CONTROL OF AN ACTIVE MAGNETIC BEARING SYSTEM USING PSO – BASED TUNING PID CONTROLLER

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CONTROL OF AN ACTIVE MAGNETIC BEARING SYSTEM USING PSO-BASED TUNING PID CONTROLLER

Field of Study: **CONTROL SYSTEM**

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ABSTRACT

Active magnetic bearing is a study of object under levitation. Object under levitation simply mean the object are floating under some condition and for this project the object floats under magnetic field condition. Over the years human are trying to invent motors and machines that are could produce less losses of energy due to frictions and heats. The sudden emergence of active magnetic bearing provides an opportunity to achieve the dreams of efficient machine and motors. Active magnetic bearing is levitating rotor without any physical contact and able to rotate at high speed. This is reducing friction, heat loss and maintenance. Active magnetic bearing has been widely use and apply in many industries. This project idea is to simulate the active magnetic bearing system using dynamic modelling and simulate under Matlab environment to study the behaviour of the system. This project requires this system to be PID controller to be tuned using PSO method and study the behaviour of the PID parameter with the PSO parameter.

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ABSTRAK

Pengesanan pejalan kaki ada salah satu bidang yang penting dalam visi komputer. Pengesanan pejalan kaki adalah untuk megesan pejalan kaki dalam satu imej berdasarkan ciri-ciri pejalan kaki dengan histogram kecerunan dan pengesanan pinggir. Laporan ini adalah unutk menyampaikan satu cara untuk mengesan and mengira bilangan pejalan kaki dengan tepat menggunakan kaedah pengkelasan bertingkat. Pengesanan ini mengunakan teknik tingkap gelongsor unutk mengesan pejalan kaki. Pengesanan ini adalah pengesanan bertingkat sebab itu pengesanan ini dapat menyingkirkan kebanyakan tingkap gelongsor sebagai sampel negatif dari peringkat bermula dan memendekkan masa pengiraan. Pengesanan pejalan kaki bertingkat dapat mengesan pejalan kaki dalam masa 0.06859 saat. Oleh itu, ia sesuai untuk aplikasi masa nyata. Pengesanan pejalan kaki project ini sudah diuji dengan lebih kurang 800 imej. Ketepatan pengesanan pejalan kaki adalah memuaskan dan ia dapat mengenalpasti bilang pejalan kaki dengan betul.

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This project would not be successful without the help of people. There were many people helped me throughout this project to complete this project and make into a successful one. I would like to express my gratitude to the person that has been guiding me from the start until this hardbound book today Dr. Marizan Mubin my supervisor for this project.

She had been guiding throughout this project in every aspect that he could help. She spares her time for me and spend time to go through my updates from time to time and excuse me for my laziness during completion of this project.

There are no words to express the gratitude and appreciation to them. They been helping me from the day I step into the degree until the hardbound book today. My family had been providing me with moral support and financial support throughout the entire project. There are times felt to give up half way but without them, I would not succeed in completing this project.

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LIST OF ABBREVIATION & SYMBOLS

A

AMB	Active Magnetic Bearing

B

B	Magnetic flux

D

ds	Differential with respect to time

G

GA	Genetic Algorithm

H

H	Magnetic field

I

i	Current

P

PID	Proportional Integral Differential
PSO	Particle Swarm Optimization

Z

ZN	Ziegler - Nichols

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND OF ACTIVE MAGNETIC BEARING

Magnetic bearing is known as bearing that are magnetized to levitate object. The terms levitate simply means that object is lifted without any form of physical contact and can be subject to rotation. Magnetic bearing has no mechanical wear and extremely low friction. Magnetic bearing also can support weight and has no maximum relative speed. Magnetic bearing system consists of two types Active and Passive. Active Magnetic Bearing are the system can be control using controller meanwhile, passive magnetic bearing system that are standalone. Passive magnetic bearing system uses passive magnet hence, they do not require any power to produce the magnetic field.

There is limitation to this system as is difficult to design. Certain passive magnets can produce the magnetic field force based on the strength of the magnet. Therefore, it is difficult to design based on passive magnetic system. Active magnetic bearing system are easy to be design comparing with passive because this system is build based on materials that are coiled to produce magnetic field. Therefore, this kind of system, the magnetic field can be controlled, the magnetic force and magnetic flux by controlling either the current entering the wire or voltage.

Electromagnets requires continuous power input to keep the system in stable therefore permanent magnets are used to lift the object under levitation in case the object deviates from its eccentric due to sudden power loss. Magnetic bearing study were start during World War II era. During the World War II era people are busy creating stuff and patent to protect their creation from being steal by others. Magnetic bearing study sudden immersion into the study was during 90's. Levitation an object itself can easily attract people's attention to this topic.

Imagine an object are floating without any physical force or contact with the ground. The history of magnetic bearing begins with the creation of permanent magnets and followed by passive magnets and electromagnet until end up to levitation magnet. The application of the magnetic bearing is vast and keep expanding from time to time. Considering the general idea, an object is levitate using magnet without any physical contact. This could save the time to create the system to lift of the object and the cost.

The lifting using magnet could be done by analyzing the object to be lifted and supplying the require current to the coil to produce the sufficient force to lift off the object. This system is widely used in industry. The most famous train well known across the globe maglev train by Japan. This entire train are operating based on the principle of active magnetic bearing system. The train are levitated and capable to move with load with a maximum speed of 500km/h. This is a greatest invention in mankind history.

A train normally are made on tracks or electric cable but will be always a physical contact between the surface of the track and the bottom of the train which restrict the speed of the train and maintenance to ensure the rotor and track does not lose contact due to friction. In Maglev train, it is opposite as there is no physical contact between the train bottom and the track. The track is treat as the stator and the rotor are treat as the magnets.

Since there is no physical contact, the train can travel faster and require less maintenance. The train can lift passengers with addition the weight of body of the train to levitate and travel fast is a great invention. The train are record as to be stable and undisturbed from small obstacles trapped in between the track and the rotor. Another application would be the Flywheel ('97) and turbo molecular pump.

1.2 INTRODUCTION OF PID – PSO TUNING

PID controller are known for the flexibility and easy implementation. Despite the drawback from the PID parameters that dependent on each other, PID controller is the most favorable controller till date. PID controller have been applied in various application from heavy industries to commercial use. The challenge that often face by PID controller is the parameter. The parameter tuning is so crucial that good parameters produce stable system performance and weak parameter produces weak system performance.

Over the years plenty of approach was taken to tune the PID parameter and kept improving till the PSO was introduced. PSO able to optimize a problem with the given fitness function in shorter period of time and strong PID parameters. (Parsopoulos & Vrahatis) strongly agree the reason PSO become popular due to the ability to solve in short period of time.

Optimizer are known to optimize a function to achieve the stability or the best performance. PSO therefore were used as optimize in this research to study the parameter effect towards PSO algorithm. PID parameters has the theory behind it and the challenge is how does PSO affects the PID parameter to achieve stability. There is few research done based on PSO – PID tuning for the AMB system.

Other methods that used before to tune PID parameter was GA and ZN. ZN were the oldest method used to tune parameter and GA consider new method. Therefore, this methods were compared to study the performance of the system.

1.3 PROBLEM STATEMENT AND HYPOTHESIS

Active magnetic bearing study has been conducted over the years and are improving from time to time. Active mangetic bearing study are conducted more towards lab basis and simulation rather than real time. This is because a appropriate system or fix guideline are unable to be achieve due to the limitations by the magnets. There are several country succesfull utilize the active magnetic theory and manage to make application out of the system such as the maglev train.

The study of active magnetic bearing are plenty all over the net but mostly are based on the real hardware built. There are numbers of poeple commited to study this system under a control environment such as matlab. In matlab, situation are consider to ideal but the ideal situation could be harder by adding disturbances, hystersis and eddy current loss. The idea of dynamic modeling are referring to modeling the system using mathematical equation. Deriving the equations for the system could be difficult as it consuume time and requires plenty of reading and research to be done before able to derive the equation but, it helps to understand better the system and to proceed with the hardware would not be a hard time.

The main aim in the project is the study the variation of the system on different tuning method for the controllers. System often tend to perform differently based on different type of tuning method but, it is important to study which parameters of the system actually changes when the tuner is replace with another. Understanding the paramters that changes and study the performance of the system under the different tuning helps to understand the efficiency of the system better.

There are many situation that has to be take into consideration such as the disturbance, vibraration, eddy current loss and magnet hystersis. A system loaded with too much of additional system could complicate the system and causing it harder to be studied and understand. Therefore, it is important to model a basic system to ease the understanding and analyzing the behaviour of the system. The equation upon completing the mathematical modeling will be complicated enough therefore adding the additional situation could cause difficulities in studying the system.

Mathematical modeling simply means modeling the system out using mathematical equation. Mathematical equation can be complex and can be easy depending on the system but to analyze the equations and model based on the equation computed, that is a hard task. This tittle requires to model the system and control the system with two different controller. Hence, the controller must be take into consideration before computing the equations. Active magnetic bearing are relatively non-linear system.

The classification of the non-linearity are made based on the understading of the princple of the system. The systems consists of rotations, magnetic leviation that includes equations with high order power. The maximum power that a linear equation can has it one meanwhile above than that are classified as non-linear. The controller to be used for a non-linear system are to be selected carefully based on the system.

The tuning method does plays an imporant role to the system. Eventough the model were done correctly, if the PID parameter was not tune properly still the model would not able to achieve stability. Therefore the tuning has to be done carefully. PID parameter has no limits.

A normal system or controller has a limit of value or error but in AMB the only limit has is the air gap. The air gap are the main objective of the entire system. Therefore the tuning is to ensure the air gap distance are maintained and the vibration of the rotor are minimize. The information has is to little. PSO is known to send particles to search for the optimum solution by moving position until the best solution is obtained.

Therefore the fitness function will be compromising of the error. The error alone can not be used to create a fitness function due to the value too small. Hence performance indices were used to create the fitness function. The particles will optimize the fitness function based on the error data input. The particles will keep searching but the particles has no control over the robust. Robust is a condition whereby the system can maintain the stability despite any form of disturbance occur to the system.

The tuning method differs from system to system therefore the paramter that affects the tuning has to be identify to understand beter the system and the tuning method to identify the suitable tuner. There are plenty of tuner available for PID. Therefore the problem statement for this project is, " How much understanding can be achieved based on the tuning method and the parameters that affects the tuning method" and the hypothesis for this project is " The more variation in the tuner is made the more information can be gained".

1.4 OBJECTIVE OF STUDY

The objective of the research is listed as below:

i. To control active magnetic bearing system using PSO – based PID controller.

ii. To study on PID parameter tuning using Particle Swarm Optimization (PSO).

iii. Compare results between the proposed method with other type of PID parameter tuning method.

The first objective is to model the system using selected method and control using PSO based PID controller. The modeling method selected is mathematical modeling where by the model were based on existing system. AMB system was further compare with the existing system to linearize the model. The linearize equation was transformed to Simulink. Upon completion of the model, PID controller was added to test for the stability.

PSO algorithm was coded in separate platform called workspace. The selected approach was offline tuning due to the time consuming for building online tuning. Offline tuning uses fitness function that compromise of the error signal and produces the PID parameter upon completion of the algorithm.

The second objective is to study the PID parameter that affected from the tuning and how does the code affect the system. The PSO algorithm has the own way to converge to the optimum PID parameter and the second objective requires to study the method PSO algorithm used to achieve the optimum results.

The third objective was to compare the results obtained with other type of tuning method available for this system and controller. The comparison was done by comparing the transient response parameter. Performing the research without any comparison with previous work would not make the research valuable. The comparison makes the research valuable because comparison offers improvement for the system and the approach.

Therefore, the research question for this research is “How stable the system is under PSO tuning method and the robustness compared to other tuning method?”

1.5 SCOPE OF RESEARCH

The scope of research was targeted on the optimizing the system using PSO. The system was modelled first based on mathematical modelling. After modeling the system was tested for stability and study the transient response. The condition for the system was inspect for the allowable air gap and overshoot.

The system was added with PID controller and the PID parameter was obtained using PSO algorithm. The PSO algorithm required fitness function and each of the fitness function was tested and the best was selected for further testing. The parameter that affects the optimizing and tuning for PID was studied and further tested. The performance stability was asses based on the transient response.

The system was added with disturbance to test for the robust condition. The system was tested and asses through transient response. The vibration was studied to reduce further to the allowable tolerance.

Overall the entire research scope is to control the system and study the parameter that affects the tuning of PID controller.

CHAPTER 2: LITERATURE REVIEW

2.1 MODELLING OF ACTIVE MAGNETIC BEARING

Active magnetic bearing system is a popular system among research due to the advantages the system offers. Active magnetic bearing is an ongoing research topic have not found its saturation point. This means this system has a lot of door to be explore to add more information on this topic related research. (Ritonja, Polajžer, Dolinar, Grčar, & Cafuta, 2010) mentioned the system offers levitation through the electromagnetic force. The electromagnetic force is controlled by the supplied voltage to ensure the rotor maintain its position known as the air gap.

There are plenty of method to perform the modeling for this system. (Lee & Jeong, 1996) mentioned the system becomes complicated when the modeling is done sophisticatedly. Therefore the modeling has to be done as simple as possible which leads to the linearize model. (Shelke, 2016) suggested by simplifying the system, it allows research to study the system better for improvement. The axis and losses was replaced as disturbance to the system.

(S. Y. Zhang, Wei, Li, & Wu, 2017) mentioned as the speed of the rotor increases, the system tends to be unstable therefore controller should be designed for robust. (Tshizubu & Santisteban, 2017) mentioned in the publication that linearize system offers more flexibility to studied and control. Therefore, the system will adapt the linearize model for this research. Several theories must be understood beforehand modeling the system.

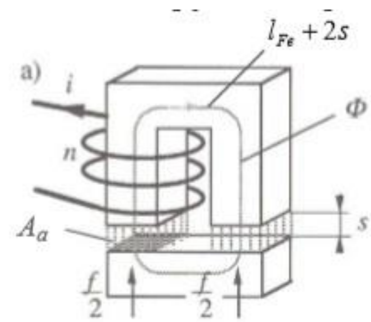


Figure 2.1: U-shape Electromagnet. (Adapted from Hillyard 2006)

Figure 2.1 shows the U-shaped electromagnet with the bottom is a bar of ferromagnetic material between the air gaps s . The variable $\emptyset$ demonstrates the closed-circuit path of the magnetic flux. Referring to Equation 2.1, the energy contained within the air gap can be obtain easily. Equation 2.1 shows the Energy contained within the air gaps.

$$U_a = \frac{1}{2} B_a H_a V_a \tag{2.1}$$

$$U = \frac{1}{2} B_a H_a A_a 2s \tag{2.2}$$

According to Hillyard (2006), the variable N is the number of coils within magnet and the reasoning behind the capitalization of the variable NI is because NI are always stick together as variable therefore NI are also called as the magnetomotive force.

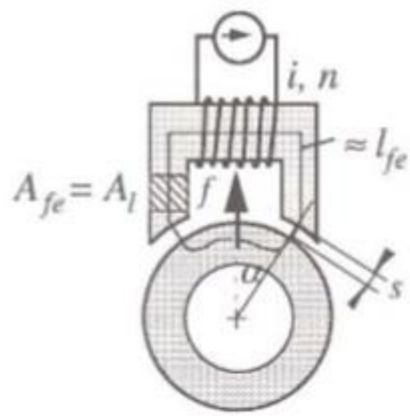


Figure 2.2: Rotor under levitation using a U-shape electromagnet. (Adapted from Hillyard 2006)

The principle of virtual displacement will be use often for solving most of the equation. Referring to Figure 2.2, the principle of the operating is the same. A u-shape electromagnet is place at a fixed position and current are being supply to the electromagnet through the wire coiled up in the u-shaped magnet.

The u shape magnet produces attractive force towards the ferromagnetic material rotor to levitate the rotor within the air gaps of variable s. According to Hillyard (2006), Variable A is the cross-sectional area of the air gaps and l the magnetic flux travel within the u shape electromagnet to produce the desire force. Equation 2.1 are use with the principle of virtual displacement to achieve the force equation for the system as Figure 2.2.

$$F_c = \frac{N^2 \mu_o A_g I^2}{4L_g^2} = \frac{B_g^2 A_g}{\mu_o} \tag{2.3}$$

Referring to equation 2.3, the levitation force F_c (Schweitzer, Bleuler, & Traxler, 2009). N has been explained earlier meanwhile A_g is the air gap area, I is the current to be controlled, L_g is the air gap length and B_g is the air gap flux density.

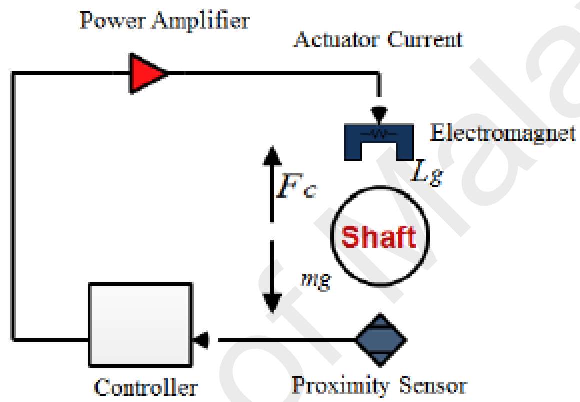


Figure 2.3: Construction of AMB (Shata, Hamdy, Abdel-Khalik, & El-Arabawy, 2016)

The figure 2.3 and equation 2.3 can be related and noticed the levitation force and the current is non-linear. The electromagnetic force and the air gap are inversely proportional which makes the system unstable. Therefore, the differential mode must be applied as figure 2.4.

$$F_c = \frac{N^2 \mu_o A_g I^2}{L_g^2} I_c + \frac{N^2 \mu_o A_g I^2}{L_g^3} X \tag{2.4}$$

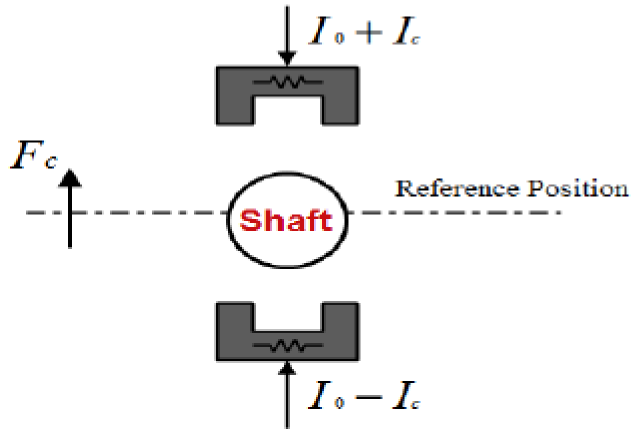


Figure 2.4: AMB under differential mode. (Shata et al., 2016)

Referring to equation 2.4, formed based on the differential mode as Figure 2.4. Since equation in 2.3 has inverse relation, by applying differential mode enables two opposite electromagnet force to summed (Shata et al., 2016). The equation 2.4 can be further reduce to equation 2.5.

$$F_c = K_i I_c + K_s X \tag{2.5}$$

Equation 2.5 are same as equation 3.2.7. Both equation is the same whereby one is used for modeling and one for theory. The equation 2.5 and 2.4 are the same. The K_i of equation 2.5 is the force current factor meanwhile the K_s is the control current factor. The two-huge parameter are treated as constant for linearizing purpose and I_c is the control current.

$$f = k\frac{i^2}{s^2}\cos a \tag{2.6}$$

Equation 2.6 are to ease the linearization. Active Magnetic Bearing system are relatively non-linear system and unstable therefore linearization is required to model the system and control the system. Based on Equation 2.6, the constant k was simplified as Equation 2.7.

$$k = \frac{1}{4}\mu_o n^2 A_a \tag{2.7}$$

Referring to equation 2.7, the relationship between the force and current is directly proportional. This system has two methods of controlling either through current control or voltage control. Based on equation 2.7, the current control will be used because the change in current will directly change the force. The force is the magnetic force that controls the air gap between the rotor and the stator. Only single axis rotor will be considered in this system to simplified the purpose of the study.

Despite plenty of model available, not all the model could not achieve stability by itself without the help of controller. (Wei & Söffker, 2016) mentioned that the factors that affects the performance of the system are magnetic saturation, vibration, losses in current, fluctuation in the voltage supplied and interference of the axis. Therefore, controller is needed to compensate the error.

2.2 PID CONTROLLER

PID controller are known as Proportional, Integral and Derivative controller. This controller required all the three parameters to perform as controller. Each of the parameter has different purpose to compensate the error. PID controllers measures the error produced by the system and output signal to compensate the error. PID controller is one of the oldest controller and can be used easily and implemented easily.

The Proportional parameter commonly used as K_p compares the desire output and the targeted output. The deviation in the comparison will compensated constantly. Basically, the P controller reduces the rise. Comparing the effect with the current system, rise time refers to the time taken for the system to reach the peak output. In AMB system, the peak output refers to the highest value of gap between the rotor and the stator.

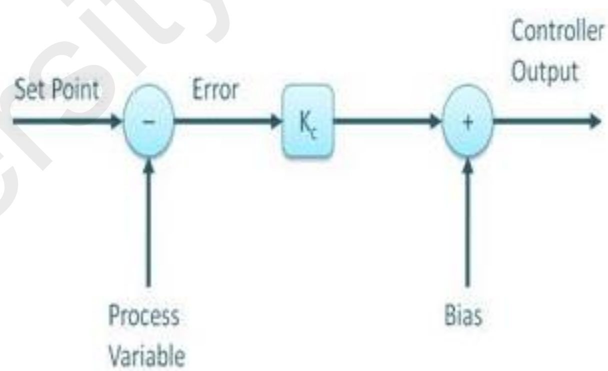


Figure 2.5: P – Controller (Adapter from elprocus, 2015)

The Integral parameter commonly used as K_I eliminates the steady state error by integrating over time until the error drops to zero or the minimum value it could. Sometimes this controller drops until below zero which affects the performance of the system. Comparing for this system, the rotor might hit the stator downward direction since the simulation consider x – axis only. The I controller reduces the steady state error but affects the transient response of the system. This controller reduces oscillation of the system. Direct comparison, this controller reduces the vibration of the rotor and compensate to make the rotor stable.

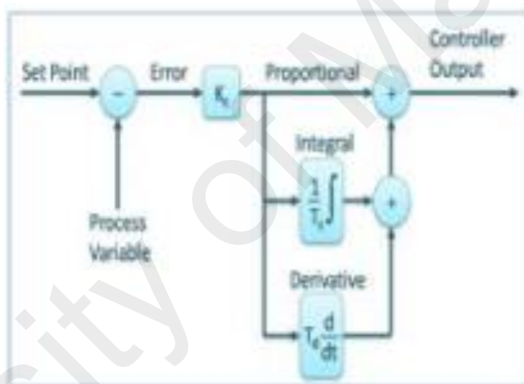


Figure 2.6: PI – Controller (Adapter from elprocus, 2015)

The derivative parameter commonly used as K_D predicts the future error that might appear and perform adjustment accordingly. D controller is the final controller in the PID controller hence it multiplies by time and predicts the behavior of the system and keep the error at minimum. K_D parameter is responsible for reducing the system overshoot and improving the system transient response. In AMB, the system overshoot must be kept at minimum this is because if the overshoot is too high, this indicates the peak value is too high hence it will cause defect to the stator.

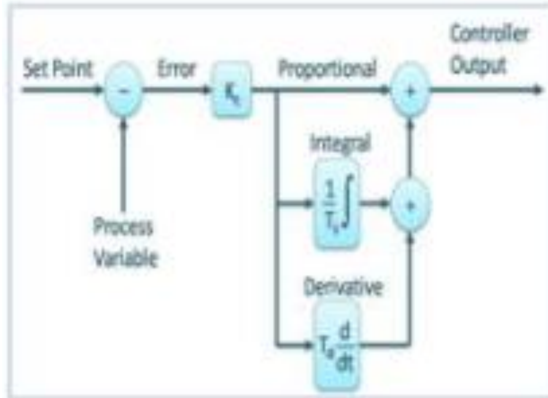


Figure 2.7: PID – Controller (Adapter from elprocus, 2015)

Referring to figure 2.7, the complete controller of PID. As a summary, K_P adjusts the rise time for the system, K_I adjust the steady state error of the system and reduces the oscillation of the system and K_D reduces the system overshoot and improve the system transient performance. (Jakovljević, Šekara, Rapaić, & Jeličić, 2017) mentioned that the K_P, K_I and K_D are required to stabilize a system. All three variables are dependent each other. Varying any of this parameter will indirectly change the remaining two therefore a tradeoff is required in PID controller.

The system cannot have a high system response, low system overshoot and low steady state error. Either one of the criteria must be trade off depending on the application. As for AMB system, the air gap distance is important therefore the system response time and steady state error can be trade off but must be ensure within the limits. (Noshadi, Shi, Lee, & Kalam, 2014) mentioned the response time and the steady state error was compromise because of the nature of PID controller. Combination of PID controller with other type of controller provides better results as the follow researcher did with fuzzy logic controller.

Therefore, the three parameters must be tuned appropriately to achieve high system performance. There is various of PID tuning method available but the method selected for the research is Particle Swarm Optimization PSO and the results was compare with Genetic Algorithm (GA), Ziegler Nicholas (ZN) and trial and error. Despite plenty of research has carried out on this topic but there are few research done on tuning PID parameter. Most research are based on other controller.

Therefore, the research gap can be clearly seen. The reason because there is plenty of tuning method available but research preferable to try other controller to study the system performance. (Smirnov, Uzhegov, Sillanpää, Pyrhonen, & Pyrhönen, 2017) stated that AMB system widely used in many rotary industry and levitation industry. Rotary refers to high speed motor and machining.

Maglev train in Japan uses the same technology to levitate the train which reduces friction enabling the train to move faster. (Chen, 2008) suggested that using optimization method to tune PID parameter could produce a more stable system and stated that PID controller is widely used and easy to be implemented but difficult to optimize the parameter for PID controller because AMB system has non linearities. Despite linearizing the parameters, the non-linear will always inherited in the behavior of the system which put serious test to the tuning method to optimize the value.

2.3 PID – PSO (PARTICLE SWARM OPTIMIZATION)

PSO known as Particle Swarm Optimization is artificial intelligent system used for optimizing problems. This system requires optimizing to tune the PID parameters. (Eberhart & Kennedy, 1995) introduces the PSO optimizer which revolutionize the controllers and fits for various applications. PSO can be used to solve for another optimizer and controller problem as well. The optimizer is designed based on nature or behavior or nature either insect, plant, animals or bacteria.

PSO was designed based on the behavior of birds. Whereby a flock of birds search for food and any of the birds discovered food, will return to update the remaining birds at the meeting point so that all the birds will converge to the same place at the same time inform if there is no food at the other location. The birds are referred as particle in PSO algorithm and the pbest is the bird personal location for food and global best is the destination for birds to achieved the food.

Birds has velocity and weight hence the velocity and the weight are used as the iteration and the weight is used to tune the parameters. In PSO fitness function is required. Fitness function means a function that specify what is required to be optimize and ensure the value remain low within the fitness function. PSO will search for the optimum value for the fitness function at the hyperspace and keep update the location until the correct There is various of ways to design fitness function. (Li, Yu, & Wang, 2007) mentioned that the simplest way to obtain fitness function is through utilizing performance indices.

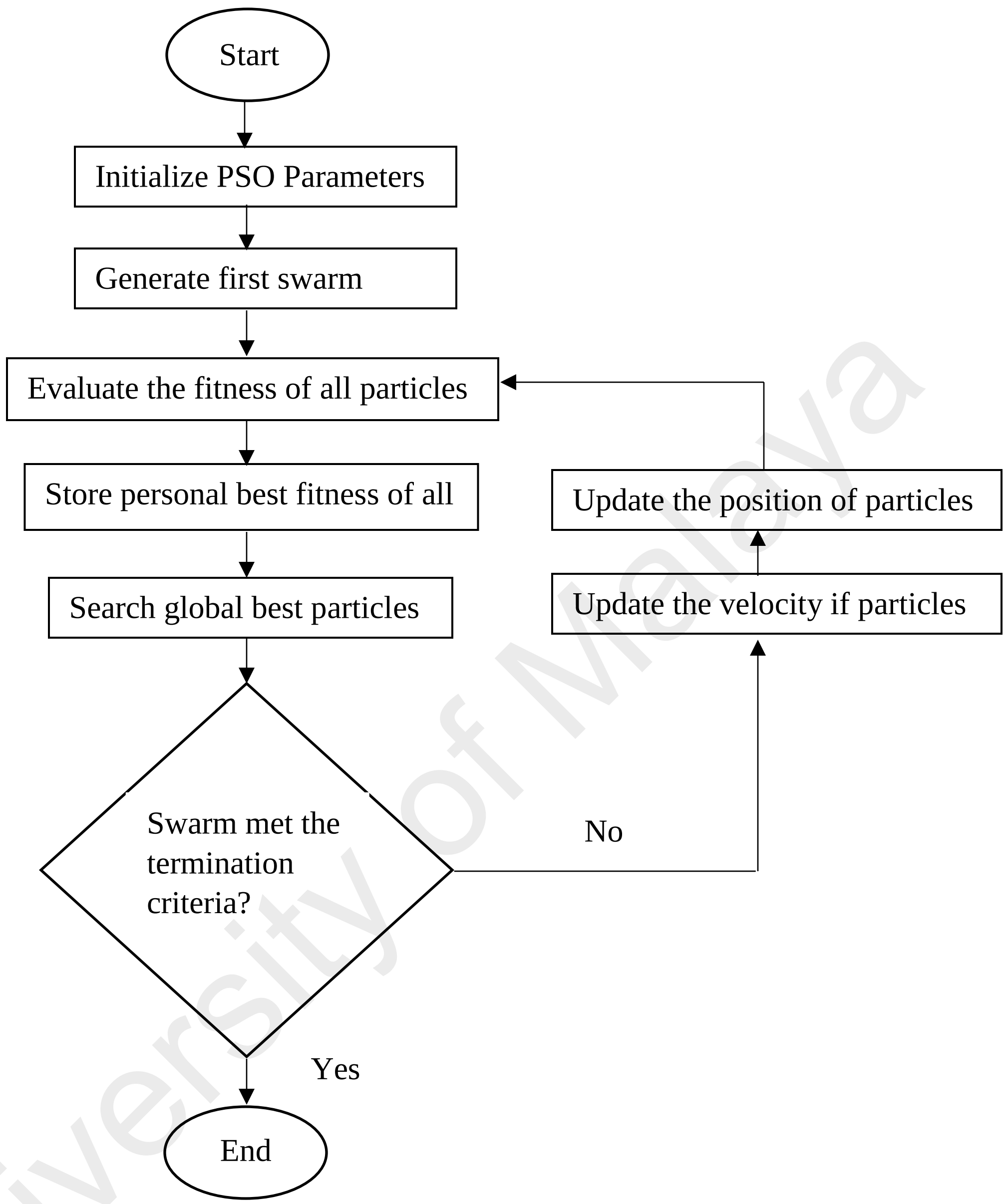


Figure 2.8: Flow Chart of Particle swarm optimization (PSO)

Referring to figure 2.8, illustrate the flow chart for PSO algorithm. The coding follows the same flow chart. At the initial stage, the PSO parameters must be declared. The parameter meter refers to the weight, learning rate, swarm size and bird step. This are important as the more number does not mean the system will be optimize better it depends on the fitness function as well.

If the fitness function is designed poorly, during the optimization process the system will face difficulties to optimize the system hence the error will persist despite performing optimization. Therefore, the fitness function plays an important role in PSO. The next step is generate the first swarm this is to help to predict the swarm size and the number of bird step because the larger the swarm size, the longer time taken for the system to optimize. (Yang, Li, & Yang, 2008) mentioned that the larger the fitness value, the better the system performance.

The next step would be each particle will store as Pbest and compare with others and if there is better value it will store as gbest. Upon the gbest formed, the fitness will be compare with the termination criteria and if the criteria did not match, the system algorithm will continue search till the termination criteria is met. Particles updates the position and velocity based on equation 2.8 and 2.9 after discovering the best values.

$$v[\,] = v[\,] + c1 * rand\,(\,) * (pbest[\,] - present[\,]) + c2 * rand\,(\,) * (pbest[\,] - present[\,]) \tag{2.8}$$

$$present[\,] = present[\,] + v[\,] \tag{2.9}$$

$rand\,()$ is a random number range between 0 to 1 meanwhile $c1$ and $c2$ are learning factors and usually the values are two. (Y. Zhang, Qiao, Lu, Wang, & Wu, 2010) mentioned that the $c1$ and $c2$ is best to set equals to two because plenty of research has done before and achieve success at that value. Meanwhile to utilize the PSO to solve optimizing problem for PID controller require modification on the dimension and fitness function.

Since PID controller consists of three parameters, hence the dimension of the problem to be set should be to search the space for the parameters. PSO have been used as tuning for PID controller before by few researcher. (Shata et al., 2016) used IAE as the performance indices to form the fitness function and the objective was the control current should not exceed the magnetic saturation and the maximum overshoot must not exceed the available clearance.

(Shata et al., 2016) mentioned the IAE performance indices may not minimized which results in the 60% overshoot. There is not plenty research done on this system thereby the only paper can be compare would be this paper. Therefore, IAE will be avoid being used as performance indices for this research. Performance indices is crucial for the controller.

(Gupta & Padhy, 2013) mentioned performance indices works differently for different system. Hence, all four performance indices will be used to study the behavior with the system.

2.4 COMPARISON ANALYSIS USING GA, ZN AND TRIAL AND ERROR

The results obtained from PSO – PID will be compared with other tuning method such as Genetic Algorithm (GA), Ziegler Nicholas (ZN), and trial and error method. These methods were selected to perform the comparison because of the nature and the research done before with this system. (Pham & Karaboga) mentioned that genetic algorithm is formed based on inspiration from nature.

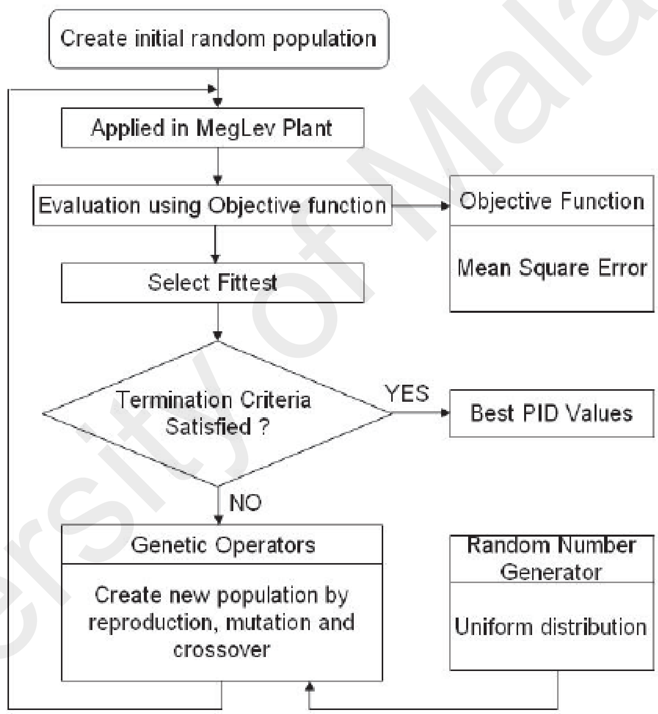


Figure 2.9**:** Flowchart of Genetic Algorithm (Ishtiaq, Mohsin, & Peter, 2014)

Figure 2.9 illustrates the flowchart for genetic algorithm to search for optimize values for the fitness function. Genetic algorithm requires initial population to set the set of chromosomes. The population size should be in medium size because too big size will slow down the search speed and too small might miss the mating pool.

Chromosomes are stored in binary and it will follow the fitness function set to search for the optimize value. The algorithm will go through the crossover and mutation to verify the best value and survivor selection will select the best value. If all the condition met, the loop will be terminated and return the best value. Figure 2.9 the maglev plant should be replace with AMB plant and the performance indices used are mean square error MSE.

Meanwhile Ziegler – Nichols is a popular method been using for years. There are plenty of Matlab toolbox available to be used to optimize the PID parameters. The last method would be the trial and error method. Trial and error method are based on the previous value obtained from other tuning method or by the toolbox itself. By constantly varying the parameters, the stability can be achieved but time consuming.

Parameter	Value
Selection Method	Normalized Geometric Selection
Population size	120
Generation Size	40
Cross Over Method	Arithmetic Crossover
Mutation Method	Uniform Mutation
Selection Probability	0.08
Number of Crossover points	4

Figure 2.10: Table of GA parameters (Ishtiaq et al., 2014)

Figure 2.10 is the parameters used to set the GA. The population size is 120 and the generation size is 40 but the number of crossover points are 0.1 times of the generation size. The crossover method is selected to perform step incremental.

Item	GA Tuned	ZN
Rise Time (sec)	0.0065	0.0028
Settling Time (sec)	1.25	4.12
Overshoot (%)	78.69	72.06
Peak Amplitude	1.78	1.72
Final Value	1	1

Figure 2.11: Table of system performance comparison.

Referring to figure 2.11, the table illustrates the system performance of AMB using GA tuning and ZN tuning for the PID parameters. The table will be discussed in detail under chapter 4. Rise time are the time taken for the system to reach the peak value for this table peak amplitude. The settling time is the time taken by the system to reach steady state condition. Overshoot is measure in percentage to calculate the difference of the peak output and the steady state value. Final value is the final steady state value.

CHAPTER 3: METHODOLOGY

3.1 INTRODUCTION

The research is divide into two major part as the research involves two disciples. The first part is the modelling the system using mathematical method. Upon completion of the modeling, the system was tested under Simulink environment for the stability. Controller were added prior to the requirement of the research to ensure the stability of the system. The active magnetic bearing system was modeled based on existing system to ease the job of the modelling. The controller was specified in the system which is PID. The controller purpose is to maintain the error at minimum level to maximize the stability of the system. PID controller is well known and easy to be implemented. The challenging task in the controller is to identify the PID parameters namely as below:

1. K(P) = Proportional
2. K(I) = Integral
3. K(D) = Derivative

Each of the parameters has a prominent role. Neglecting either one of the parameters will affect the performance of the system. Therefore, the value the three parameters above must be determine with respect to the system. Different system works well with different parameters. Therefore, the parameters are application specific. There are various of method to identify the PID parameters and for the research PSO (Particle Swarm Optimization) will be used to identify the suitable parameters for the system.

The comparison analysis was carried upon the completion of the parameters searching process. The comparison analysis was done by comparing with another controller with the same system to study the stability. The system performs differently under different controller. Hence it is important to study the behavior of the system under different controller. The system behavior was studied to understand the relation between each parameter with the behavior of the system.

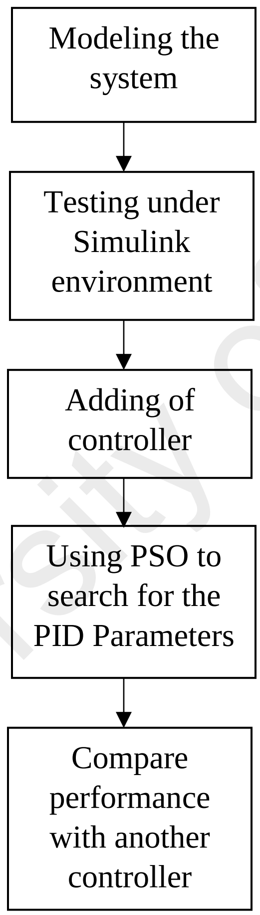


Figure 3.1: Flow chart of the entire process

3.2 MATHEMATICAL MODELING OF THE SYSTEM

Modeling process of the active magnetic bearing system are done by comparing with other system that exhibits similar behavior. The only system that exhibits similar behavior was spring system. Spring system lift objects under spring suspension like active magnetic bearing by levitating object under magnetic suspension. The reason this system was modelled in such way to ease the study and research purpose. This method is known as linearize to avoid non-linear system which will challenge the controller to be used. Non-linear system is difficult to be control by nature.

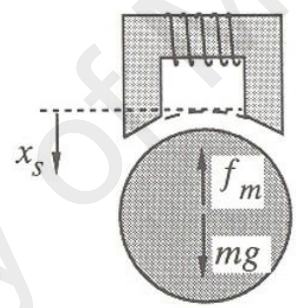


Figure 3.2**:** U-shape electromagnet with rotor under levitation. (Adapted from Hillyard 2006)

Based on figure 3.2, the x_s is the distance between the pole of the u-shape electromagnet and the rotor. The rotor has a force of f_m which acting upwards and mg acting downwards. The upward force is the attractive force by the magnetic system meanwhile the downward force is the weight that are being pull down due to gravitation force. This exact scenario can be compare with Hooke's law of spring force. Figure 3.3 illustrates the Hooke's Law.

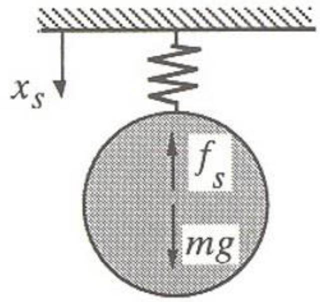


Figure 3.3: Rotor under suspension using spring. [Adapted from Hillyard 2006]

Figure 3.3 shows the rotor is place under suspension by a spring. The variables remain the same as Figure 3.2 exceptional for f_s which is the spring force. Comparison between Figure 3.2 and Figure 3.3 result into the similarities of the function. In Figure 3.2 shows rotor are being levitate under a magnet force meanwhile in Figure 3.2.3 shows rotor are being suspended by a spring which restrict the movement of the rotor. The concept the build the equation is similar. As Figure, 3.2 is the spring force, which are the results from Hooke's Law. Equation 3.3 are the Hooke's Law.

$$F = -kx_s \tag{3.1}$$

Referring to Equation 3.1, the constant k is the spring constant, which decides the stiffness of the spring. On the other hand, Figure 3.2 shows the magnet force which has been identified to be Equation 2.4. Comparing Equation 2.4 and Equation 2.5 shows both equation is like each other.

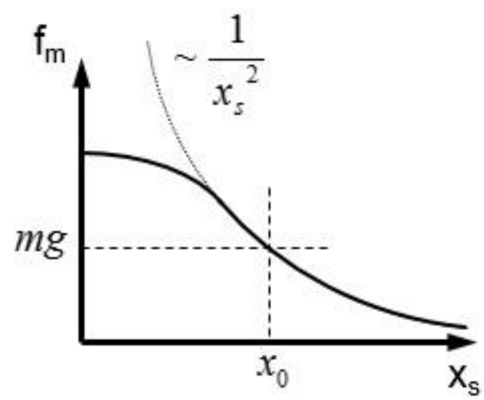


Figure 3.4: Graph of inversely proportional function.

Referring to Figure 3.4, the variable $x_o$and mg are selected such as the current is constant in contrast with Figure 3.5. Figure 3.5 shows the graph obtained from the spring force. Figure 3.5 shows the constant $x_o$and mg are selected to obtain the k_s force-displacement factor constant. Therefore, a conclusion can be drawn that to achieve a stable distance based on the desired mass a constant k are required and for the magnetic force linearization two constant are required.

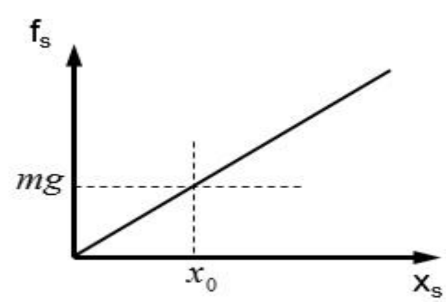


Figure 3.5: Graph of directly proportional relationship.

Figure 3.5 illustrates the relationship between the both variable. The weight and the distance are directly proportional which indicates increase in weight results increase in the gap as well. The gap refers to the distance between the rotor and the magnet. Shorter gap distance results in collision. Hence it is important to maintain the distance significantly for better performance.

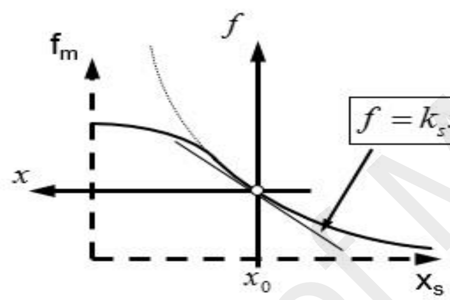


Figure 3.6**:** Graph of the force displacement function.

Based on figure 3.6, taking the gradient at the operating points provides the current equation which is constant. This information helps to form the equation 3.2.

$$f = k_s x \tag{3.2}$$

$$f_{m,s}\Big|_{i_m = i_o} = k_s x \tag{3.3}$$

Equation 3.3 shows the current being assume as constant therefore Equation 3.2 is obtained. The constant k_s is the force-displacement factor. The distance s had to be re-define, as the current is constant. Figure 3.7 illustrate the process of re-defining distance.

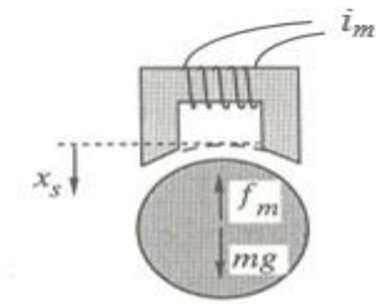


Figure 3.7**:** U-Shape electromagnet with rotor under levitation by setting current constant. [Adapted from Hillyard 2006]

Referring to Figure 3.7 the new distance is Equation 3.4.

$$x = -(x_s - x_0) \tag{3.4}$$

Equation 3.4 the variable x_s is the distance of the air gap and x_o is the center known as eccentric. Therefore, the equation for the constant current has successfully obtained. Figure 3.7 shows the constant position on the electromagnet. Referring to Figure 3.7, it can be notice the coiled wire around the u-shape electromagnet, the current is label as i_m since the current is assumed as constant which can be clearly notice in Equation 3.3 when the $i_m = i_o$.

Variable i_o is the excitation current in the coil meanwhile i_m is the maximum current and assumed to be same. The next constant that are required is force-current factor by assuming constant position. s^2 is in inversely quadratic relationship. Therefore, inverse graph will be plot with respect to variable s^2 and a tangent to the curve drawn to obtain the new equation with the force-current factor.

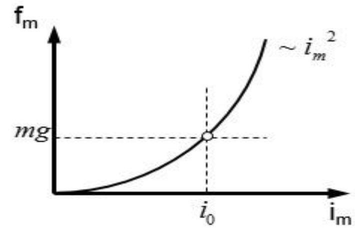


Figure 3.8: Graph of force vs current by assuming distance constant.

Referring to Figure 3.8, the plotted graph is the equation of i_m^2 by assuming the distance is constant. The point mg and i_0 were selected and a tangent line drawn to compute the force-current factor.

$$f_{m,i}\big|_{x_s = x_o} = k_i i \tag{3.5}$$

Equation 3.5 shows the final equation based on the assumption made. Figure 3.8 illustrates the tangent line draw to obtain the equation with the k_i force-current factor.

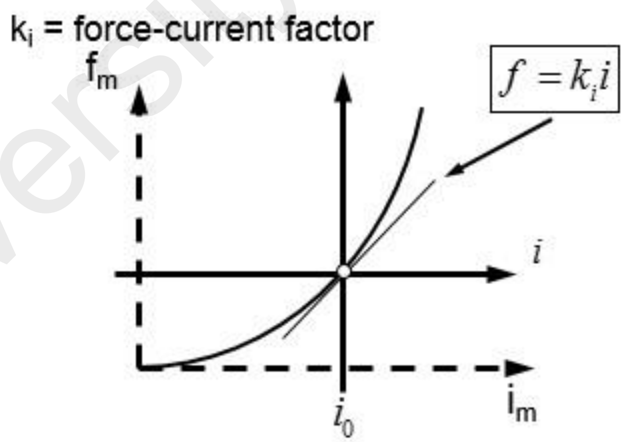


Figure 3.9: Graph of current force function.

Figure 3.9 illustrates the graph with the tangent line drawn on the point (i_0, mg) and the equation $f = k_i i$ were obtained. The constant k_i is the force-current factor. The graph purpose is to illustrate the linearizing process. k_i force-current factor and k_s force-displacement factor is combined to form one equation to form the linearized model equation. Equation 3.5 shows the combine equation.

$$f(x,i) = f_{m,s}\big|_{i_m=i_o} + f_{m,i}\big|_{x_s=x_o} \tag{3.6}$$

Referring to Equation 3.6 is the combination of Equation 3.3 and 3.5 and since each final equation already obtained, therefore it leads to Equation 3.7.

$$f(x,i) = k_s x + k_i i \tag{3.7}$$

Equation 3.6 is the final equation to compute the force exerted by the u-shape electromagnet. The force is important to be model because the force will maintain the rotor under the levitation. The force in terms of distance and current and this is because of the linearization process. This equation is not valid for magnetic saturation, rotor-bearing contact and small currents analysis.

This is due to the limitation of the model. To linearize a model, several assumptions was made and for this model magnetic saturation, rotor-bearing contact and small currents was neglected. The neglect condition of course affects the performance of the system therefore these conditions is acts as a disturbance in the model under Simulink environment to study the behavior under a controller. Figure 3.10 illustrate the system of Active Magnetic Bearing that will be use.

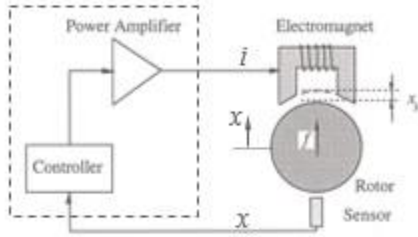


Figure 3.10: Complete system model of Active magnetic bearing. [Adapted from Hillyard 2006]

Figure 3.10 is the complete system of the active magnetic bearing. The equation for the system was solved and linearized but to control the rotor distance a controller and power amplifier is needed. controller provides output signals to the amplifier to control the current supplied to the electromagnet to control the distance of the air gap.

The system is such in a way that a sensor will be place right below the rotor and the output of the sensor is transmitted to the controller. The controller adjusts its parameter to compensate the error, which is the difference of the eccentric value. The controller produced output signal after comparing the error and send to power amplifier to amplify the current supplied to the u-shape electromagnet. Therefore, in modeling the system under Matlab Simulink environment, it is important to consider the controller and amplifier and the sensors. The suggested sensor would be Hall Effect sensor as to detect position of the object even while under rotation.

3.3 MATHEMATICAL MODELING OF THE SYSTEM IN SIMULINK

The equations are arranged into the Matlab Simlink environment. Figure 3.11 illustrates the Active Magnetic Bearing simulated in Matlab Simulink Environment.

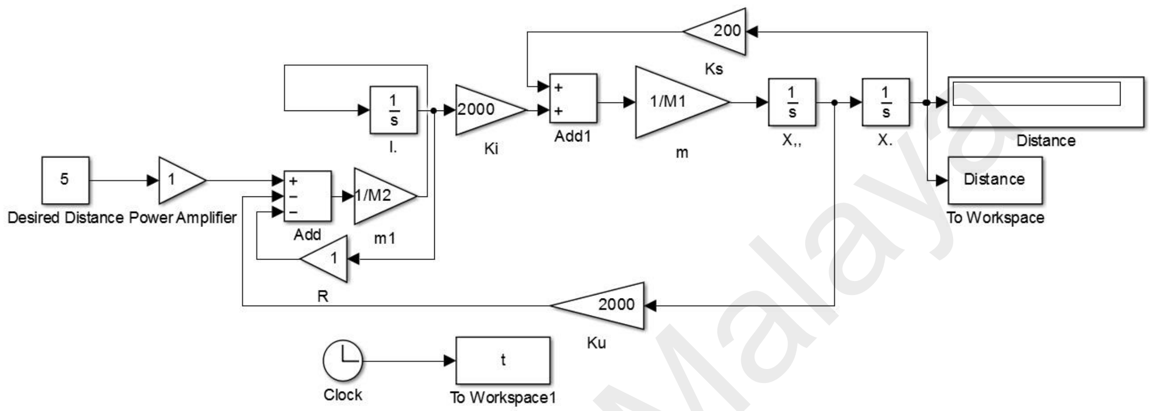


Figure 3.11: System modelling without controller using Matlab.

This system is relatively unstable without controller. Controller are used to control the distance. Selection of controller are important by first considering the system linearity. Considering from the steps before the final equation, the system is non-linear and gone through linearization step. Therefore, the controller selected should be a non-linear controller to maximize the performance of the system.

Table 3.1: Parameters values of the system

Parameters	Values
Mass,m	$4kg$
Area of Pole a	$17cm^2$
Inductance of coil	$10mH$
Resistance of coil	$1\ Ohm$

3.4 PSO-PID CONTROLLER IMPLEMENTATION

Controller is the outmost important element of a system. If the system is relatively stable, then it is ideal system and does not require controller. Figure 3.12 illustrates the control loop of the system. Referring to figure 3.12, the open loop system is directly from the input voltage to the active magnetic bearing system meanwhile the close loop is the feedback loop are channel to the sensor and from the sensor channel to the controller to compare with the desired distance and change the input voltage to maintain the desired air gap.

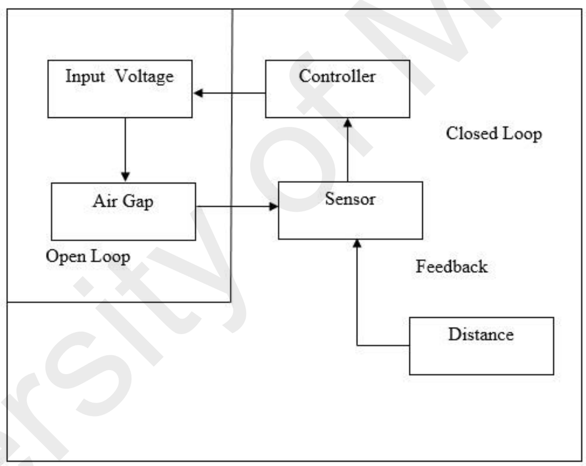


Figure 3.12: Block diagram of the control loop system

Therefore, controller is needed. In this system, there are two methods can be used to control the system which is current control and voltage control. In this system voltage control are choose over current as current control as discuss in chapter 2. There are plenty of linear controller and the controller selected for this system would be PID.

Following flowchart briefly describe the process involves in designing the controller for the system as in Figure 3.12.

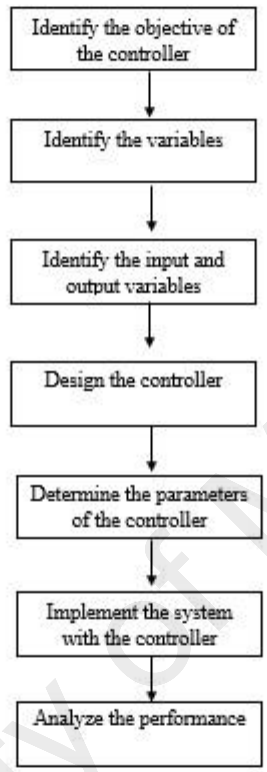


Figure 3.13: Flowchart of controller designing steps.

Figure 3.13 illustrates the process taken to design a controller but for this research the controller has been set as PID controller. The focus will be targeted on step number 5. There are plenty of tuning method for PID parameters and PSO was used in this research.

$$K_p + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s} \quad (3.8)$$

Referring to equation 3.8 is the Laplace transform of the transfer function of PID. As mention, earlier there are 3 parameters used in PID controller to control a system. PID controller stabilize a system by reducing the error produced by the system. A good PID parameters will produce stable system with excellent performance. Determining the PID parameters is not easy task either. As for this system, the error produced will be the variation in the distance gap. The rotor gap is important because if the gap exceed the maximum limit, the rotor will cause damage to the magnet and the system. If the gap fluctuates constantly, that indicates the rotor are vibrating at its position which reduces the system performance.

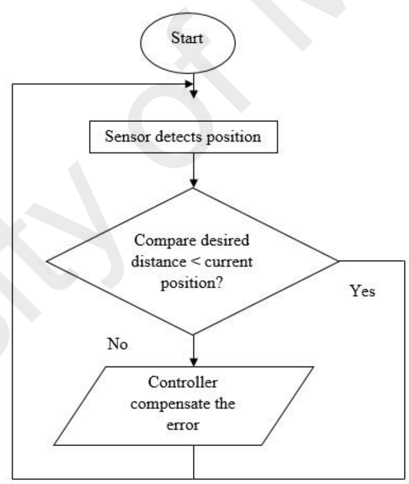


Figure 3.14**:** Flowchart of Closed Loop System.

Figure 3.141 is the flowchart for the closed loop system because this system compromise under control system as well. Whereas this system is classified as closed loop system. Referring to the flow chart, the controller role takes place at the decision point whereby the error will be calculated and the controller controls the error to a minimum level.

This controller is fully dependent on the KP, KD and KI parameters. Hence it is important to obtain a proper parameter to maintain control the system. The minimum gap for the rotor are set at 5mm between the stator and rotor. Hence in Simulink the unit is mm. Particle Swarm Optimization is used to obtain the best value for the PID parameters.

Figure 2.8 is the process for PSO. The same flowchart was used to search the correct parameters for the PID controller. The model was done in Simulink environment and the PSO algorithm was done in workspace known as coding. The offline tuning was used to search for the PID parameters. There are two techniques to be used to search for the PID parameters. The first through input the transfer function of the system as fitness function in the PSO algorithm or input the Simulink file into the PSO algorithm through another call function. The technique used was Simulink file into another call function.

The model was done in Simulink environment because the flexibility offered by the Simulink. Through Simulink, any changes to the system or addition of parameter to the system can be done easily through Simulink meanwhile transfer function requires to recalculate the transfer function again. Simulink method was used but the fitness function was created separately due to the limitation by the method.

A separate file called trackslq were created to define the PID parameters and to call the Simulink file. The file will collect the error generated by the Simulink file and perform the optimization based on the fitness function created to generate the PID parameters. The fitness function is based system overshoot and error. System overshoot was targeted prior to the limitation of the system to avoid collision with the stator and error to ensure the stability. The error is recorded and stored based on the performance indices ISE.

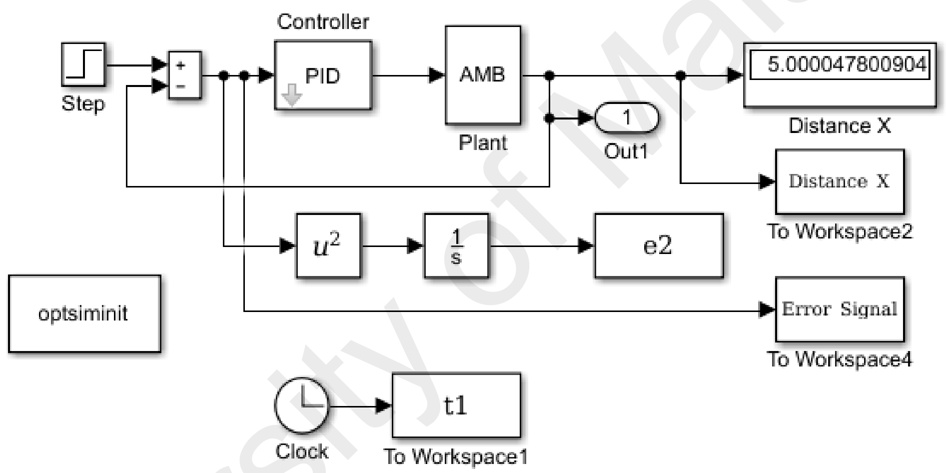


Figure 3.15: Simulink of Complete system.

Referring to figure 3.15, PID controller required manual input. The PSO algorithm calculates the parameter and display in workspace and the value should be key in manually. Offline simulator was used to enhance the ease of study of the parameters.

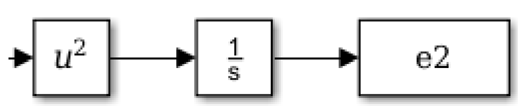


Figure 3.16: Performance Indices ISE

Referring to figure 3.16, performance indices Integral Square Error ISE was used in this system as error signal for the fitness function. Equation 3.9 is the equation for the performance indices ISE.

Integral of Squared (ISE)

$$I = \int_0^\infty e^2(t)\, dt \tag{3.9}$$

The learning rate and weight in PSO algorithm was varied to study the effect towards the performance. There are total of 4 performance indices available. All four performance indices were used to compare the results between the performance indices. The main performance indices are ISE due to the literature study conclusion deduced the suitable performance indices is ISE. The remaining performance indices as follow:

Integral of Time Multiply Squared Error (ITSE)

$$I = \int_0^\infty te^2(t)\, dt \tag{3.10}$$

Integral of Absolute Error (IAE)

$$I = \int_0^\infty |e(t)|\, dt \tag{3.11}$$

Integral of Time Multiply Absolute Error (ITAE)

$$I = \int_0^\infty t|e(t)|\, dt \tag{3.12}$$

Referring to equation 3.2.10,11 and 12, those are the equation for the performance indices and each of them has significant role towards the performance of the system. The appropriate weight and learn rate was obtained first through trial and error. once the appropriate weight and learning rate obtained, the performance indices were varied to study the impact towards the PID parameters and the converging rate.

```
clear
clc
n = 100;              % Size of the swarm " no of birds "
bird_setp  =50;     % Maximum number of "birds steps"
dim = 3;             % Dimension of the problem


c2 = 1.6;             % PSO parameter C1
c1 = 1.4;           % PSO parameter C2
w = 0.7;              % pso momentum or inertia
fitness=0*ones(n,bird_setp);
```

Figure 3.17: Parameters setting in the PSO Algorithm

Figure 3.17 illustrates the parameter setting in the PSO algorithm and the c1 and c2 is the learning rate meanwhile the w is the weight of the system. Towards the upper part the n represents the size of the swarm and bird_setp represent the number of bird step to search and dim represent number of dimension. Since for this research there is 3 parameters in search for, hence the dimension was set to be 3.

```
function F = tracklsq(pid)
         % Track the output of optsim t

         % Variables a1 and a2 are sha
         Kp = pid(1);
         Ki = pid(3);
         Kd = pid(2);

         sprintf('The value of interat
         % Compute function value
         simopt = simset('solver','ode
         [tout,xout,yout] = sim('FYP_P
         e=yout-1 ;  % compute the erro
         sys_overshoot=max(yout)-4; %

      alpha=1000;beta=1000;
      F=e2*beta+sys_overshoot*alpha;
```

Figure 3.18: Function coding for the fitness function

Figure 3.18 illustrates the coding for the fitness function. The PID parameters was declared earlier and the Simulink file named was called by the function. The error labelled as e, is the output deduct by 1 due to the close loop parameters and the sys_overshoot represent the system overshoot. The F represent the fitness function and it compromise of the error and the system overshoot. This deduced the objective of this algorithm minimize the system overshoot and the error to optimize the system. Constant was added due to the values were way too small to be performed by the algorithm.

Each of the parameters was varied including the weight, learning rate, the constant value, bird size and bird step. This is the ensure the second objective are studied. Finally, the system was compare with Genetic Algorithm, Ziegler - Nicholas which was done by other researcher and trial and error method. The comparison was done through system performance to deduced the ability PSO.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 MATHEMATICAL MODELING IN SIMULINK

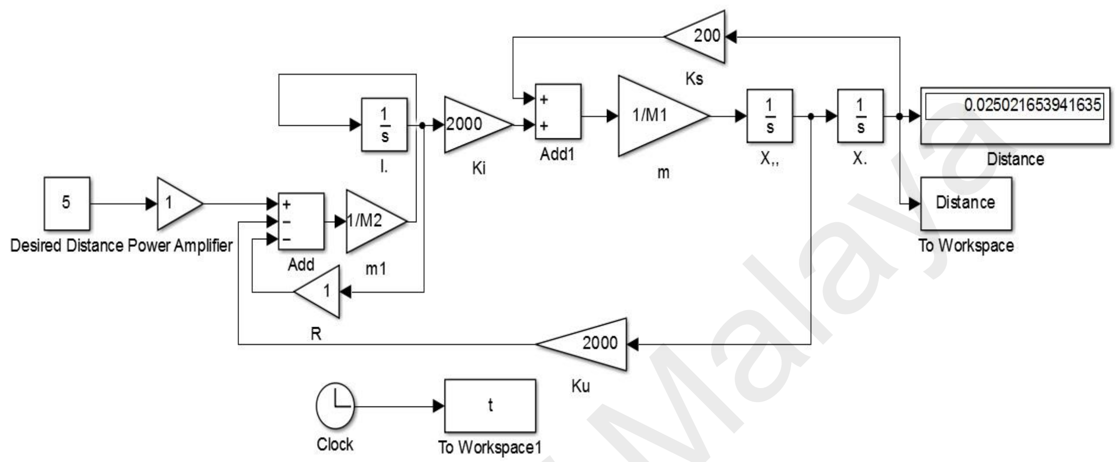


Figure 4.1**:** Mathematical Modeling of Active Magnetic Bearing**.**

The modeling of the system are as follows in the figure 4.1. The system is run under Simulink environment and the results are as discussion below. Referring to the figure 4.1, the complete system without PID are illustrate and together with the associated variable are label in the block diagram. The following model will be shortened into sub system to ease the viewer and to ease the understanding of the system.

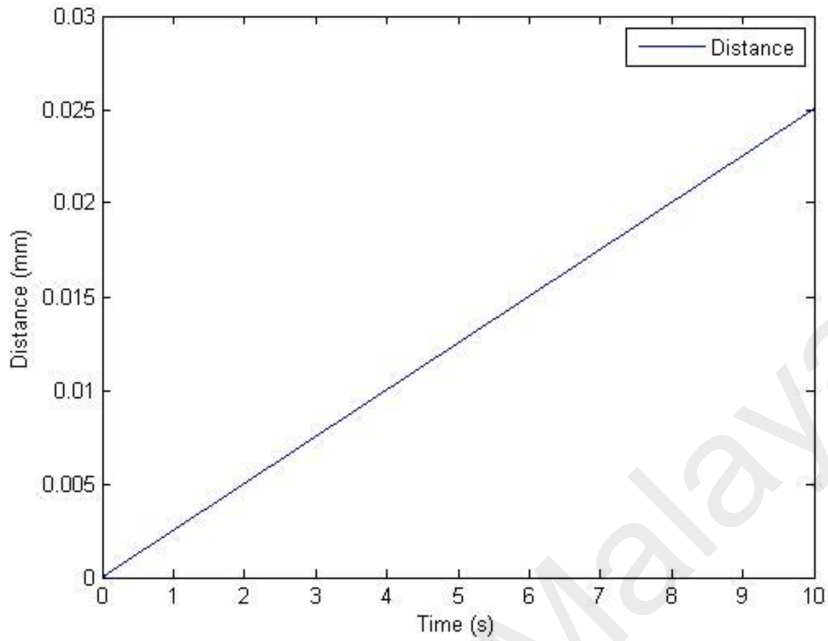


Figure 4.2: Graph of Distance (mm) vs Time (s).

The figure 4.2 illustrates the graph of distance vs time and the graph shape are linear. Referring to the graph 4.1, the distance is increasing over the time 10 seconds, which means the system, are relatively unstable. The distance refers to the air gap displacement from the center to the air gap, which is the eccentric. Therefore, from graph 4.2, the necessity of controller is clearly can be deduce. There are no trick or methods to ensure that the eccentric of the rotor can be maintain without the aid of controller.

4.2 IMPLEMENTATION OF CONTROLLER ON SYSTEM

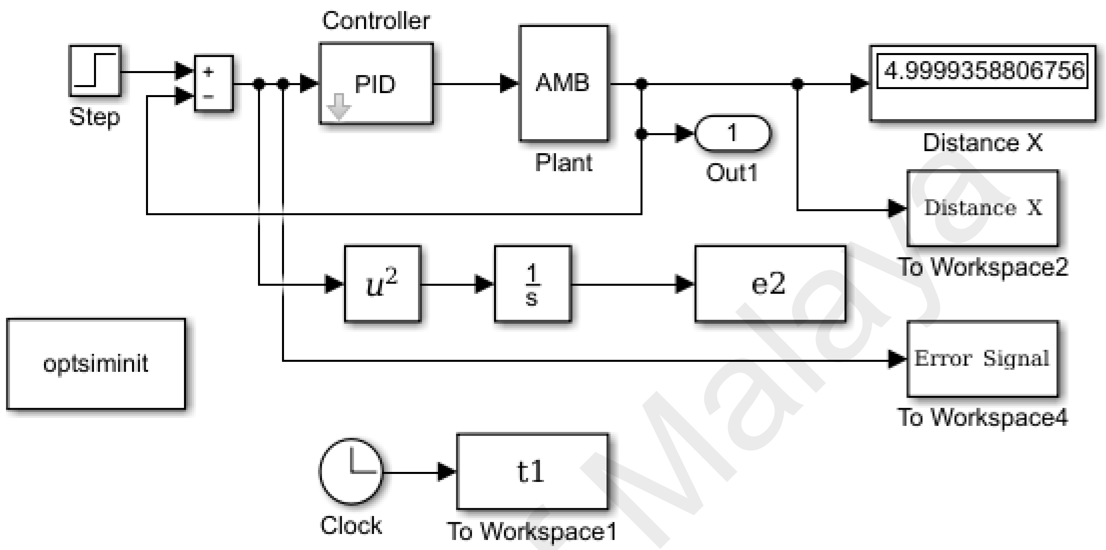


Figure 4.3**:** Implementation of Model using PID Controller

Figure 4.2.1 illustrates the system implemented with PID controller. The AMB are the sub-unit for the system as figure 4.3. The block optsiminit purpose is to optimize is to initiate the optimization process whereby clicking the box registers the error into the workspace. The PID parameter input are obtained through the offline algorithm and are input manual into the block.

The value obtained from the PSO algorithm as table 4.1.

Table 4.1: PID Parameters from PSO

K_p	43.2998
K_I	14.8598
K_D	-46.9370

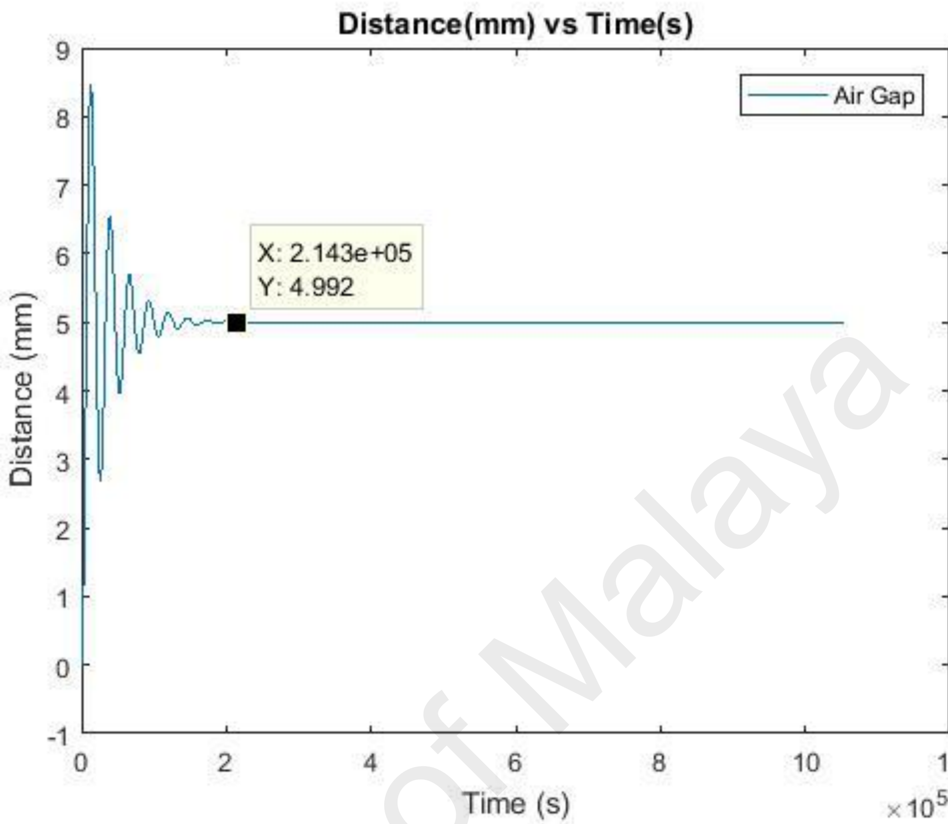


Figure 4.4: Graph of Distance(mm) vs Time(s) PID

Referring to figure 4.4, it could be observed that the system reaches steady state after 2.143×10^5 seconds which is consider long tough and the overshoot is relatively high but the system began to settle down at 4.992 mm whereby the set point is 5mm.

```
    RiseTime: 4.4673e+03
SettlingTime: 1.2300e+05
 SettlingMin: 2.6861
 SettlingMax: 8.4574
   Overshoot: 69.1479
  Undershoot: 3.5015e-68
        Peak: 8.4574
    PeakTime: 12892
```

Figure 4.5: Transient Analysis for PID parameters as table 4.1

Referring to figure 4.5, the transient analysis was obtained by performing the function stepinfo command in Matlab workspace. The overshoot is 69% which is relatively high and the settling max value before reaches steady state value and the settling min is the lowest value before it reaches steady state value and it can be observed that the settling max and settling min both exceeded the allowable air gap. The rotor will be vibrating up and down vigorously before settling to 5mm. The peak value is 8.4574 which is high therefore the PID parameter required tuning.

```
%% Initialization
clear
clc
n = 100;            % Size of the swarm " no of birds "
bird_setp  =50;    % Maximum number of "birds steps"
dim = 3;           % Dimension of the problem


c2 = 0.65;            % PSO parameter C1
c1 = 0.65;          % PSO parameter C2
w = 0.7;             % pso momentum or inertia
fitness=0*ones(n,bird_setp);
```

Figure 4.6: PSO parameter setting for PID tuning.

There are no changes made to the fitness function because based on chapter 2, previous study proved that the parameter that affects the tuning is the PSO parameters. Therefore, the c1 and c2, weight, and swarm size will be changed to tune again the PID parameters. The step is repeated and the search time increases as well with the increase in the size of the swarm. Based on chapter 2, increase in swarm size increases the hyperspace therefore more time required for the PSO to search for the optimize value for the PID parameters.

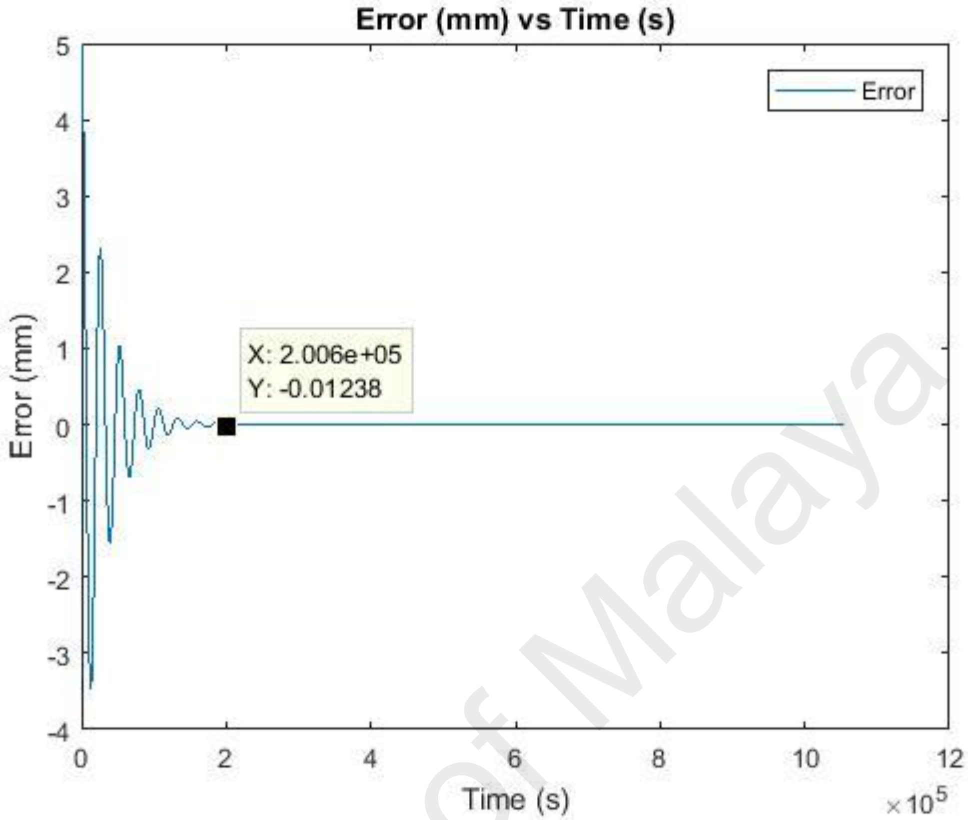


Figure 4.7: Graph of Error Signal

Referring to figure 4.7, the graph of error signal reaches steady state value of 0 after few oscillations therefore the PID require more tuning to increase the P and the D parameter to reduce the oscillation and overshoots. It was learnt that there are plenty of iteration and parameter changing must be made to achieve the optimize value for the system. Increase in the c1 and c2 which known as the learning rate changes the PID parameter as well together with the weight. After few testing, the parameter that affects the optimizing is the learning rate.

The weight was maintained constant meanwhile the learning rate was varied and there is changes in the system. when the weight varied, the system performance changes but not as significant as the learning rate changes. The testing results are presented under appendices.

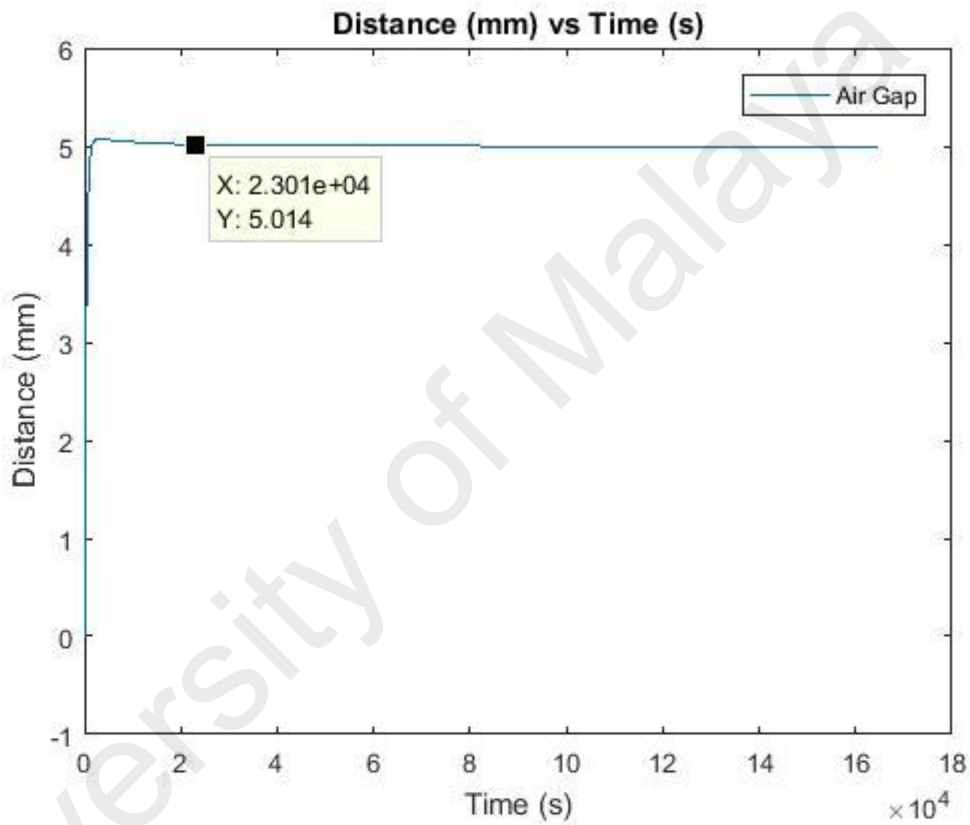


Figure 4.8: Graph of Distance vs Time for PID parameter as table 4.2

Referring to figure 4.8, the system has better performance compare to the previous. This performance was attained after several testing's by varying the learning rate in the PSO to get a better optimize value for the PID parameter.

Table 4.2: PID Parameters from PSO

K_p	4300.2998
K_I	140.8598
K_D	-46.9370

Referring to table 4.2, the PID parameter are the best optimize value obtain through PSO tuning. It can be notice that the value for the P and I had changes compare to the prediction did earlier. The P and I value changes only by a fixed amount of multiplication but able to achieve the optimize results.

```
       RiseTime: 760.0042
   SettlingTime: 1.2494e+03
    SettlingMin: 4.4979
    SettlingMax: 5.0677
      Overshoot: 1.3539
     Undershoot: 3.4959e-72
           Peak: 5.0677
       PeakTime: 3075
```

Figure 4.9: Transient analysis for figure 4.8

Referring to figure 4.9, the rise time could be neglected for this case based on the study done on chapter 2. The settling min produced 4.479 meanwhile the settling max produced 5.0677 which is relatively low compare to the previous value obtained. The percentage of overshoot settles at 1.3539 percentage and there is undershoot presented but at extremely low value. This system is stable because the values are within the allowable air gap and the vibration could be minimized as it deals with mm relatively too small to be observed.

```
%% Initialization
clear
clc
n = 150;            % Size of the swarm " no of birds "
bird_setp  =100;    % Maximum number of "birds steps"
dim = 3;           % Dimension of the problem


c2 = 1.65;           % PSO parameter C1
c1 = 1.65;         % PSO parameter C2
w = 0.65;            % pso momentum or inertia
fitness=0*ones(n,bird_setp);
```

Figure 4.10: PSO parameter setting for the table 4.2

Referring to figure 4.10, it can be observed the only value changed is the learning rate, weight, swarm size and the bird step (iteration). Hence it can be concluded that the parameters that affects the PID optimization for this system is the learning rate and the weight mainly. There is few testing made. Learning rate and weight affects the optimization the most.

Referring to figure 4.8, the oscillation can be observed to be extremely small which relatively which can be neglected due to the error in mm. Hence, for the PSO optimization, this system can be concluded as the most optimize system. Of course, with more testing the system could be optimize further but to meet the requirement of the research, the parameter that affects the system optimizing was identified successfully.

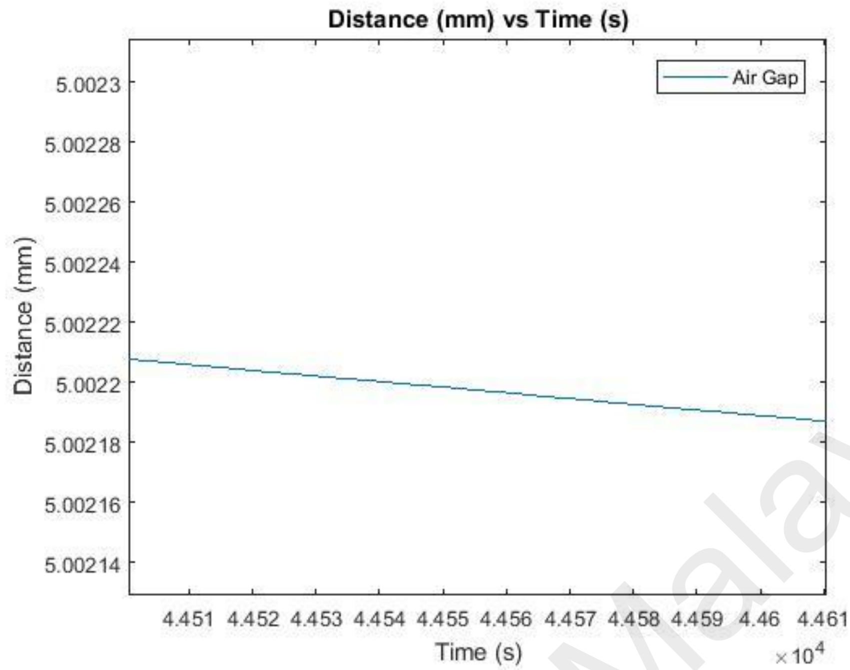


Figure 4.11: Zoom graph for figure 4.8

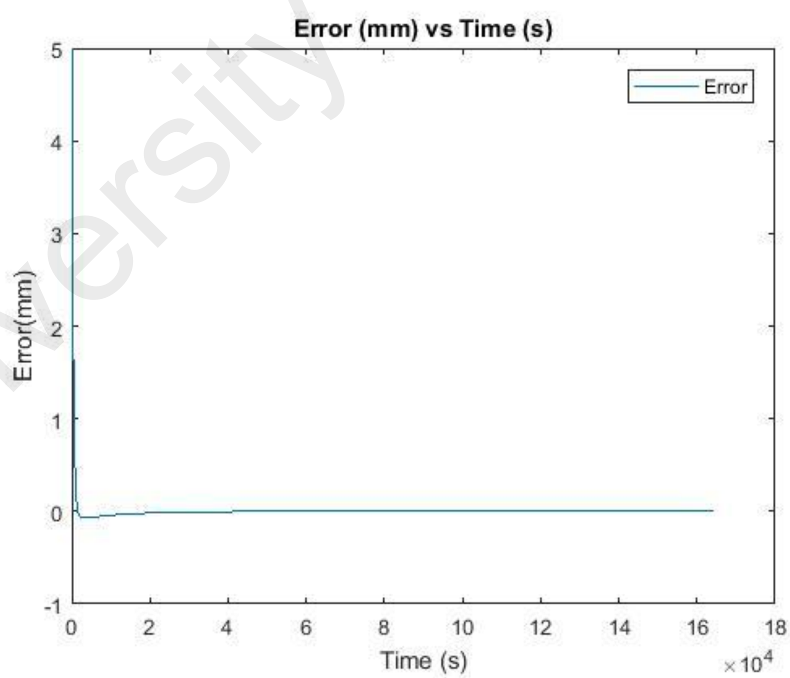


Figure 4.12: Graph of Error signal for graph 4.8

Referring to graph 4.11, the error signal can be observed less than few seconds and reaches the steady state error faster compare to figure 4.7. As a conclusion for the PSO tuning for PID parameter, the table 4.2 is the optimize value for the system.

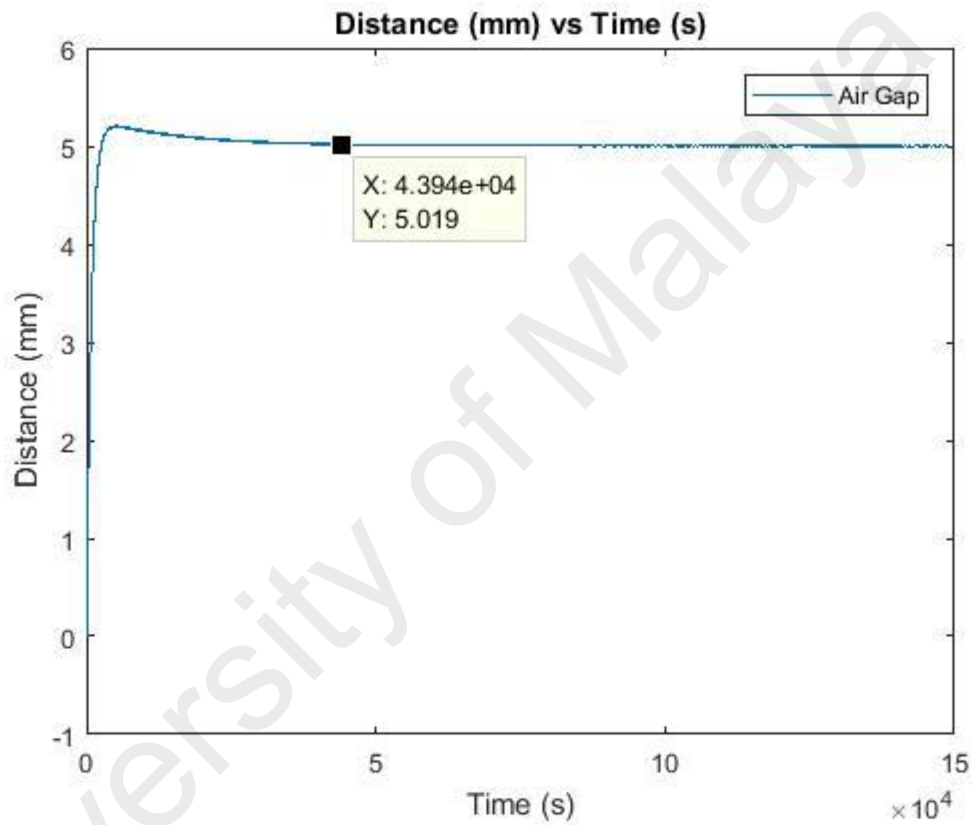


Figure 4.13: Graph of Distance (mm) vs Time (s) for table 4.3.

Graph 4.13 illustrates the graph for PID parameters obtained through trial and error method as in table 4.3. It can be notice from the graph there is plenty of vibration despite achieving steady state condition of 5mm.

Table 4.3: PID Parameters from Trial and Error

K_p	2000
K_I	100
K_D	0

Referring to table 4.3, the PID parameter obtained from the trial and error method. It can be notice that the value for Derivative is zero which means the Proportional and Integral are sufficient to stabilize the system. In chapter 2, the study mentioned that P reduces the rise time meanwhile I reduce the overshoot therefore the two was well defined in the trial and error method.

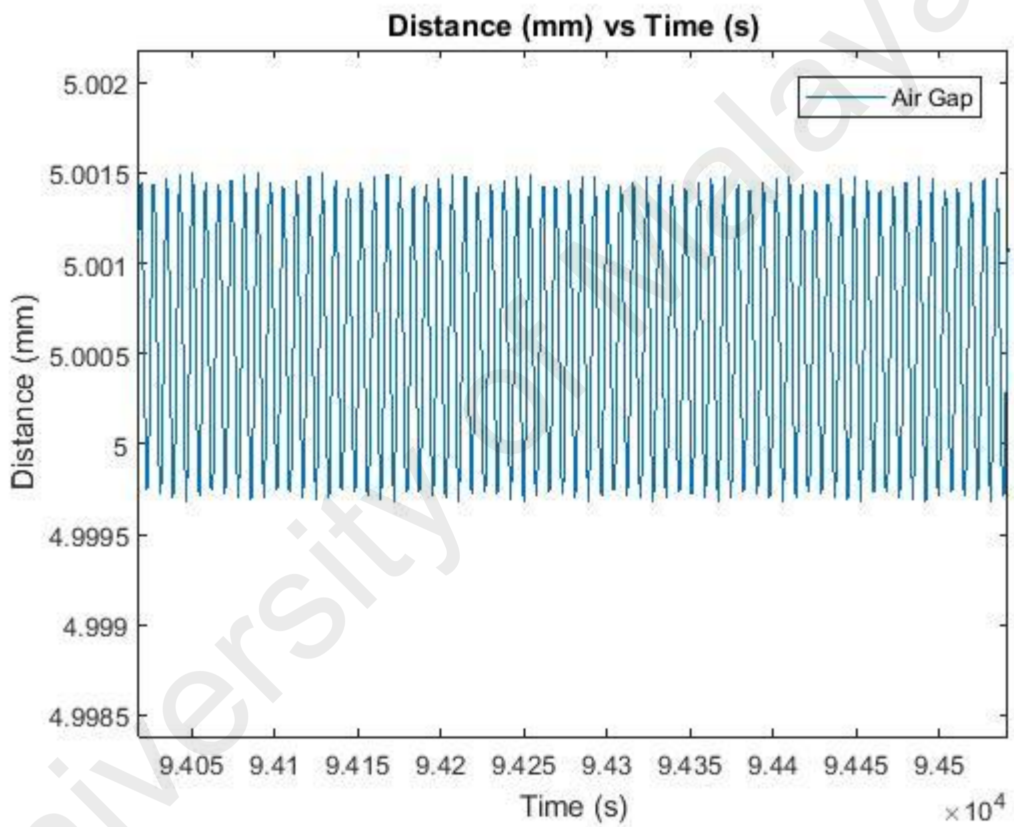


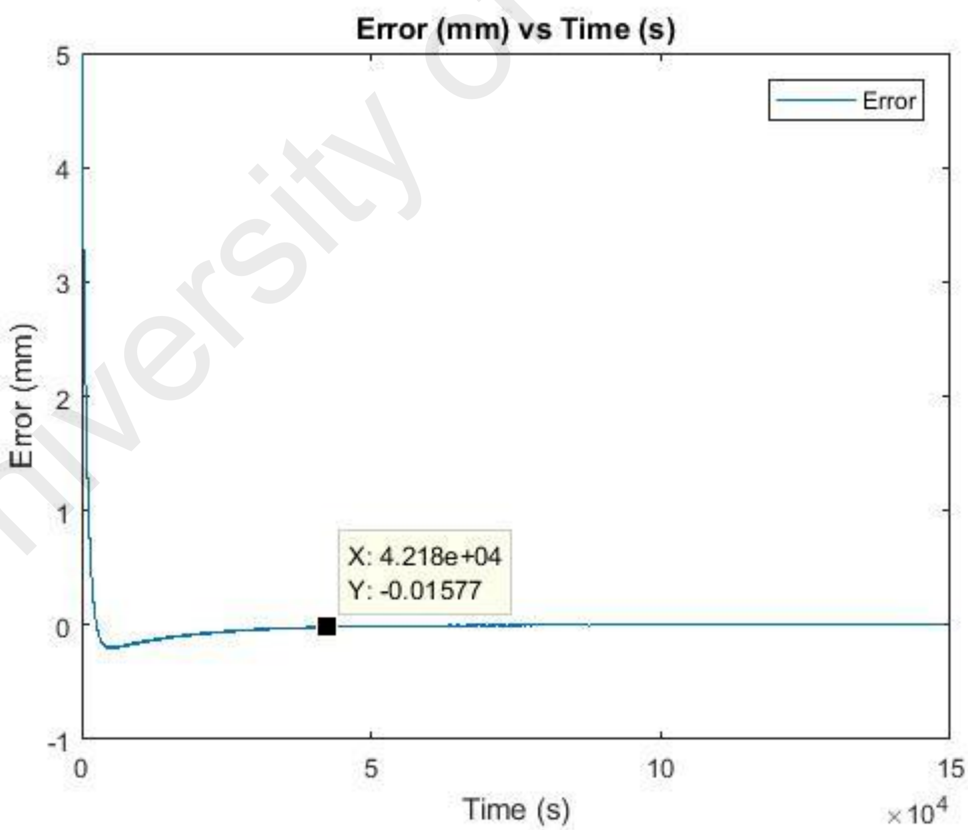
Figure 4.14: Zoom Graph

Referring to graph 4.14, the zoomed graph is plotted based on the PID parameter for the trial and error. It could be noticed that the system oscillates extremely high which causes poor system performance.

```
    RiseTime: 1.5276e+03
SettlingTime: 1.7308e+04
 SettlingMin: 4.4902
 SettlingMax: 5.2050
   Overshoot: 4.1030
  Undershoot: 1.6153e-71
        Peak: 5.2050
    PeakTime: 5172
```

Figure 4.15: Transient Response based on table 4.3

Referring to the figure 4.15, it can be observed that the system performance is poor compare to the value obtain through PSO tuning. The reason because the graph 4.14 shows that the oscillation is heavy and could be observe clearly meanwhile the PSO are promising.



Graph 4.16: Error signal based on table 4.3.

Referring to figure 4.16, the error signal settle down quite fast and reached the steady state error. The figure 4.16 graph is based on table 4.3 trial error method. The entire simulation take place using ISE as the performance indices. The reason ISE was used because the simulation was tested using other performance indices but the error did not converge to minimum value instead the error increasing. The parameter in PSO was changed but the error kept increasing. Therefore, the only suitable performance indices used was ISE.

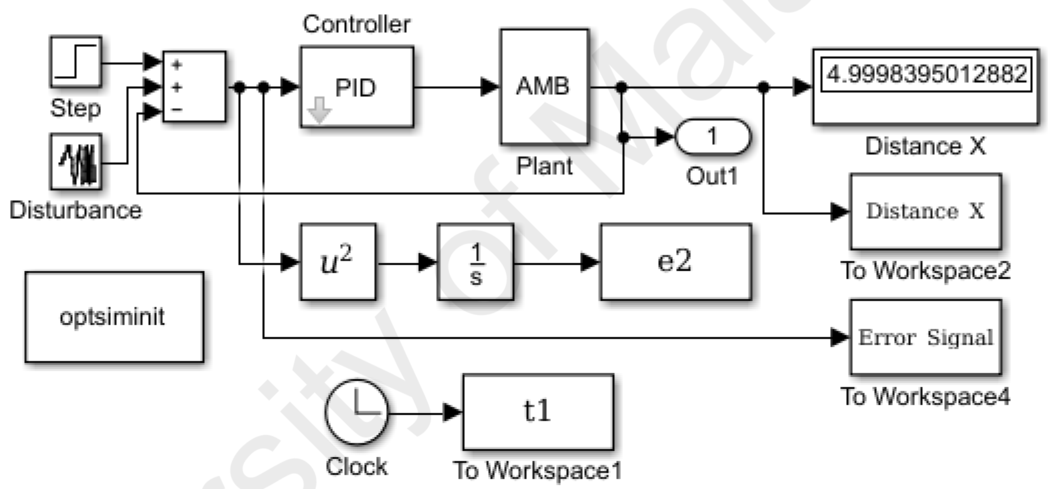


Figure 4.17: AMB system with disturbances.

Referring figure 4.17, the AMB system are added with disturbance. The disturbance is used as chirp signal. The disturbance is added to compensate the neglection made earlier. The PID parameter used based on table 4.3 to test for the system robust.

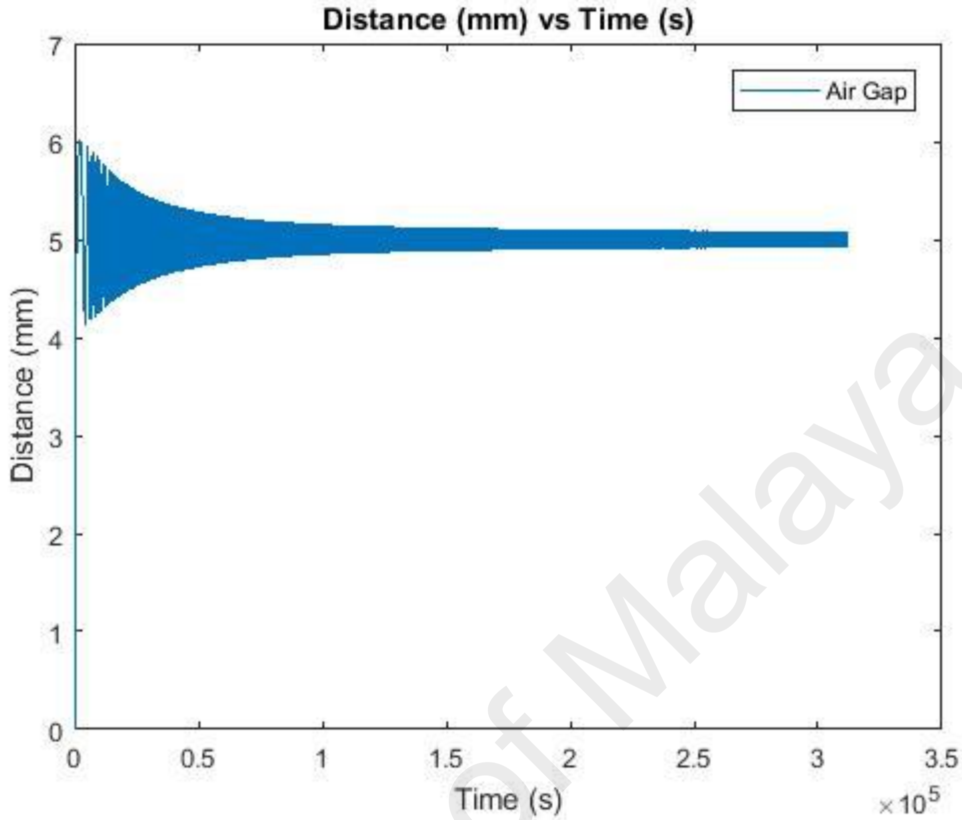


Figure 4.18: Graph of Distance of air gap after adding disturbances.

Referring to graph 4.18, it can be observer there is plenty of oscillation after the disturbance is added.

```
    RiseTime: 628.8689
SettlingTime: 2.8503e+05
 SettlingMin: 4.1310
 SettlingMax: 6.0204
   Overshoot: 19.8439
  Undershoot: 0
        Peak: 6.0204
    PeakTime: 2176
```

Figure 4.19: Transient analysis after adding disturbances

Referring to figure 4.19, the overshoot is still minimum but still exceed the allowable limit for the air gap. The rise time is decent meanwhile the peak is decent but due to the high oscillation after adding disturbance. Therefore, the system require improvement but the system still reach the steady state value after some time. Hence stability achieved without disturbances and the parameter that affects the PID parameter optimizing are the learning rate and the weight.

The performance indices used in this system is ISE. The same performance indices are used as the fitness function because the previous PID optimization was done using the similar performance indices. Previous testing has proved that the system does not converge to stability if replace with other performance indices.

Therefore, to avoid the error ISE was used and the fitness function for all testing remains the same. The fitness function uses the output of the performance indices to reduce the error and the system overshoot. This is because of the condition set by the system as discussed in chapter 2.

4.3 COMPARISON ANALYSIS WITH GA, ZN AND TRIAL AND ERROR

The comparison analysis is necessary to understand the performance of the system compare to other system. The selected tuning methods are Genetic Algorithm (GA), Zeigler Nichols (ZN and trial and error method. GA is choosing because it shares the same method as PSO whereby the difference is PSO is swarm technique whereby GA is evolutionary technique.

Table 4.4: Comparison based on different tuning method

Item	GA	ZN	PSO	Trial
Rise Time (s)	0.0065	0.0028	759.0133	1.5×10^3
Settling Time (s)	1.25	4.12	1.2×10^3	1.7×10^4
Overshoot (%)	78.69	72.06	.1.3538	4.0870
Peak Amplitude	1.78	1.72	1.0135	1.0410
Final Value	1	1	1	1

Referring to table 4.4, the table illustrates the comparison between four tuning method using transient analysis. The GA and ZN are based on (Ishtiaq et al., 2014) . The best rise time produce was ZN meanwhile. But as mentioned in chapter 2, rise time was neglected due to the PID nature itself. In chapter 2, study mentioned that each PID parameter are dependent on each other therefore rise time drops but the settling time increase for ZN.

Genetic Algorithm managed to produce the lowest settling time for the system for a amplitude of 1 whereas the overshoot registered to be 78.69%. Despite low settling time compare to the other tuning method, the peak amplitude is high and the overshoot is extremely high. As mentioned, the percentage of overshoot is important to kept at low value.

The PSO managed to produce the lowest value for the percentage of overshoot and lowest peak amplitude which is much favorable compare to other tuning method. The value is only 1.0135 which would not cause much vibration compared to the other values that has higher overshoot percentage. Despite PSO has higher rise time and settling time, the peak time explains all. The system will continue oscillates at 0.01 difference which would not affect the system performance and the peak gap is within the allowable air gap. Therefore, PSO manage to produce an optimize results to tune the PID controller for such a stable system.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

As a conclusion, this research completed successfully by accomplishing all three objectives. Upon completing this research, the concept and theory behind active magnetic bearing fully explored. The modeling process was completed successfully.

The possibilities and advantage that PID controller offers was explored and utilize successfully. Through this research, plenty tuning method for PID controller was learnt and understood. The tuning method can be used for other applications as well since the tuner are optimizer. The possibilities of PSO was explored and each parameter link was explored and understand successfully.

This put advantage at the usage of PSO controller for future use for other applications. The flow and system within the PSO was understood and applied in the system. The important aspect to be consider and neglect could justify. Comparative analysis pushes the understand further. PSO was not the only tuner available and other tuner can perform as close as PSO and some even further than PSO.

Literature review study conducted proved tuner combine with other tuner could solve optimizing problem even better. Therefore, all the objective was successfully completed and justified.

5.2 RECOMMENDATION

There is still plenty of recommendation for improvement can be done on this system. The modeling method can be improvised to include more disturbances and implemented in Simulink environment. There is plenty of research done before but to implement in Simulink environment is difficult therefore the modeling method should be made convenient.

The PSO should be able to tune better or another system should integrate with the PSO to search for the optimum learning rate and weight for the fitness function provided. PID controller reached the saturation point for further research therefore the PSO can be further improvised.

The PSO should be able to compensate error better and disturbance. A proper method for the performance indices should be done to ease the selection for fitness function. The simulator for the optimizing should be improve as for now the only simulator that are easy to be use is the offline. If there is online optimizing therefore the PSO algorithm could constantly vary the PID parameter to minimize the error and keep the system stable despite disturbances.

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