Flexible Underwater Manipulator Modelling Using Intelligent Method

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***Abstract*— This research aims to study the dynamic modelling of experimental manipulator rig underwater condition. The experimental manipulator has been used as a single link pipe derived by motor to monitor the pipe angles under disturbance water. After studying the output system previously for manipulator hub-angle and vibration, Flower pollination method (FPM) employed to predict and model the dynamic behavior as a transfer function after collecting the motor torque as an input data and hub-angle only due to little affection of the vibration underwater compared with the hub-angle. However, many types of testing methods have been implemented to validate of proposed method; which are stability, correlation tests and Mean square error (MSE) methods. As a result, FPM has been performed as a good prediction to model the system as a transfer function based on number of model order. Whereas, the best model order has been noticed are 3rd model order for FPM that recorded lowest MSE of 1.23021×10^{-4} and 1.72250×10^{-4} for modelling and validating respectively..**

***Index Terms*— manipulator system; parametric system identification; modelling algorithms; flexible and rigid manipulators; transfer function**

I. Introduction

The reason behind designing the manipulator systems in the world are to increase the number of productivity from one side of view and to help humans through decrease the effort, time and work dangerous. The importance of robot manipulator system can be noticed industrial sector in very wide applications such as welding using machine. The robot manipulators systems acquired very big importance specially in underwater applications to do several tasks such as discover of coral reef, inspection of pipelines lines, fixing the devices underwater like seismometers and finally, recovering the geological samples [1-2].

Because of the high weight and heavy metals that leads to the system stability in underwater environments, the inflexible manipulators (rigid) are used currently in underwater applications. In the other hand, the disadvantages of inflexible manipulators are need the high consumption of energy and speed limitation during operation. Furthermore, the system maintenance for the mechanical and electrical parts are costly compared with flexible systems as well as the low performance [3]. A little attempts have been discussed the flexible manipulator systems in underwater environments [2]. The motivations of utilizing flexible bodies is to decrease the cost, weight in addition to harvest a high performance of the response to reach the targets [4-5]. So, the contribution for this work is to model the manipulator system in underwater conditions with flexible links.

Due to the high nonlinearity and the total lack of identification of the hydrodynamic effects, Suboh and his assistant proved the big challenges of manipulator system underwater is to control it during ocean currents disturbances [6]. Consequently, there is an increasing need to improve appropriate control strategies for these types of systems. Based on the previous researches, Mat Darus and Al-Khafaji, referred the any system should be modelled well in order to get the high control performance [7].

The dynamic modeling and control techniques related with the land manipulators have been studied widely by numerous researchers. In 2004, apartial survey has been conducted by Benosman and Levey for manipulator system flexible control techniques [8]. Based on Dwivedy and Eberhard, 2006, studied the dynamic modelling of the flexible manipulator system as a continuous system typified by an infinite number of degrees of freedom and are ruled by partial differential, coupled, nonlinear and ordinary equations [9].

To build an efficient and accurate underwater manipulator system model, an additional parameters should be considered during the motion such as weight and payload in order to find a suitable torque to generate the motion in additional to the another parameters for example lift and drag forces, gravity, buoyancy and additional masses that effect on the manipulator system [10].

Recently, one of the ways to model the systems in many fields based on input and output data known as system identification (SI) technique in order to build appropriate model for different systems. In this applications, many attempts have been recorder to model the flexible structures using SI approach for instance beam [11], plate [7] and manipulator [12]. Therefore, there is a great incentive to model the systems using SI method based on real data. Thus, the new main objective in this paper is to model the underwater manipulator system using flower pollination and Cuckoo search algorithms through presenting the system dynamic

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behavior under hydrodynamic forces effects without needing to complex mathematical equations. The main classification of SI method is parametric and non-parametric methods. The proposed algorithms methods in this work can be classified as a parametric system identification (PaSI).

In order to implement the PaSI methods, its need to specify the estimation methods in order to determine unknown parameters to achieve a best results. Estimation methods in PaSI technique divided into traditional and intelligent approaches. Many estimation techniques as a traditional identification used previously to find the system parameters such as Recursive Least Squares (RLS), least Mean Square (LMS). Based on the different researches, traditional identification methods were unsuitable to find the model structure because of some limitations for these approaches [13]. Otherwise, intelligent estimation methods consider one of the other way to get the best identification solutions. For the land manipulator, many intelligent approaches used previously to find the estimation parameters for flexible systems in order to model the system such as Particle Swarm Optimization (PSO) [14], Genetic Algorithm (GA) [14] and Differential Evolutionary (DE) Algorithm [12]

In this work, modeling the flexible underwater manipulator (FUM) using intelligent method (FPM) in order to implement it in future experimentally for tracking the manipulator angles.

II. Experimental Set-up Design

In order to collect the input and output data and implement the experimental work for FUM system, a pipe made from PVC with length of 85 cm and diameter of 1.8 cm and 2 cm as inner and outer diameters used to simulate the real life application, Also an extended rods employed to make the connection between the motor and rig in order to transfer the rotation as shown in Figure 1. A DC motor manufactured by Maxon Company utilized to apply the rotational motion with maximum power 150 W in addition to derive the motor by ESCON 50/5 driver. The hub-angle for the system measured by encoder type HEDL-5540 and the submersible pump to generate a different water flow. Data acquisition system (DAQ) type PCI-6259 form National Instrument Company employed to apply the torque and record the hub-angle results in addition to use SCC-68 as a connector block that be compatible with Matlab program. According to Figure 2, a basin made from Aluminum profile and surrounded by glasses used to specify the water flow and the system immersed inside it.

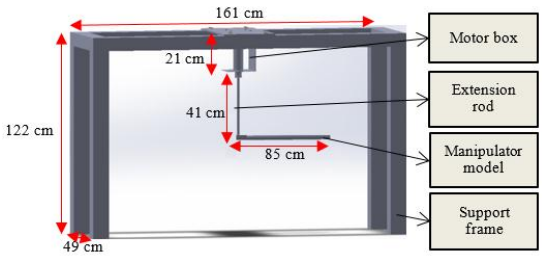

Figure 1. FUM system.

Figure 2. Basin test

III. Experimental Preparations and Output Outcomes

In order to record the hub angle results to use it later to model the system, many preparations have been done such as the connection between DC electromechanical systems and DAQ device from one hand of view and with the important blocks in Matlab form the other hand as shown in Figure 3. Type of the input torque was bang-bang ranged from -5 V and +5 V during 8 s as shown in Figure 4 with sample time of 0.01 s based in previous work [12].

An 800 data have been recorded for the output (hub-angles) as shown in Fig. 5 under flow rate 0.47 m/s bases on pervious verification.

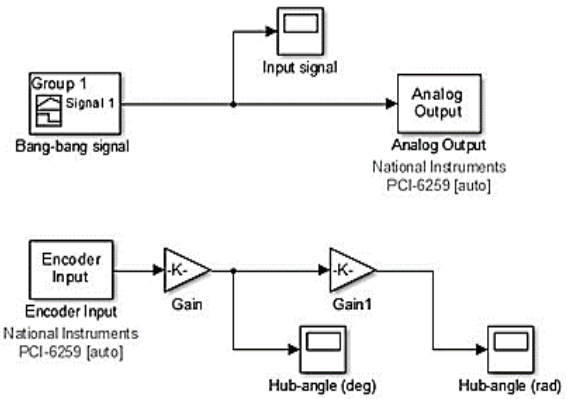

Figure 3. Real time Matlab blocks

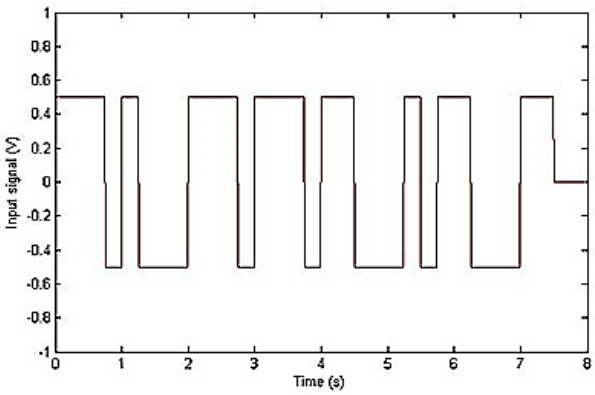

Figure 4. Torque Voltage

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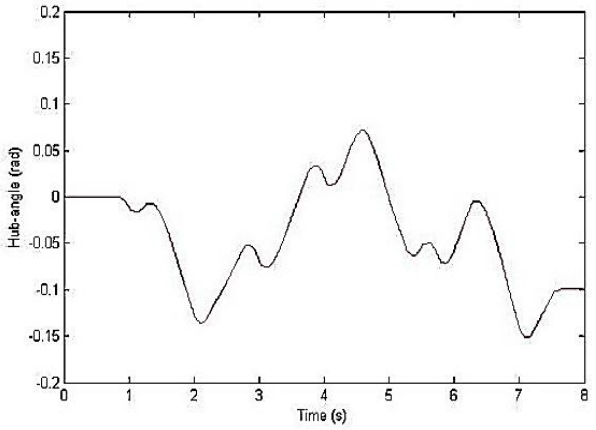


Figure 5. Hub-angles output

IV. FUM System Modelling

Input and out output data that collected through experimental setup will be used in this section to build the FUM model as a parametric structure in order to find the final transfer function for the system. Autoregressive moving average model (ARX) model is utilized here to build the main matrix that represent the system behavior as shown in Fig. 6.

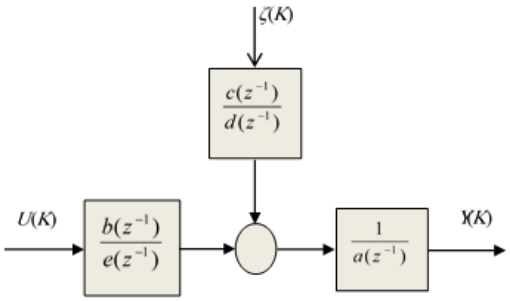


Figure 6. General Schematic of the system structure

U(K) and *Y(K)* are refer to the input and while, *ζ(k)* refers to the noise that be equal to zero. The polynomials for the final matrix in the numerator are $b(z^{-1})$ and $c(z^{-1})$. The polynomials for the final matrix in the denominator are, $d(z^{-1})$, $a(z^{-1})$ and $e(z^{-1})$. The expression ARX structure can be expressed as:

$$Y(K)=\frac{b(z^{-1})}{a(z^{-1})}U(K)+\frac{1}{a(z^{-1})}\xi(K) \quad (1)$$

After neglecting the noise factor due to collect the actual data [16], the final expression for ARX model will be:

$$Y(K)=\frac{b(z^{-1})}{a(z^{-1})}U(K) \quad (2)$$

V. Estimation of the Parameters

In order to find the final transfer function tor FUM system after selecting the ARX model structure, after choosing the type of model structure, it's very important to find appropriate method to estimate the parameters and validate it later as shown in Fig. 7.

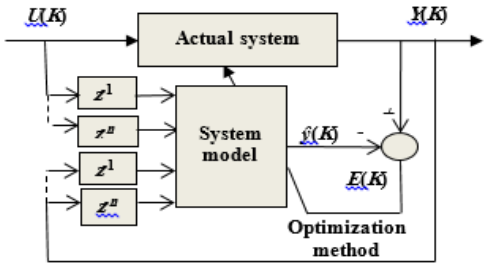


Figure 7. Methodology of system modelling using ARX model

ŷ(K) refers the predicted data of the output while, *E(k)* is the prediction error which represent the subtraction between the actual and predicted error. Finally, FPA method will be used to calculate the unknown values and validate it by Mean Square Error (MSE).

A. Method of Flower Pollination

It is considers one of the inspired method by the process of flower behavior and had evolutionary characteristics for optimizing through the spread of flowers in plants [17].

In order to implement this method, the parameters should be set based on size of population *(N)*, generation number *(G)*, switch of probability *(Pa)*, dimension of pollen *(D)*, step size of flight *(α)* and finally, the boundary (*L*, *H* and *C*) as a first step. In this work, 0.01 and 0.25 were used for α and Pa respectively, according to Yang and Deb [17]. The other parameters were calculated by heuristic method due to the difficulty of finding.

The second step is initialization the pollen before start the optimization. The general pollen equation depends on dimension of pollen that depends on random initialization for the *D* as shown in equation below.

$$Pop_{ij}=L+(H-L).*\text{rand}(1,\text{D}) \quad j=1,\cdots\cdots,N \quad i=1,\cdots\cdots,D \quad (3)$$

The updating of ARX parameters will be conducted based on updating of population. Finally, after start the optimization, MSE method will evaluate the system based on the predicted and actual output as shown in equation below. Generation of population and initialization can be seen in Figure 8.

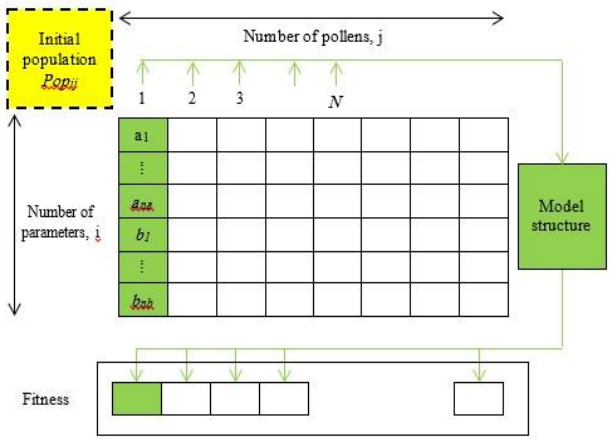


Figure 8. Generation of population and initialization of FPM

After specifying the first parameters values, pollen grains working on discover a new generation (x_i^{t+1}) compared with the previous generation (x_i^t) as shown in equation below.

$$x_i\ (t+1) = x_i\ (t) + \alpha \times \text{step} \times (x_i\ (t) - \text{best pollen}) \times \text{randn}\ (N) \quad (4)$$

The step in equation above can be calculated by

$$\text{step} = \frac{U}{|V|^{(1/\eta)}} \quad \text{Where,} \quad U = \text{randn}(N) \times \omega \ , \quad V = \text{randn}(N) \quad \text{and}$$

$$\omega = \left(\frac{\Gamma(1+\eta) \times \sin(\pi \times \eta/2)}{\Gamma(1+\eta/2) \times \eta \times 2^{(\eta-1/2)}} \right)^{(1/\eta)} \quad \text{at } \eta = 1.5.$$

The general presentation between FPM and ARX parameters can be shown in Fig. 9.

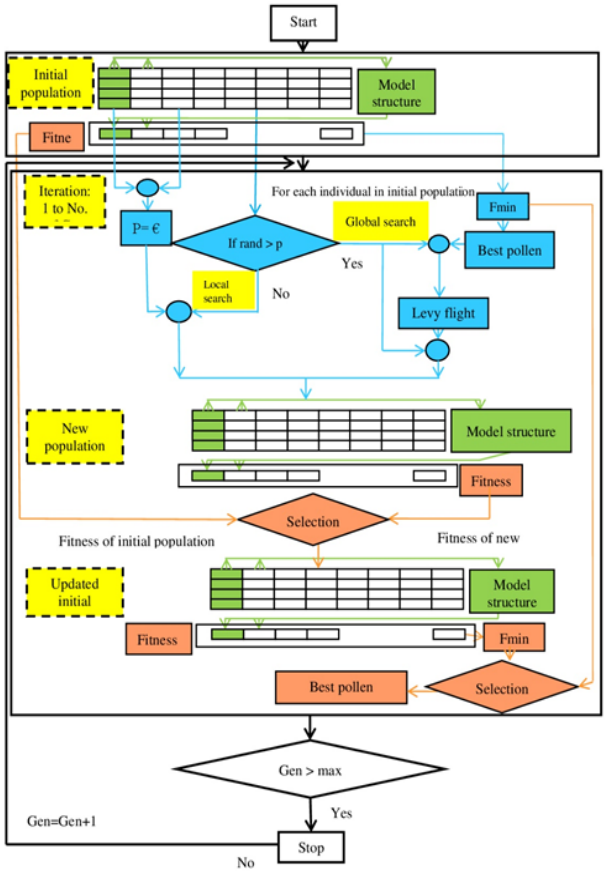


Figure 9. General representation for FPM and ARX parameters discovering

VI. Validation the FUM Model

In order to validate the system after calculating the parameters and selecting the best transfer function that represent the FUM system, several ways have been employed which are, model prediction, MSE approach and test of the stability. As a final decision, if the FPM can pass tow of these ways, will be successful method to predict the FUM and can be used in future to validate the system experimentally.

A. Prediction of the Model

In this part, the type prediction model that used was one step-ahead prediction (OSAP) in order to find out and specify the ability of model to predict the correct behavior for the FUM using the equation below:

$$\hat{y}(t) = f(u(t), u(t-1), \ldots, u(t-n_u), y(t-1), \ldots, y(t-n_y)) \quad (5)$$

where, f refers to the nonlinear function, u refers to the input, y and $\hat{y}$ are refer to the actual and predicted output respectively. The evaluation of this method depends on the value of residual that comparing between measured and predicted output and be satisfied when this value be small.

B. Mean Squared Error

It is considering one of the common evaluation method that depends on the square difference between predicted and measured output. The formula of this method is [19]:

$$f(e) = \frac{1}{n} \sum_{i=1}^{n} \left(|y(n) - \hat{y}(n)| \right)^2 \quad (6)$$

C. Test of the Stability

The main criterion of this test is depends on the poles determination for discrete or continuous transfer function. In case of continuous transfer function, the poles should be appeared in the left side of S-plane. Otherwise, the solution will ignore. In case of discrete transfer function, the poles should be in within the Z-plane circle. Otherwise, the solution will ignore [12].

D. Analysis of the Model Residual

The main advantage of this method is to analyze the predicted error in order to depict the FUM system. This method depends on to types on correlation test which ae, auto and cross correlation. The function of autocorrelation to make sure the error is independent of the previous value while, the cross correlation is to make sure the error is independent from input signal [12]. The formulae of autocorrelation test is:

$$\varphi_{\varepsilon\varepsilon}(\sigma) = e(\delta(t-\sigma)\delta(t)) = \varepsilon(\sigma) \quad (7)$$

where, δ refers to the residual, φ refers to the auto correlation and finally, ε refers to the value of an impulse function. At $\sigma \neq 0$, the φ value of $=0$ ideally and is called a white noise. Practically, $\varphi \neq 0$ at $\sigma \neq 0$. The φ be confidence band if the error reach between the 95%which define as $1.96/\sqrt{n}$ that n refers to the length of data. However, the formula of cross correlation is:

$$\varphi_{u\varepsilon}(\sigma) = e(v(t-\sigma)\delta(t)) = 0 \quad \forall\sigma \quad (8)$$

where, $\varphi_{u\varepsilon}$ refers to the cross correlation, v is the input signal and δ refers to the residual. The same behavior of autocorrelation is applicable for cross correlation.

VII. Outcomes and Discussion

This section presents and discuses modeling of the FUM system after collecting input as a torque and output

as a hub-angle in order to find the best transfer function that represent the dynamic behavior for the system based on ARX structure and finding the parameters by FPM. An 800 data have been collected for input and output using real time Matlab Simulink. The data has been divided into two parts. The first part (400 data) utilized to train the system while, the other part utilized to verify the system by different validation approaches.

Different model order selected for the system and each model verified. FPM initial parameters were selected as size of population was 20, generation number was 600, number of pollens was 0.25, step size of flight was 0.001 and finally, the boundaries ranged between 3 and 2. Table 1 shows the results for several model orders under different validation approaches. While, Figures 10-15 show the proposed method convergence, estimation of FPM parameters, predicted and actual FUM responses, FPM poles-zero and finally, cross and autocorrelation results respectively.

TABLE I. MODEL ORDER PERFORMANCE UNDER DIFFERENT VALIDATION METHODS

Model order	MSE validation	MSE modelling	Correlation test	Stability
2	1.863×10^{-4}	1.247×10^{-4}	Out of confidence level	stable
3	1.722×10^{-4}	1.230×10^{-4}	Out of confidence level	stable
4	2.893×10^{-4}	1.460×10^{-4}	Out of confidence level	stable
5	1.809×10^{-4}	1.288×10^{-4}	Out of confidence level	stable
6	5.976×10^{-4}	4.465×10^{-4}	Out of confidence level	stable
7	4.356×10^{-4}	3.546×10^{-4}	Out of confidence level	stable
8	0.0098745	0.0054637	Out of confidence level	unstable
9	0.00583956	0.00584756	Out of confidence level	unstable
10	0.00799454	0.00737601	Out of confidence level	unstable

According to the Table I, 3rd model was the best model order has been noticed that recorded lower MSE of 1.23021×10^{-4} and 1.72250×10^{-4} for modelling and validating respectively compared with the other model orders. Based on Figure 10, the estimation method reached to the best values after generation 120 form 600 and recorded the best ARX parameters values which are, 2.31 for a1, 1.490 for a2, 0.2673 for a3, 0.000677 for b1, 0.0004859 for b2 and 1.446×10^{-5} for b3 as shown in Figure 11. Figures 12 and 13 show the response for actual and predicted hub-angle for FUM system and it observed a good matching between them by proposed method. Therefore. Fig. 14 show the system performance based on poles-zero validation method. It's noticed that poles-zero within the Z-plan that made the system stable. The final validation as cross and autocorrelation test. Fig 15 shows the model wasn't within the confidence level for each type due to the little number as used to check this test (20 samples only). Therefore, the proposed method was successful to represent the dynamic behavior for the FUM system due to exceed more than two validation approaches and the final transfer function for the system is:

$$\frac{0.000677\,z^{-1} + 0.0004859\,z^{-2} + 1.446\times10^{-5}\,z^{-3}}{1 - 2.31z^{-1} + 1.490\,z^{-2} - 0.2673z^{-3}}$$

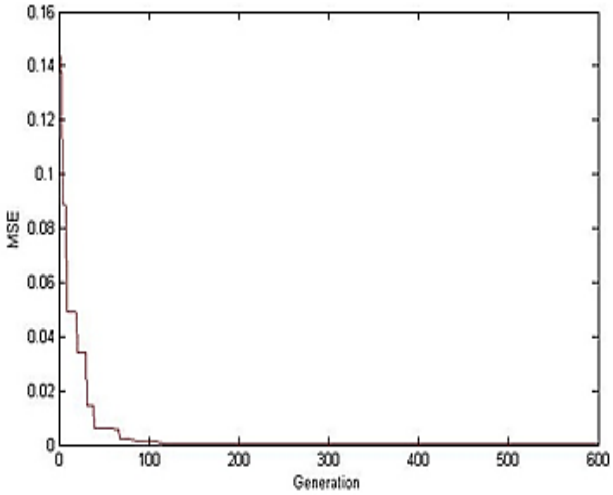


Figure 10. Convergence of FPM

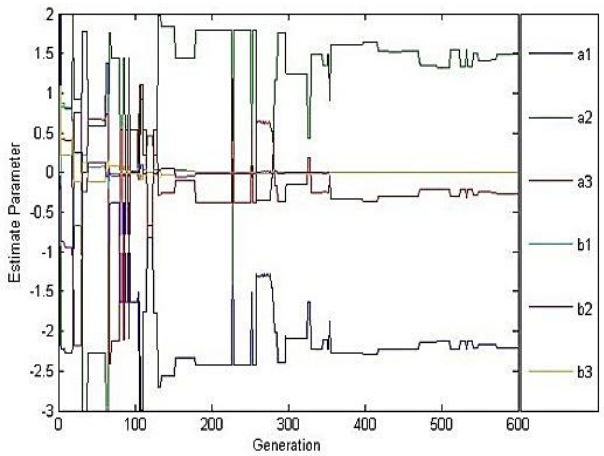


Figure 11. Estimation parameters of FPM

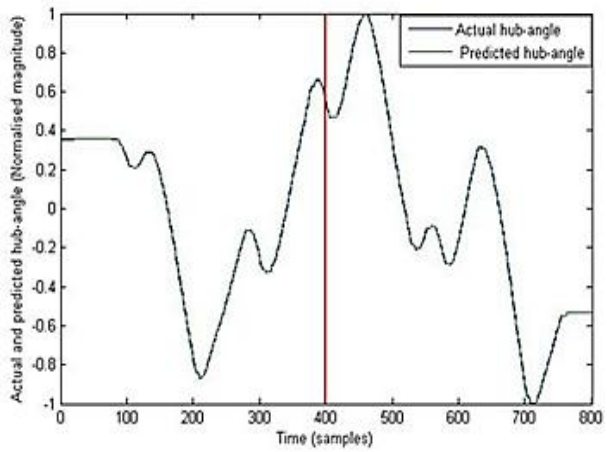


Figure 12. Actual and predicted response of FUM system by FPM

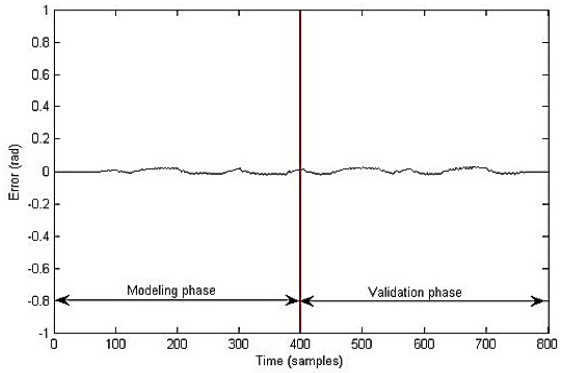


Figure 13. Difference between actual and predicted error of FUM system by FPM

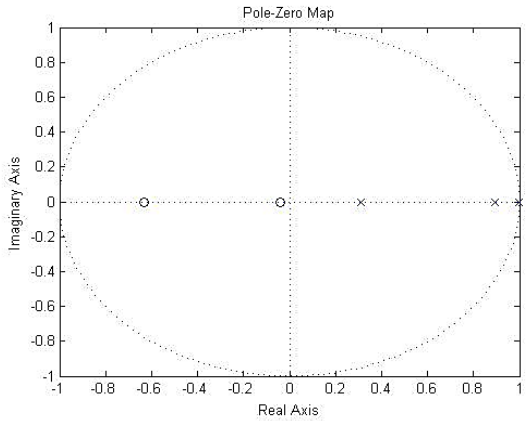
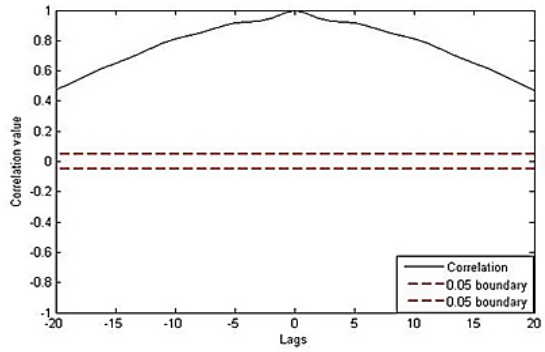
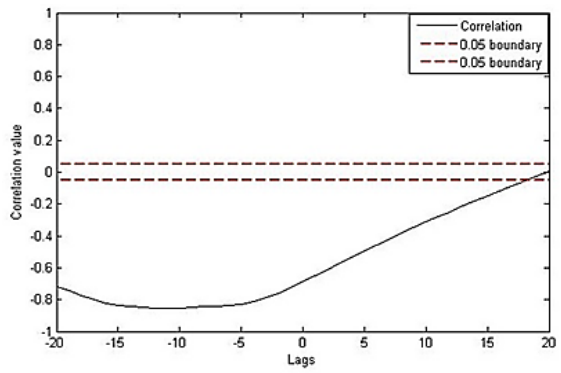


Figure 14. Diagram of Pole-zero for FPM



a) Auto correlation



b) Cross correlation

Figure 15. Auto and cross correlation for FPM

The results of hub-angles modelling for FUM system based on parametric method (FPM) has been conducted for response and validation. According to fig. 16, Its observed that the proposed method was succeeded to track the actual response and represented the system based on input and output data. Based on the results analysis, the proposed method recorded at the 3rd model order lowest MSE with stable performance but out of the confidence level due to choice low data for this test.

VIII. Conclusion

This work present modelling of FUM system FPM as an intelligent approach to describe the system behavior and use it later for control strategy. The main contribution of this work is to represent the system behavior through modelling and using it later to control the hub-angle. The system built based on ARX model and the parameters have been calculated based on FPM. Several validation methods were employed to test the proposed method based on MSE, Pole-zero, stability and correlation tests. The experimental setup for FUM system has designed and implemented to record of 800 input and output data. Its found that the FPM was able to track the actual hub-angle for FUM system successfully at 3rd model order with lowest MSE of 1.23021×10^{-4} and 1.72250×10^{-4} for modelling and validating respectively with stable performance. The best ARX parameters values were 2.31 for a1, 1.490 for a2, 0.2673 for a3, 0.000677 for b1, 0.0004859 for b2 and 1.446×10^{-5} for b3 that represent the transfer function parameters.

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