# Utilizing P-Type ILA in tuning Hybrid PID Controller for Double Link Flexible Robotic Manipulator

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***Abstract*— The usage of robotic manipulator with multi-link structure has a great influence in most of the current industries. However, controlling the motion of multi-link manipulator has become a challenging task especially when the flexible structure is used. Currently, the system utilizes the complex mathematics to solve desired hub angle with the coupling effect and vibration in the system. Thus, this research aims to develop the controller for double-link flexible robotics manipulator (DLFRM) with the improvement on hub angle position and vibration suppression. The research utilized DLFRM modeling based on NARX model structure estimated by neural network. In the controllers' development, this research focuses on adaptive controller. P-Type iterative learning algorithm (ILA) control scheme is implemented to adapt the controller parameters to meet the desired performances when there are changes to the system. The hybrid PID-PID controller is developed for hub motion and end point vibration suppression of each link respectively. The controllers are tested in MATLAB/Simulink simulation environment. The performance of the controller is compared with the fixed hybrid PID-PID controller in term of input tracking and vibration suppression. The results indicate that the proposed controller is effective to move the double-link flexible robotic manipulator to the desired position with suppression of the vibration at the end of the double-link flexible robotic manipulator structure.**

***Keywords—robotic manipulator, flexible, Iterative learning algoritmn , vibration suppression***

## I. INTRODUCTION

The advancements in various field of life inclusive of domestic and industries create a great demand for flexible robot manipulator. Many robot manipulator applications are categorized as multiple-input-multiple-output (MIMO) systems due to multi-link structure. The design and tuning of multi-loop controllers to meet certain specifications are often the pullback factor because there are interactions between the controllers. The system must be decoupled first to minimize the interaction or to make the system diagonally dominant. Moreover, the reduction of vibration on flexible structure of robot manipulator must be treated at the same time. The continuous stress produced by the vibration can lead to structural deterioration, fatigue, instability and performance degradation. Thus, the reduction of vibration on flexible structure of robot manipulator is of paramount importance. Though many researchers have successfully produced the controllers for multi-link flexible manipulator, the control scheme developed involves complex mathematics to solve the coupling effect and vibration simultaneously. As a result, it consumes a lot of time in numerical computation which leads to higher computational cost. Thus, the drawback received substantial attention to cater recent industries demand in various applications. On-going researches focused on improving the control methods to fulfill all the conflicting requirements.

The study of adaptive controller in flexible manipulator remained until today due to its significant contribution in actual plant. Among them, a new Nonlinear Adaptive Modal Predictive Controller on two link flexible manipulator with various payload was carried out [1]. The controller could generate appropriate adaptive torque to control tip trajectory tracking and fast suppression of tip deflection. Besides, indirect control of Self-Tuning PI controller of two link flexible manipulator tune by Neural Network was proposed [2]. Simulation results showed that the tuning parameters obtain could suppress the vibration and track the desired joint angles effectively. E. Pereira et al. have investigated the use of adaptive input shaping using an algebraic identification for single-link flexible manipulators with various payloads [3]. Experiment results proved that the proposed control managed to follow tip trajectories in shorter time. Another research on adaptive controller was comprised of a fast on-line closed-loop identification method combined with an output-feedback controller for single link flexible manipulators [4]. Experimental results showed that the controller manage to follow the trajectory tracking.

Another type of adaptive controller that is iterative learning algorithm (ILA) has been implemented in different control scheme in the flexible manipulator system. For example, two phase ILA controllers to carry out the ideal input and output signals of iterative learning control (ILC) where the error is used to calculate the parameters of the proportional-derivative (PD) controller by using standard least squares (LS) algorithm for the SLFM [5] which the controller is effective in tracking the desired trajectory over interval time. Zhang and Liu employed an adaptive iterative learning control scheme based on Fourier basis function for single-link flexible manipulator (SLFM) [6] whereby the controller portrayed successfully tracks the actual trajectory. Besides, genetic algorithm was applied to tune three combinations of controller for single link flexible manipulator in vertical plane motion that is PID, PID-PID and PID-ILC controller [7]. Simulation demonstrated that the PID-ILC parameter obtained in the optimization outperform other controllers and allow the system to perform well in reducing the vibration at the end-point of the manipulator. However, none of the research based on iterative learning algorithm (ILA) was implemented on DLFRM.

Apart from that, ILA have been used in different control engineering problems such as robot manipulator for industry and healthcare, machining machine, process plant, power plant, nanotechnology area etc. Among them, Jain and Garg, have proposed ILC for the nano-positioning system to reject disturbances [8]. Besides, a back-stepping adaptive iterative learning control incorporating fuzzy neural network was implemented to approximate the unknown and robust learning term to compensate the uncertainty for robotic systems with repetitive task [9]. Mola *et al.* presented a new intelligent robust control method based on an active force control (AFC) strategy for anti-lock brake system (ABS) [10]. Another research employed PID active vibration controller using ILA for marine riser whereby ILA was used to optimize the value of PID parameters based on the error portray in the system [11]. A novel method to control mobile manipulator was developed where ILA is combined with active force control (AFC) and PID scheme to compensate the dynamic effect of the disturbances that includes impact force and vibratory excitation applied to each wheel and joint of mobile manipulator [12].

The variety of application of ILA shown in literatures review has proven the competency of ILA especially in dealing with non-linear system.

In this paper, P-Type ILA in tuning the hybrid PID controller was developed. The dynamic model of the system was established through system identification using Neural Network. NARX model structure based on multi-layer perceptron was employed to obtain the non-parametric modeling networks of DLFRM. The control structure of PID controllers optimized by P-Type ILA was proposed for position tracking and end point vibration suppression. Performances of the proposed controllers were implemented through simulation in MATLAB/Simulink environment.

This paper is organized as follows; Section 2 presents the modeling and system identification of the system; Section 3 describes the control scheme applied to the system; and Section 4 discusses the obtained results and draws the conclusions.

## II. MODELING AND SYSTEM IDENTIFICATION

### *A. Experimental Data*

The planar DLFRM was developed and fabricated to perform the angular movement of manipulator as shown in Fig. 1. The schematic diagram of the system was illustrated in Fig. 2.

A bang-bang signal with ± 0.7 V amplitude and ± 0.5 V amplitude were used to provide required torque to excite the double-link simultaneously. Four outputs were collected from two encoders and two accelerometers which represent the hub angles and end point acceleration of each link respectively. The experiment was carried out for the duration of 9 s with sampling time of 0.01 s.

Fig. 1. Double Link Flexible Robotic Manipulator rig

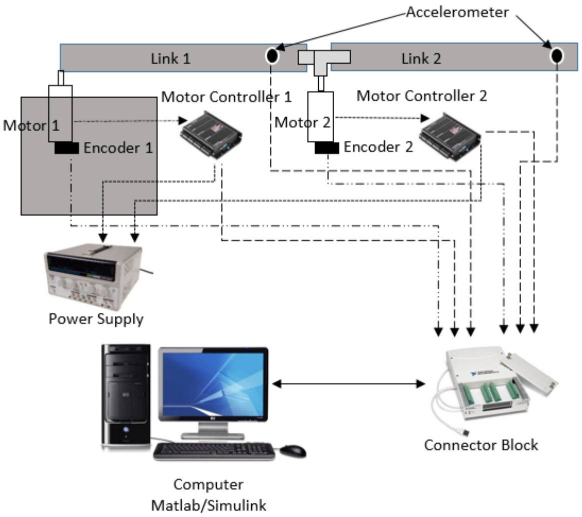


Fig. 2. Schematic Diagram of DLFR

### *B. Modeling Estimation*

The DLFRM is categorized under highly non-linear, thus non-parametric modeling is preferred to model it. Among non-parametric model, NARX have the simplest structure. NARX model is the nonlinear generalization of the well-known ARX model, which constitute a standard tool in linear black-box identification. For estimating the nonlinear part of the ARX structure, the neural network was utilized. The research utilized back propagation for multi-layer perceptron (MLP) neural network and Elman neural networks (ENN) for modeling four set of a Single input Single output (SISO) DLFRM system. The developed model was validated by Mean Squared Error (MSE) and Correlation Test. The details of the modeling is elaborated in previous study [13].

## III. CONTROL SCHEME

The control scheme is shown in Fig.3 and 4. The $\mathrm{PID}_{i1}$ controller is developed for hub angle motion while $\mathrm{PID}_{i2}$ controller is applied for flexible body motion. The entire PID controllers are tuned by P-Type ILA. The two loops of each link (*i=1,2*) are combined together to give control inputs to the double link flexible robotic manipulator system.

### *A. Controller Design*

In this work, the intelligent PID controllers are utilized to ensure the hub follows the reference trajectory and the vibration of the system is eliminated simultaneously through end point acceleration feedback.

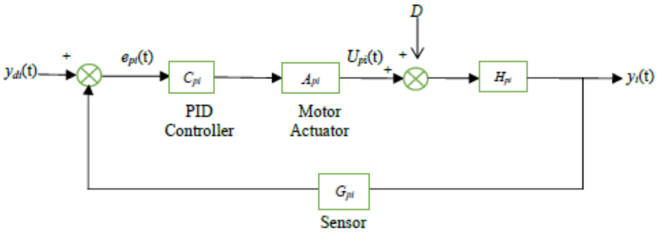


Fig. 3. Block diagram of control rigid body motion

For the hub angle motion, $\theta_{di}$ , and $\theta_i(t)$ represents reference hub angle and actual hub angle of the system respectively. By referring to the block diagram in Fig. 3, the close loop signal of $U_{mi}$ can be written as;

$$U_{mi}(t) = A_{mi}\left[\left(C_{mi}(t)e_{mi}(t)\right)\right] \qquad i = 1,2 \tag{1}$$

where $U_{mi}$ is PID control input, $A_{mi}$ is motor gain and $C_{mi}$ is PID controller. The controller gains are $K_{Pi}$*,* $K_{Ii}$ *and* $K_{Di}$. And;

$$\theta_i(t) = H_{mi} \tag{2}$$

$$H_{mi} = U_{mi}(t) + D \tag{3}$$

The error function of the system is defined as in Eq. (4);

$$e_{mi}(t) = \left[\theta_{di}(t) - G_{mi}\theta_i(t)\right] \qquad i = 1,2 \tag{4}$$

Therefore, the closed loop transfer function obtained as in Eq. (5);

$$\frac{\theta_i}{\theta_{di}} = \frac{[C_{mi}]A_{mi}H_{mi}}{1 + [C_{mi}]A_{mi}G_{mi}H_{mi}} \tag{5}$$

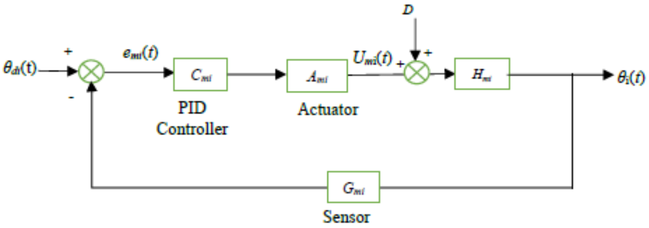


Fig. 4. Block diagram of control flexible body motion

For the flexible motion as illustrated in Fig. 4, the control input is given by;

$$U_{pi}(t) = A_{pi}\left[C_{pi}(t)e_{pi}(t)\right] \qquad i = 1,2$$

where $U_{pi}$ is PID control input, $A_{pi}$, are piezoelectric gain, $C_{pi}$ is PID controller as derived in Eq. 5.1. The controller gains are $K_{Pi}$*,* $K_{Ii}$ *and* $K_{Di}$. The deflection output represents by $y_i$ and the desired deflection $y_{di}$ is set to zero. And;

$$y_i(t) = U_{pi} \tag{7}$$

$$H_{pi} = U_{pi}(t) + D \tag{8}$$

Thus, the error $e_{pi}$ is defined as;

$$e_{pi}(t) = \left[0 - G_{pi}y_i(t)\right] \qquad i = 1,2 \tag{9}$$

Therefore, the closed loop transfer function obtained as;

$$\frac{y_i}{y_{di}} = \frac{[C_{pi}]A_{pi}H_{pi}}{1 + [C_{pi}]A_{pi}G_{pi}H_{pi}} \tag{10}$$

All the parameters of $K_{Pi}$, $K_{Ii}$ and $K_{Di}$ were tuned so that $U_{mi}$ and $U_{pi}$ provide acceptable performance of DLFRM. The performance of the PID controller was based on minimizing the MSE value.

### *B. P-type ILA*

Iterative learning algorithm is a scheme that uses information in previous repetitions to improve the control signal which ultimately enabling a suitable control action. In this work, ILA is used to improve the performance of PID control structure. The schematic diagram of the ILA tuner with PID controller is shown in Fig. 5.

In this scheme, the ILA performed a self-tuning to the PID controller parameters to minimize the overall system error so that the performance iteratively gets improved as presented in the following equations [14]:

$$\begin{aligned} K_P(k+1) &= K_P(k) + \varphi_1 \times e(k) \\ K_I(k+1) &= K_I(k) + \varphi_2 \times e(k) \\ K_D(k+1) &= K_D(k) + \varphi_3 \times e(k) \end{aligned} \tag{11}$$

where $K$ ($k$) is the stored value from the previous iteration (from memory), $K(k+1)$ is the updated value (to memory), $\Phi_1$ is the proportional learning parameter, $\Phi_2$ is the integral learning parameter, $\Phi_3$ is the derivative learning parameter and $e(k)$ is the system error.

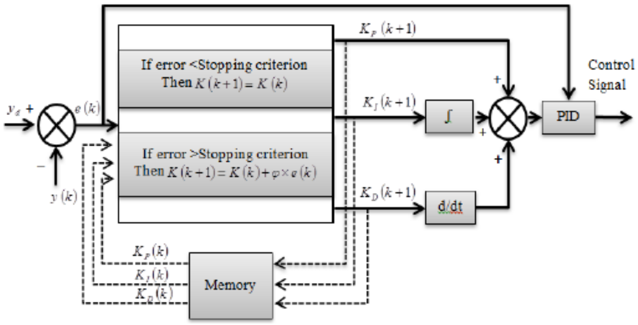


Fig. 5. P-type ILA with PID controller

ILA computes successive approximations such that the system output approaches a suitable value as the time increases. However, the over learning might occur during the learning processes as the time increased continuously. This condition might lead to system instability when it enters a dangerous zone [14]. Thus, a stopping criterion is implemented into the ILA to overcome this drawback.

In this study, there are two errors are considered that is to minimize the error from the hub angles and the error from the end point acceleration. For hub angle, the smaller value indicates precision in positioning the link to desire position. Meanwhile, the smaller value of end point acceleration implies that the vibration in the system is very much reduced. The system error is calculated as:

$$e(k)=y_d(k)-y(k) \tag{12}$$

where $e(k)$, $y_d(k)$ and $y(k)$ is the system error, desired input and actual output respectively.

The new signals $K_P$ ($k$+1), $K_I$ ($k$+1) and $K_D$ ($k$+1) are calculated based on Eq. (11) if the error is larger than the set stopping criterion error. However, if the error is smaller than the stopping criterion error, then the new signals are calculated by using the following equations:

$$\begin{aligned}K_P(k+1)&=K_P(k)\\K_I(k+1)&=K_I(k)\\K_D(k+1)&=K_D(k)\end{aligned} \tag{13}$$

## IV. RESULTS AND DISCUSSION

Simulation was carried out to study the effectiveness of the PID-ILA controller in trajectory tracking and vibration suppression control of DLFRM with no payloads. The simulation was implemented and tested within MATLAB/Simulink environment. The Simulink models were based on block diagram shown in Fig. 6 and 7. Step signals were employed as input reference with magnitude of ± 2.1 rad and ± 1.1 rad for links 1 and 2 respectively. The learning parameters were tuned through trial and error method. The simulations were run for 9 s with sampling rate of 0.01 s. During simulation, the controller stores information of parameter gains. These values are used as references in the next parameter gains' computation which is identified by error difference.

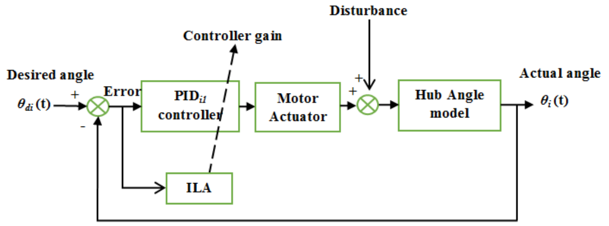


Fig. 6. Block diagram of self-tuning control scheme based on ILA for hub angles 1 and 2

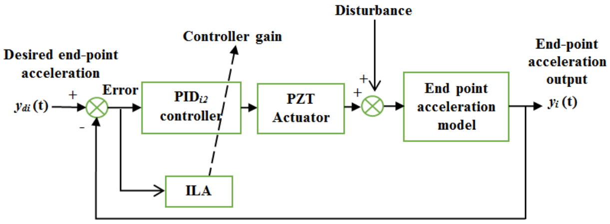


Fig. 7. Block diagram of self-tuning control scheme based on ILA for end point accelerations 1 and 2

### A. Hub angle Motion

During the simulation, the learning process was executed to find new controller parameters based on the learning parameters. The learning parameters presented in Eqs. (11) were tuned through trial and error method. During simulation, the controller stores information of parameter gains and uses these values as references to compute the next parameter gains which is identified by error difference. The control parameters of $K_P$, $K_I$, and $K_D$ converge when it reached the constant values. At this point the minimum output error is reached. The time taken for the controller parameters $K_P$, $K_I$, and $K_D$ of both links to settle at those constant values are about 2.81 s and 2.65 s respectively.

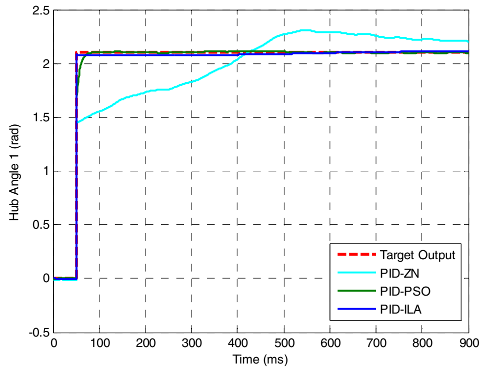


Fig. 8. Comparison between PID-ZN, PID-PSO and PID-ILA of hub angle 1

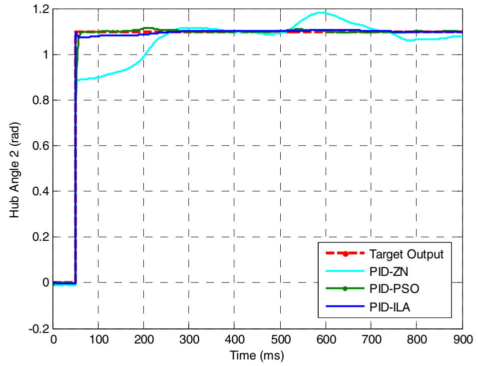


Fig. 9. Comparison between PID-ZN, PID-PSO and PID-ILA of hub angle 2

The intelligent PID-ILA controller was compared with the fixed controller, PID-PSO. PID-ZN worked as the control benchmark. The results for closed-loop hub angle 1 and 2 of PID-ILA controller were shown in Fig. 8 and 9 respectively. The stopping criterion is 0.02 rad which was obtained through heuristic method. The performance of self-tuning PID-ILA control structure is observed in terms of rise time, *tr* (s), settling time, *ts* (s), maximum overshoot, *Mp* (%) and steady state error, *Ess* (rad).

The numerical results are tabulated in Table 1. It can be noted that PID-ILA control structure for link 1 and 2 were able to track the desired hub-angle of DLFRM. There are significant improvements observed on PID-ILA. The percentage of improvement achieved by PID-ILA controller compared with PID-PSO controller for $t_r$, $t_s$ and $M_p$ are 86.2 %, 44.94 % and 86.21 % for link 1 and 80.95 %, 16.95 % and 17.91 % for link 2.

TABLE 1 PERFORMANCE OF CONTROLLERS FOR HUB ANGLE

| Controller | Parameters of controllers | | | | | |
|---|---|---|---|---|---|---|
| | $\Phi_1$ | $\Phi_2$ | $\Phi_3$ | $K_P$ | $K_I$ | $K_D$ |
| HUB 1 | | | | | | |
| P-Type ILA | 3 | 1 | 10 | 13.8 | 8.30 | 40.9 |
| PID-PSO | - | - | - | 3.7 | 57.8 | 3.4 |
| PID-ZN | - | - | - | 2.1 | 0.54 | 2.0 |
| HUB 2 | | | | | | |
| P-Type ILA | 3 | 1 | 10 | 21.3 | 7.01 | 60.5 |
| PID-PSO | - | - | - | 2.19 | 88.2 | 0.79 |
| PID-ZN | - | - | - | 4.15 | 1.29 | 3.32 |

| Controller | Rise Time (s), $t_r$ | Settling Time (s), $t_s$ | Over shoot (%), $M_p$ | SSE, $E_{ss}$ |
|---|---|---|---|---|
| HUB 1 | | | | |
| P-Type ILA | 0.008 | 0.49 | 0.16 | 0 |
| PID-PSO | 0.058 | 0.89 | 1.16 | 0.003 |
| PID-ZN | 2.965 | 7.147 | 4.69 | 0.68 |
| HUB 2 | | | | |
| P-Type ILA | 0.008 | 0.49 | 1.10 | 0 |
| PID-PSO | 0.042 | 0.59 | 1.34 | 0.002 |
| PID-ZN | 1.460 | 5.45 | 5.45 | 0.21 |

## B. *Flexible Motion*

The same simulation process applied to the end-point acceleration control. The learning process to find the new controller parameters is executed based on the learning parameters. The parameters value become constant once the minimum output error reached the set stopping criterion error that is 0.0015 m/s$^2$. This value is obtained through heuristic method. The time taken for the controller parameters $K_P$, $K_I$, and $K_D$ of both links to settle at those constant values are about 7.34 s and 8.27 s respectively.

The intelligent PID-ILA controller was compared with the conventional controller, and PID-PSO. The results show that PID tuning through ILA managed to improve the performance of vibration suppression than those obtained by the PSO method. These can be observed from Fig. 10 and 11 respectively.

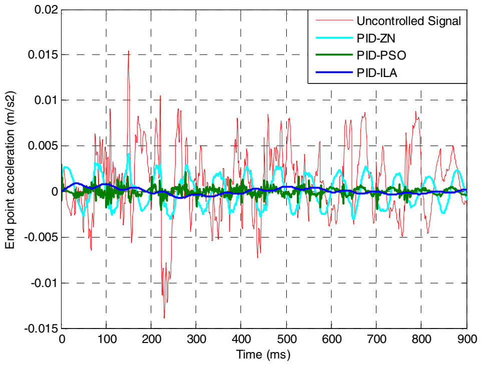


Fig.10. Comparison between controllers for end-point acceleration 1

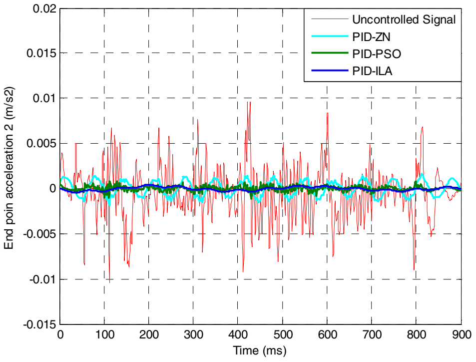
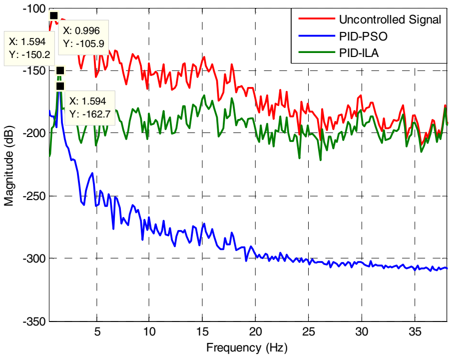


Fig. 11. Comparison between controllers for end-point acceleration 2

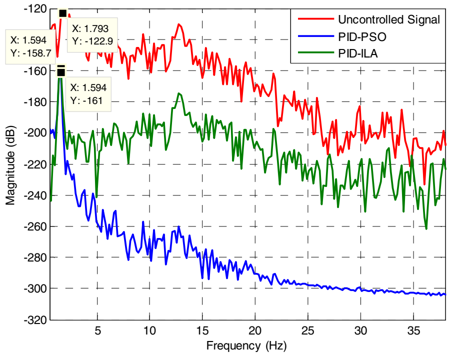
TABLE 2 PERFORMANCE OF CONTROLLERS FOR END-POINT ACCELERATION

| Controller | Parameters of controllers | | | | | | MSE |
|---|---|---|---|---|---|---|---|
| | $\Phi_1$ | $\Phi_2$ | $\Phi_3$ | $K_P$ | $K_I$ | $K_D$ | |
| Link 1 | | | | | | | |
| PID-ILA | 3 | 1 | 5 | 7.38 | 21.24 | 1.81 | $1.810 \times 10^{-8}$ |
| PID-PSO | - | - | - | 2.07 | 498.1 | 2.33 | $3.948 \times 10^{-8}$ |
| PID-ZN | - | - | - | 7.2 | 21.18 | 0.61 | $2.822 \times 10^{-6}$ |
| Link 2 | | | | | | | |
| PID-ILA | 3 | 1 | 5 | 16.11 | 55.12 | 3.05 | $4.054 \times 10^{-8}$ |
| PID-PSO | - | - | - | 8.06 | 817.9 | 1.03 | $4.315 \times 10^{-8}$ |
| PID-ZN | - | - | - | 4.16 | 55.08 | 1.28 | $7.564 \times 10^{-7}$ |

This could be further investigated from frequency domain result as shown in Fig.12 (a) and (b).



(a) Link 1



(b) Link 2

Fig. 12. Spectral density of the system output not label axes with a ratio of quantities and units.

PID-ILA control provides higher attenuation value for link 1 that is 56.8 dB as compared to PID-PSO that is 44.3 dB. The attenuation value of PID-ILA for link 2 shows the same pattern is that is 38.1 dB as compared to PID-PSO that is 35.8 dB. The comparison focused on mode 1 since the first mode is dominant and contributes substantial effect to the system.

## V. CONCLUSIONS

In this work, the proposed P-Type ILA to tune the PID controller in tracking the desired hub-angle and suppress the vibration of DLFRM was investigated and compared with corresponding fixed control structure that is conventional PID and PID-PSO. It was noted that PID-ILA control structure performed well as compared to those fixed PID control structure specifically PID-PSO manages to give a good response. For the hub angle, the percentage of improvement achieved by P-Type ILA controller compared with PID-PSO controller for $t_r$, $t_s$ and $M_p$ are 86.2 %, 44.94 % and 86.21% for link 1 and 80.95 %, 16.95 % and 17.91 % for link 2. Meanwhile, the percentage of improvement for flexible body control achieved by PID-ILA controller compared to PID-PSO controller for MSE is 54.15 % and 6.05 % for link 1 and 2 respectively. It can be concluded from this observation that the performance of the proposed adaptive PID-ILA control scheme is better than the fixed PID controller**.**

## ACKNOWLEDGMENT

The authors would like to express their gratitude to Minister of Education Malaysia (MOE), Universiti Teknologi Malaysia (UTM) and Universiti Malaysia Sarawak (UNIMAS) for funding and providing facilities to conduct this research

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