Chapter 38
Intelligent Tuning of PID Controller for Double-Link Flexible Robotic Arm Manipulator by Artificial Bee Colony Algorithm

A. Jamali, I. Z. Mat Darus, M. H. A. Talib, H. M. Yatim, M. S. Hadi, and M. O. Tokhi

Abstract Robotics system particularly robotic arm has received tremendous demand in various fields especially manufacturing industries. Robotic arm is highly needed to enhance production, to improve output, and reduce human error. The current robotics arm not only they are expensive and required specialist for maintenance, but they are also bulky and very heavy. Thus, the option is employing lightweight, stronger, and more flexible robotics arm. However, the lightweight robotic arm can be easily influenced by unwanted vibration which may lead to problems including fatigue, instability, and performance reduction. These problems may eventually cause damage to the highly stressed structure. This research focuses on the development of intelligent controller utilizing artificial bee colony (ABC) algorithm to tune proportional integral derivative (PID) parameters for controlling two-link flexible manipulator (TLFRM). The essential objective of the designing the controller is to improve the performance of desired position and vibration suppression of TLFRM. The MATLAB environment is utilized to verify the accomplishment of the recommended control system. An assessment is conducted to illustrate the efficiency of PID-ABC controller in terms of input tracking and vibration suppression. The results show that the system with embedded new proposed controller is capable to achieve preferred angle at decrease overshoot and the settling time is exceptionally much quicker. The vibration reduction demonstrated substantial improvement as compared to manual tuning method. Overall, the proposed controller for two-link flexible manipulator that is intelligent PID-ABC was successfully control the system to the preferred position with vibration suppression in the entire system.

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38.1 Introduction

Robotics manipulator arm system has progressively become popular not only among the heavy industries but also among small to medium enterprise industries. This is meant for simple and repetitive tasks to increase their productivity. The demand led to the changes of physical configurations of a robot such that the link structure is longer and thinner and the material used is lightweight. The developed robotic arm by using the lightweight material introduces flexibility to the system. Due to that, the flexible arm manipulator (FRM) motion tracking control is considered as a challenging problem due to the system dynamic replicated a highly coupled nonlinear and time-varying. Despite the problem, the flexible robotic manipulators have several potential applications such as in space exploration, military, medical field, automotive, oil and gas and other industrial applications. In manufacturing industries, the demand for flexible robotic arm manipulator is more imperative in order to fulfill the needs of current industrial such as higher maneuverability, superior transportability, quicker response times, and lower power consumption.

Researchers proposed various control strategies for FRM such as passivity-based velocity feedback and strain feedback schemes [1], hybrid collocated and non-collocated PID controller [2], global terminal sliding mode [3], a genetic algorithm (GA)-based hybrid fuzzy logic control strategy [4], decoupling controller based on the cloud model [5], adaptive distributed control strategy [6] and decentralized controller based on linear matrix inequalities [7]. Besides, researchers also proposed various controller strategies to design multivariable (MIMO) systems for multi-link FLM, ranging from intelligent control [8–10] to adaptive control [11], sliding mode controller [12, 13], adaptive iterative learning control scheme [14], torque controller [15, 16], optimal nonlinear controller [17], and PDE-based controller [18]. Most of the listed control schemes incorporate both conventional and intelligent control strategies to compensate the drawback of each controller.

Despite various advance control strategies proposed for the industrial environment, simple controller in which employing decentralized control scheme is preferable particularly for MIMO frameworks. The decentralized control scheme has raised interest among researchers. This is due to the fact they are frequently successful of imparting an extraordinary overall accomplishment despite their handy structure and intuitiveness. Though decentralized controller structure constraints bring about certain performance deterioration if compared with centralized full controller systems, it still gains popularity due to hardware simplicity and employ failure tolerant structure. Subsequently, it is easy to implement and maintain by plant personnel apart from delivering an adequate performance. There are few examples that showcase the decentralized control which have been implemented to two-link flexible robotic manipulator (TLFRM) system. The work in [19, 20] has proposed the decentralized PI-PID controller for TLFRM through manual tuning. Then, the overall performance has been elevated by adding ILC which have been verified in the simulation. The linear matrix inequalities (LMI)-based PID control of a nonlinear two-link flexible robotic manipulator (TLFRM) incorporating payload have been reported in [21].

In [7], decentralized proportional integral derivative (PID) controller by incorporating bounding parameters of interconnection terms in LMI formulation for an n-link robotic manipulator system was proposed. Finally, another decentralized control strategy utilized neural network (NN) to approximate the ZN-PID for every link of TLFRM in [22].

Apart from that, Alam et al. [23] applied hybrid PD-PD/ILA tune by multi-objective genetic algorithm optimization for single-link flexible manipulator (SLFM). Tijani carried out a multi-objective optimization the use of differential evolution (MODE) for PID controller of SLFM [24]. Another researcher has proposed an expanded bacterial foraging algorithms (BFA) to fine-tune the PID controller of SLFM [25]. Bee algorithm has been successful to optimize the hierarchical PID parameter of SLFM in [26]. Finally, PSO is used to tune one of PID parameters of the hybrid PID-PID controller of SLFM [27].

The literatures disclose that the application of intelligent tuning is considered in both TLFRM and SLFM. However, the survey confirms that the unique type of evolutionary algorithm such as DE, BFA, and ABC provides an effective method in optimizing the PID controller confine only in SLFM. Thus, there are relatively few PID controllers and have been used in TLFRM compared to their SLFM. The reason can be associated with the problem in the tuning coupled system. Besides, most of the time, the tuning methods showed sluggish responses when applied to a non-minimum phase system like flexible manipulator.

This paper therefore proposed hybrid PID-ABC for TLFRM, whereby ABC is used to optimize the parameters' of PID controllers. The system is modeled via system identification in which NARX model structure is utilized and the nonlinear part is predicted by neural network (Sect. 38.2). Section 38.3 presents the ABC algorithm used for optimization. The proposed control schemes that are the collocated PID controller for position tracking and the non-collocated PID controller for endpoint vibration suppression are then described in Sect. 38.4. Section 38.5 discusses the simulation results in which include the assessment of the recommended controllers in terms of reference tracking and endpoint acceleration. The conclusion remarks are presented in Sect. 38.6.

38.2 Experimental Setup and System Identification

38.2.1 Robotics Manipulator Test Rig

The planar TLFRM is constructed as shown in Fig. 38.1. The developed rig was executed to mimic the actual angular motion of manipulator. There are four outputs acquired from the sensors that are encoders and accelerometer. The outputs characterize the hub angles and endpoint acceleration of every link, respectively. The test is conducted in 9 s for every individual movement and repeated for similar angle. In order to match the mechanical system with software, the sampling time of 0.01 s

Fig. 38.1 Setup of two-link flexible robotic manipulator rig

was applied. Figure 38.2 indicates the schematic layout to illustrate the integration among all devices.

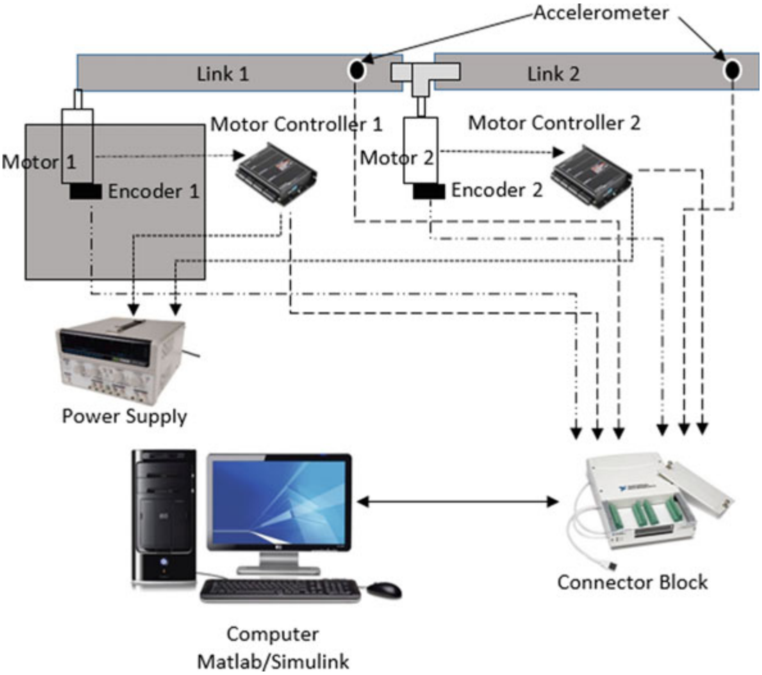


Fig. 38.2 Schematic diagram of TLFRM

38.2.2 System Identification

The TLFRM is classified under distinctly nonlinear. Thus, the development of nonparametric modeling is favored for this study utilizing neural network. NARX is chosen as model structure in this study because it has the simplest structure among nonparametric model. The research makes use of backpropagation for multilayer perceptron (MLP) neural network and Elman neural networks (ENN) for modeling the TLFRM system. All the developed models are validated via mean squared error (MSE). They are further validated via correlation test. The details can be found in [28].

38.3 Optimization Algorithm

After a system model is obtained, it can be utilized to predict the physical system behavior under different operating conditions or to control it. In this work, artificial bee colony (ABC) is employed to tune the PID parameters. In the bees' nature, they are classified into employed bees, onlooker bees, and scout bees. ABC system engaged both neighborhood search methods and global search methods. ABC algorithm contains the first half of employed bees and the second half comprises of the onlooker bees. The preliminary meals sources are randomly produced. Each employed bee generates a new candidate solution in the neighborhood of its present position. The neighbor food source vmi is chosen. The fitness is determined. Then, a greedy decision is utilized between xm and vm. The quantity of a food source is evaluated by its profitability and the profitability of all food sources. After all the employed bees have finished the search processes, they share the information of their food sources with the onlooker bees through waggle dances. An onlooker bee evaluates the nectar data taken from all employed bees and chooses a food supply with a likelihood associated with its nectar amount. The procedure of ABC algorithm is illustrated in the diagram in Fig. 38.3.

38.4 Controller Development

The recommended control structure using ABC was incorporated to tune the PID controllers. Figures 38.4 and 38.5 present a block diagram of the closed-loop system for rigid body and flexible motion control, respectively.

Step input was used as input reference. The performance of PID controllers for hub angle models was observed in terms of *tr*, *ts*, *Mp, and Ess*. Meanwhile, the performances of vibration suppression were observed in terms of the attenuation of the first three mode of vibration. The objective functions of optimization are expressed based on the MSE of the hub angle error and endpoint vibration concealment.

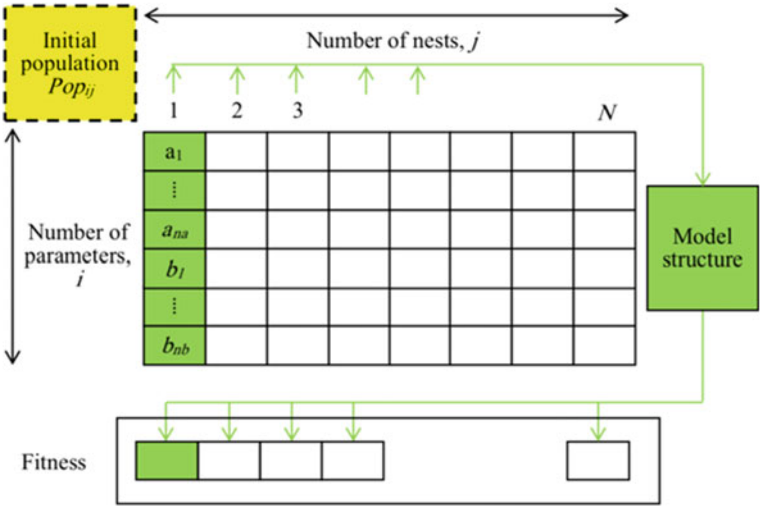


Fig. 38.3 Diagrammatic representation of generation the initial population

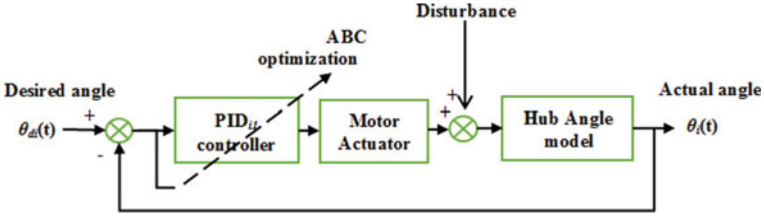


Fig. 38.4 PID control structure for hub angles 1 and 2

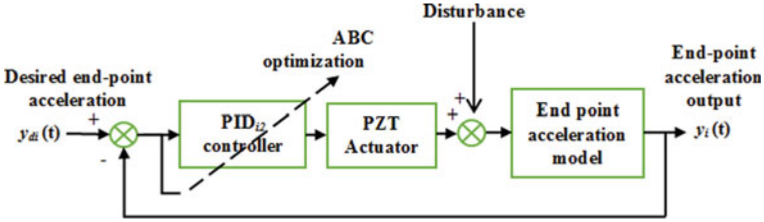


Fig. 38.5 PID control structure for endpoint accelerations 1 and 2

The collocated PIDi1 and non-collocated PIDi2 controller are applied for hub angle motion and flexible body motion, respectively. The two loops of each link (i = 1, 2) are consolidated to allow control inputs to the two-link flexible robotic manipulator framework.

38.4.1 Intelligent Collocated PID Controller

The details of hub angle motion controller can be described by referring to Fig. 38.6. The closed-loop signal of U_{mi} can be written as:

$$U_{mi}(t) = A_{mi}[(C_{mi}(t)e_{mi}(t))] \quad i = 1, 2 \tag{38.1}$$

Therefore, the closed-loop transfer function acquired as in Eq. (38.2);

$$\frac{\theta_i}{\theta_{di}} = \frac{[C_{mi}]A_{mi}H_{mi}}{1 + [C_{mi}]A_{mi}G_{mi}H_{mi}} \tag{38.2}$$

where θ_{di} and $\theta_i(t)$ represent reference hub angle and actual hub angle. 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}.

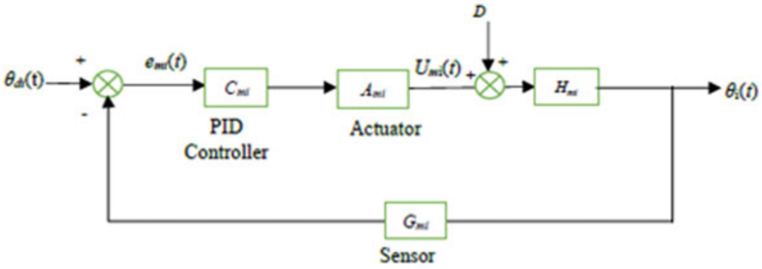


Fig. 38.6 Block diagram of control rigid body motion

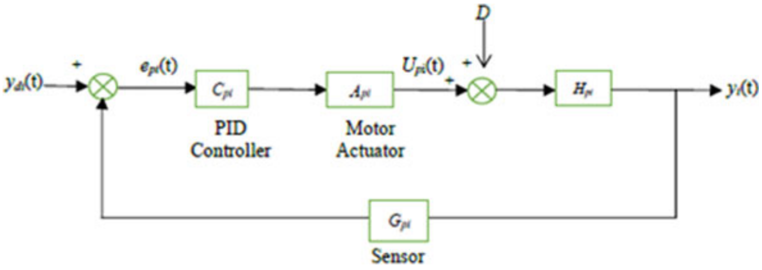


Fig. 38.7 Block diagram of control flexible body motion

38.4.2 Intelligent Non-collocated PID Controller

In Fig. 38.7, the block diagram for flexible body motion is presented to explain the details of the controller. The control input is given by;

$$U_{pi}(t) = A_{pi}\left[C_{pi}(t)e_{pi}(t)\right] \quad i = 1, 2 \tag{38.3}$$

where U_{pi} is PID control input, A_{pi} is piezoelectric gain, C_{pi} is PID controller. 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. Therefore, the closed-loop transfer function obtained as;

$$\frac{y_i}{y_{di}} = \frac{\left[C_{pi}\right]A_{pi}H_{pi}}{1 + \left[C_{pi}\right]A_{pi}G_{pi}H_{pi}} \tag{38.4}$$

The parameters of PID controller, K_{Pi}, $K_{Ii,}$ and K_{Di} were tuned accordingly to be fed into the U_{mi} and U_{pi}, thus grant satisfactory accomplishment of TLFRM. The accomplishment of the PID controller was evaluated by minimizing the MSE value.

38.5 Results and Discussion

TLFRM was modeled with the nonparametric identification approaches of neural network particularly MLP and ENN algorithm using NARX modeled structure. The best-obtained model system is then used in the control structure of TLFRM.

38.5.1 Modeling Results

Table 38.1 presents the achievement in modeling the TLFRM. The results reveal that all models predicted by ENN are one-sided. Thus, the TLFRM model obtained using MLP will be utilized in developing of control for hub angle and endpoint acceleration of the TLFRM.

38.5.2 Control Results

The recommended control strategies are applied on TLFRM system and executed through MATLAB/Simulink environment. The responses of the system are analyzed to optimize the performance of the recommended controllers.

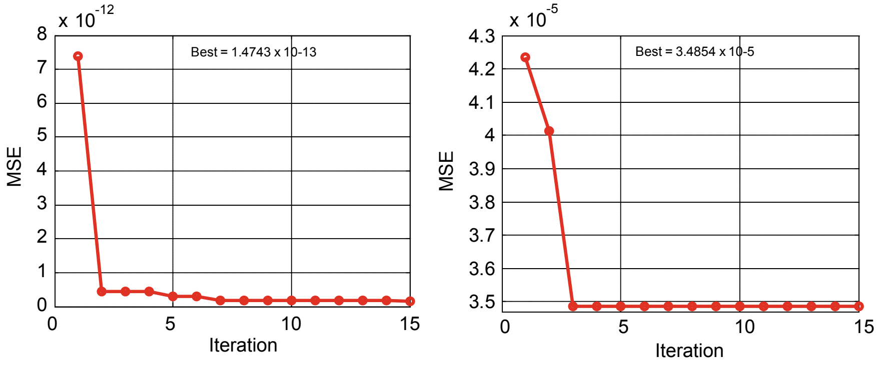
Table 38.1 Summary of the performance achieved in modeling

	Model	Spec.	*T* (s)	MSE	Correlation test
MLP	Hub1	MS: [2 2 1], Ite: 150	3	0.0000685	Unbiased
	Hub2	MS: [2 2 1], Ite: 150	3	0.000752	Unbiased
	E.P. Acc1	MS: [2 2 1], Ite: 150	3	0.0025	Unbiased
	E.P. Acc2	MS: [2 2 1], Ite: 150	3	0.0049	Unbiased
ENN	Hub1	MS: [8 8 1], Ite: 150	2	0.0047	Biased
	Hub2	MS: [8 8 1], Ite: 150	2	0.0023	Biased
	E.P. Acc1	MS: [8 8 1], Ite: 150	3	0.018	Biased
	E.P. Acc2	MS: [8 8 1], Ite: 150	3	0.015	Biased

Hub Angle Motion The hub angles were controlled by the collocated PID-ABC controller individually. The TLFRM system is required to comply with a step input of 1 rad to test the hub tracking input of link 1 and link 2. The parameters of PID controllers are obtained via ABC algorithm. The tuning is initialized by setting the number of iterations to 15 and varying the number of colony size from 10 to 50. The same procedure was repeated for 50 maximum iterations. It was found that the satisfactory result was obtained with 50 colony sizes at 15th iteration for both hub angles. Figure 38.8a, b exhibits the 15 iterations of MSE convergence of ABC for hub angle.

The fitness function of ABC optimization is formed in such a way to reduce the tracking error via MSE values. The convergence MSE values with regard to the PID parameters obtained are organized in Table 38.2. Numbers of the simulation were repeated with different colony sizes.

The results were compared with manual tuning method to examine the significant of using ABC algorithm. The controller performances are presented in Table 38.3.



(a) Link 1 (b) Link 2

Fig. 38.8 ABC convergence for hub angle

Table 38.2 Convergence of MSE for ABC algorithm

Parameter	MSE	PID parameters		
		K_P	K_I	K_D
Hub angle 1	1.4743×10^{-13}	6.54	20.5	49.43
Hub angle 2	3.4854×10^{-05}	5.48	28.3	13.72

Table 38.3 Parameters and performance of hub input tracking

	Link	PID parameters			Tracking capabilities		
		K_p	K_i	K_d	Rise Time	OS (%)	T_s (s)
PID	Hub 1	2	25	3	0.123	3.247	5.163
	Hub 2	2	57	3	0.066	2.012	2.164
PID-ABC	Hub 1	6.54	20.5	49.43	0.044	1.061	1.078
	Hub 2	5.48	28.3	13.72	0.028	0.869	1.049

The response of the hub angle for both links is shown in Figs. 38.9 and 38.10. The proposed PID-ABC controller achieved an acceptable hub angle response. It is exceptionally important enhancement in terms of rate overshoot and settling time. The TLFRM system reached the required angle at reduce overshoot by employing the recommended approach that is 67 and 56% improvement as compared to the conventional method and faster settling time that is from 5.1633 to 1.0783 s for hub 1 and from 2.1635 to 1.0499 s for hub 2.

Flexible Body Motion The PID-ABC controllers were also executed to TLFRM system to effectively stifle the vibration at the endpoint of link 1 and link 2 independently. The desired output is set to zero to minimize the vibration in the system. The parameters of PID controllers are also acquired via ABC algorithm. It was found that

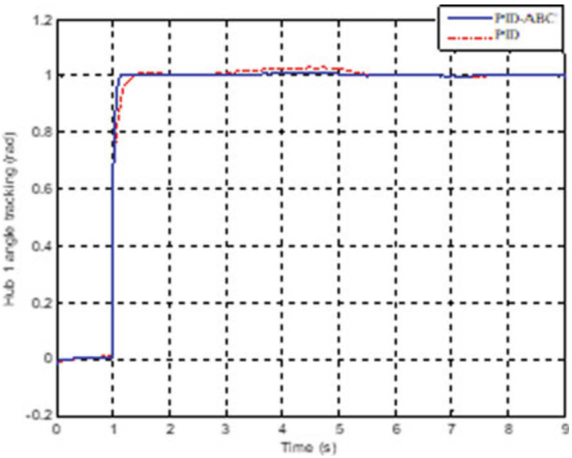
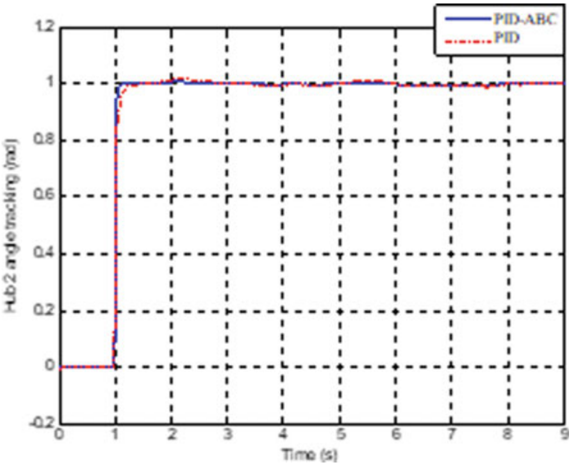


Fig. 38.9 Input tracking of hub 1

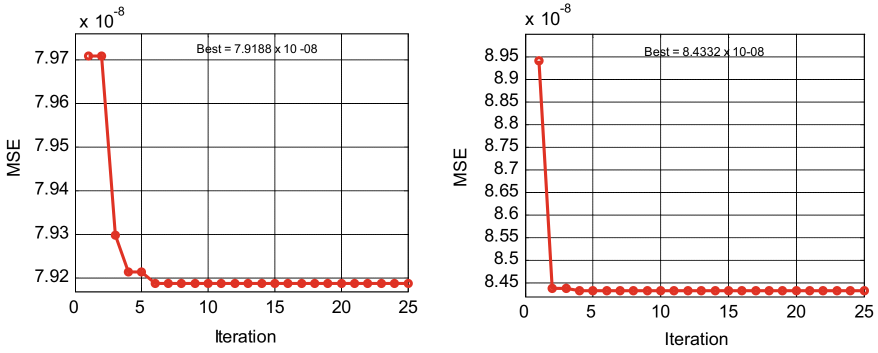
Fig. 38.10 Input tracking of hub 2



the satisfactory result was obtained with 50 colony sizes at 25th iteration for endpoint acceleration suppression. Figure 38.11a, b displays the 25 iterations of MSE convergence of ABC for endpoint acceleration. It reveals that ABC optimization merges very fast and yields a small value of MSE for all the controllers. Besides, it was discovered that when the number of iterations higher or the number of colony sizes were set to greater values, there were no noteworthy improvement of MSE.

The results were compared with manual tuning method of PID controllers to assess the noteworthy of utilizing the ABC algorithm. The controller parameters obtained, and their performances are organized in Table 38.4.

The table displays that the PID-ABC controller accomplished better MSE level as compared to manual tuning method for controlling flexible body motion of both link 1 and link 2. This is portrayed in the simulation results of vibration suppression as



(a) Link 1 (b) Link 2

Fig. 38.11 ABC convergence for endpoint acceleration

Table 38.4 Parameters and performance of endpoint acceleration

Controller	Link	PID parameters			MSE
		K_p	K_i	K_d	
PID	1	4	9	1	1.708×10^{-6}
	2	5	1	2	8.469×10^{-6}
PID-ABC	1	30.03	56.07	88.95	7.9188×10^{-08}
	2	50.1	46.96	23.62	8.4332×10^{-08}

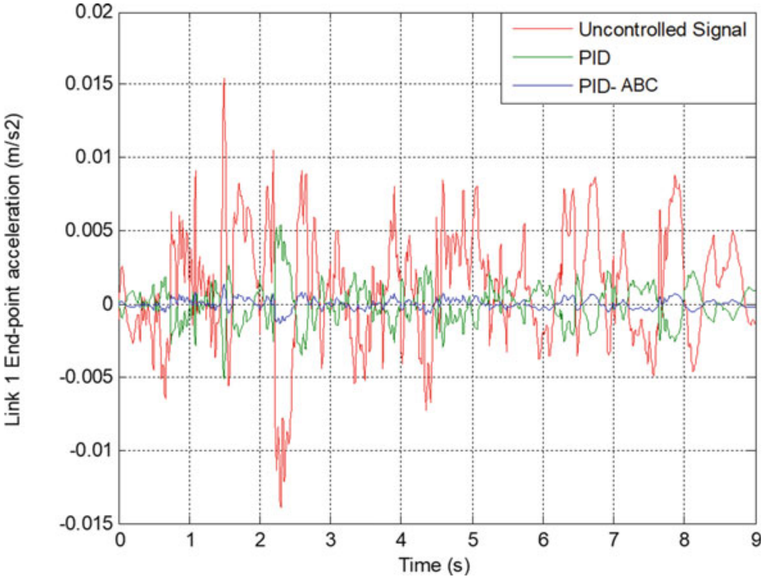


Fig. 38.12 Endpoint vibration suppression of link 1

shown in Figs. 38.12 and 38.13. The manual tuning of PID controller applied to the system undoubtedly aids to reduce the vibration in the system. However, the process is tedious and time-consuming. The vibration can be easily and additional suppressed by utilizing the PID-ABC controller. This implies that, the ABC algorithm is very effective in optimizing the PID parameters.

38.6 Conclusion

This paper has presented the optimum PID controller using ABC for controlling TLFRM. The experimental test was carried out to obtain the input–output of the real system to characterize the dynamic behavior of TLFRM was first developed. Subsequently, TLFRM was modeled using NARX model structure in which predicted

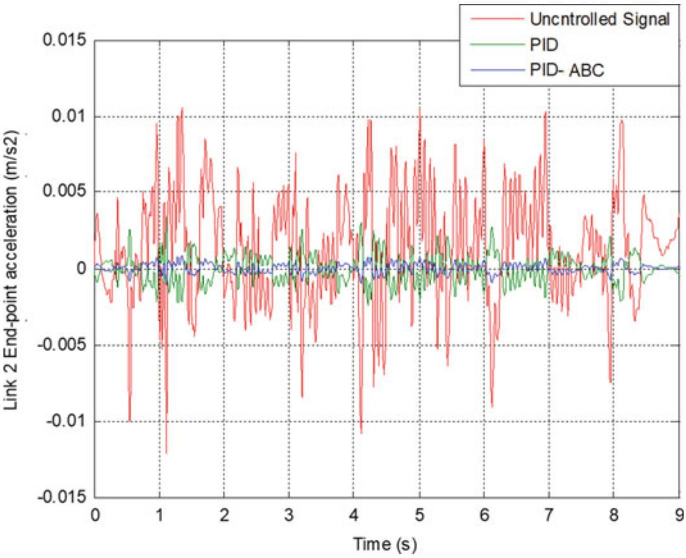


Fig. 38.13 Endpoint vibration suppression of link 2

by neural network. Then, hybrid PID controller is developed to control the hub motion and endpoint vibration suppression of each link, respectively. The optimum gains acquired through global search has been tested on the control structure. The system responses inclusive of input tracking and vibration suppression at the endpoint were evaluated. The results were compared to the heuristic methods. Though the simulation results portrayed that the manual tuning of PID controllers was able to control the system in terms of input tracking and reduce the vibration in the system, the process is tedious and time-consuming. On the other hand, the PID parameters tuned by ABC is easily obtained with less time. Besides, the results exhibit that the recommended controller is more effective to move the two-link flexible at lower overshoot with the improvement of 67 and 56% compared with the heuristic method and faster time that is from 5.1633 to 1.0783 s for hub 1 and from 2.1635 to 1.0499 s for hub 2. The vibration suppression shows 93.53% and 90.47% improvement, respectively.

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