prbs1';
PRBS1= [i;PRBS1];
PRBS2= prbs2';
PRBS2= [i;PRBS2];
PRBS3= prbs3';
PRBS3= [i;PRBS3];
PRBS4= prbs4';
PRBS4= [i;PRBS4];
PRBS5= prbs5';
PRBS5= [i;PRBS5];
PRBS6= prbs6';
PRBS6= [i;PRBS6];
```

MATLAB code to generate simulated process plant with transfer function:

```
g11= tf ([0.095], [ 56 1]);
g12= tf ([-0.07777], [ 66 1]);
g21= tf ([0.08633], [ 88 1]);
g22= tf ([ -0.09913], [ 66 1]);
G= [ g11 g12 ; g21 g22];
```

MATLAB code to extract result from the real plant process:

```
y1= Data(2, :);
y1=y1';
y2= Data(3, :);
y2=y2';
u1= Data(4, :);
u1=u1';
u2= Data(5, :);
u2=u2';
data_1= iddata ([y1, y2],[u1,u2], 1);
```

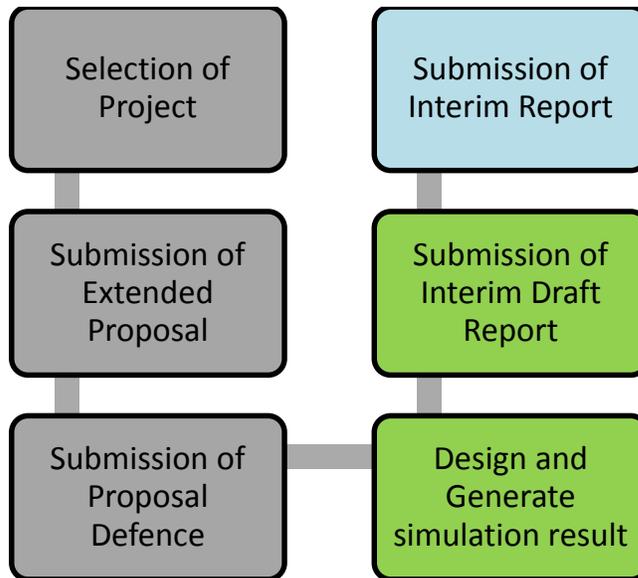
MATLAB code to obtain the shifting value for correlated signal:

```
prbs1 = idinput ([2000 1], 'prbs' , [1, 1/78.4], [0 30]);

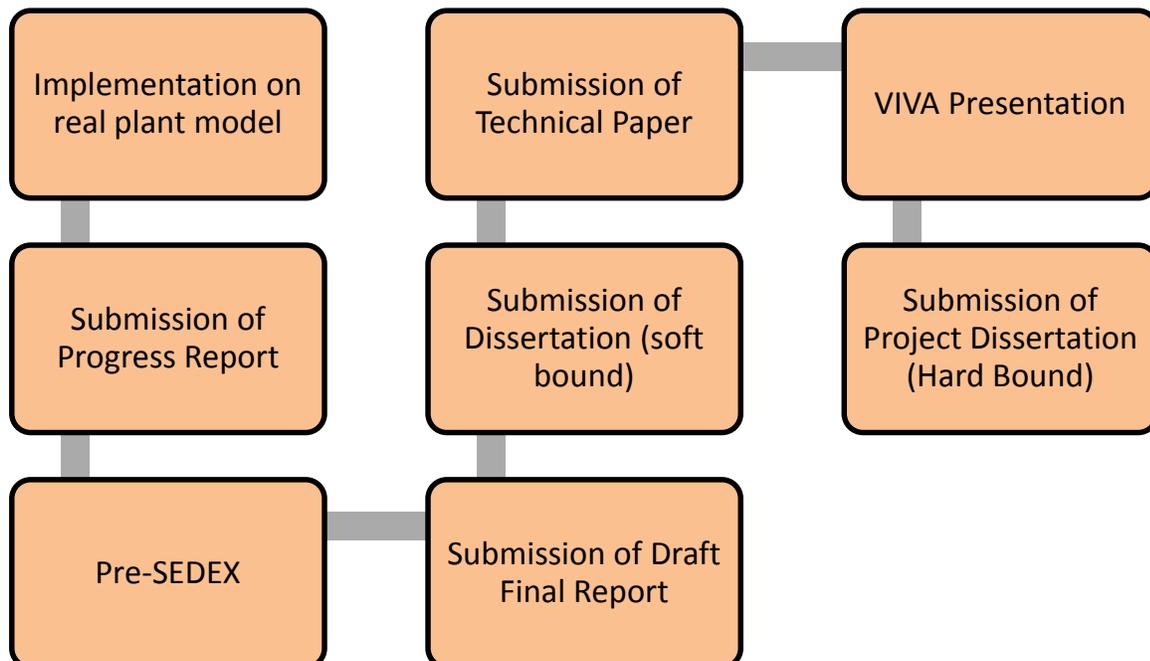
for i= 1:2000
    u= circshift (prbs1, i);
    x= corrcoef (prbs1, u);
    A= x(1,2);

    if (A>=0.7 && A<=0.8) %change this condition to generate the shift
value
        j=i
        A
    end
```

## Final Year Project I



## Final Year Project II



# Gantt Chart

Final Year Project 1:

No.	Details	No. of week														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
		22/9/2014-5/10/2014	6/10/2014-19/10/2014	20/10/2014-2/11/2014	3/11/2014-16/11/2014	17/11/2014-30/11/2014	1/12/2014-14/12/2014	15/12/2014-31/12/2014								
1	Plant Setup and understanding of manual															
2	MATLAB Simulink interfacing with process plant															
3	Determination of Steady-State Gain Matrix of Plant															
4	Determination of Transfer Function of Plant															
5	Verification of Ill-conditioned properties of Plant															
6	Design of Single PRBS test signal based on plant properties															
7	Design different combination of PRBS as test signal set															

	Past
	Present
	Future





