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Proportional integral derivative controller based on ant colony optimization for vibration cancellation of horizontal flexible plate structure

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ABSTRACT

Flexible plate structure provides many benefits as compared to their rigid counterparts including lower energy consumption, effective, lightweight, and quick response. However, the vibration easily affects the flexible plate structure resulting in structural damage. This study introduces the modelling of a flexible plate structure based on a system identification technique known as ant colony optimization (ACO) algorithm for vibration control. Firstly, the input-output vibration data that represent the actual structure of flexible plate was achieved from the experiment. Next, the acquired vibration data was used to develop a dynamic model of the flexible plate structure. The performances of the ACO algorithm were assess based on mean squared error (MSE), pole-zero plot and correlation test in order to get a precise and reliable outcome. The results show that ACO algorithm achieved the minimum MSE which was 6.7613×10^{-6}, high stability of pole-zero plot and excellent correlation test. Subsequently, the best model of ACO was chosen to create controller based on an active vibration control technique. It was noticed that the controller managed to obtain a 6.19 dB reduction at the first mode vibration in which the percentage of attenuation of the controller was 10.63% for sinusoidal disturbances and 9.64% for multiple sinusoidal disturbances.

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1. INTRODUCTION

The flexible structure has commonly been used for the past several decades. Based on previous researches, the elements for flexible structures such as beams, frames, plates, and shells were commonly used in manufacturing applications [1]. The application of flexible structure can be found in areas of mechanical, marine, civil, aerospace and others. These applications have led to high vibration when exposed to disturbance forces which may reduce the system effectiveness and structural damage [2]. Nowadays, the production of the flexible structure of thin rectangular plates is very high in the industrial market due to the significant increase in demand from the customers.

The flexible plate structures are widely utilized in a variety of industries including solar panels, electrical bridge decks and circuit board design [3]. This particular structure fulfils most of the desired design specifications which are low cost, lightweight, lower energy consumption, and capability of being operated at high speed [4]. However, despite having a large width, this structure possesses a comparatively low thickness. The thin and lightweight characteristic of flexible plate structure is subjected to higher vibration compared to rigid structures [4]. High vibrations lead to fatigue, noise, structure failure, human discomfort, wear and lessen the efficiency of the flexible plate structure [3]. Therefore, it is critical to eradicate the unpleasant vibration on the flexible plate structure in order to sustain the efficacy of the system.

Hence, vibration control was introduced as the control strategy to mitigate the undesired vibration on the flexible plate structure. One of the types of vibration control is a conventional method that applied passive vibration control (PVC) on the structure to suppress the vibration. PVC used passive material such as viscoelastic material, mechanical spring, rubber pads and dampers. However, PVC has limitations in terms of versatility and can control the vibration only at high frequencies [5]. This is because PVC depends on operational and environmental factors such as vibration frequency, temperature, and pre-stress [6]. Therefore, the active vibration control (AVC) technique is proposed to overcome the limitation of PVC.

The active vibration control (AVC) is more effective and suitable for flexible plate structure compared to PVC. This is due to the characteristic of a flexible plate structure that has a low-frequency range. AVC minimizes the vibration using a counterforce to the system that is suitable for the phase through equal amplitude to the source of vibration [7]. The technique of AVC is slightly different from PVC. Active vibration control uses sensor actuator, sources of power and a compensator to control vibration without necessarily adding damper to the system. The components used in AVC are actuators, sensors, and controllers. However, the positioning of the sensors and actuators must be conducted carefully to ensure the maximum attenuation of the vibration on the structure [8].

The development of an excellent controller needs the best model which represents an approximate flexible plate structure. Based on the previous studies, the researchers have proposed to use system identification technique for modelling the system [9]. System identification technique was utilized to develop the modelling for the linear and non-linear system. Hence, it can also be used to estimate the model of a dynamic system by acquiring the input-output vibration in a discrete-time signal [10]. The discrete-time signal consists of mathematical expressions which define the correlation between input and output signals. Besides, the system identification technique included verifying and validating the model system to identify whether the model system has fulfilled the application needs.

The recent system identification technique known as swarm intelligence algorithm (SIA) bio-inspired the real-life process. There are various types of SIA algorithms known as ant colony optimization (ACO) [11], artificial bee colony (ABC) [12], glowworm swarm optimization (GSO) [13], whale optimization algorithm (WOA) [14], bat algorithm [15] and others. Among all the algorithms that were used in system identification, the ACO is the best algorithm to provide an approximate solution for complex paths [16]. ACO is inspired by the population of ants that choose the shortest path while seeking for food. This algorithm was invented by Wang [17], where he used the inspiration of the ant colony to determine the best solution to the problems [17]. The purpose of this research is to develop a model of horizontal flexible plate structure and control unwanted vibration on the system in a simulated environment.

2. EXPERIMENTAL SETUP FOR VIBRATION DATA COLLECTION

The main objective of performing this experiment was to obtain the actual data of input-output vibration of the horizontal flexible plate system. Next, the characteristic of the flexible plate was assessed using a complete data acquisition (DAQ) system. DAQ system consists of the actuator, computer, sensor, and signal conditioning hardware. Then, the DAQ system was performed with the experimental rig that consisted of a mechanical part, an electrical and electronic component such as a magnetic shaker, power amplifier, function generator, and accelerometer of the piezo-beam type.

The proposed flexible plate structure used for this experiment was aluminium material with a dimension of 0.6 m width and 0.6 m length and 0.001 m thickness. The flexible plate was positioned horizontally and all edges of the plate were clamped. On top of that, a permanent magnet with circular condition and magnetic shaker was used to generate an actuation force at selected excitation points. The position of the circular-shaped permanent magnet was parallel with magnetic shaker with a distance of 1 cm at the excitation point. In addition, the vibration of the plate was generated using sinusoidal actuation disturbances by connecting the magnetic shaker to the power amplifier and function generator. The accelerometer of the piezo-beam was located at the detection and observation point as illustrated in Figure 1. Furthermore, Figure 1(a) depicts the integration of the experimental rig with the DAQ system, whereas Figure 1(b) indicates the sensor location. The accelerometer was used to act as the vibration of the structure to recognize the acceleration signal. The DAQ system that related to the proposed accelerometers was used to evaluate the input-output of the vibration data. Figure 1 shows the experimental setup for data collection.

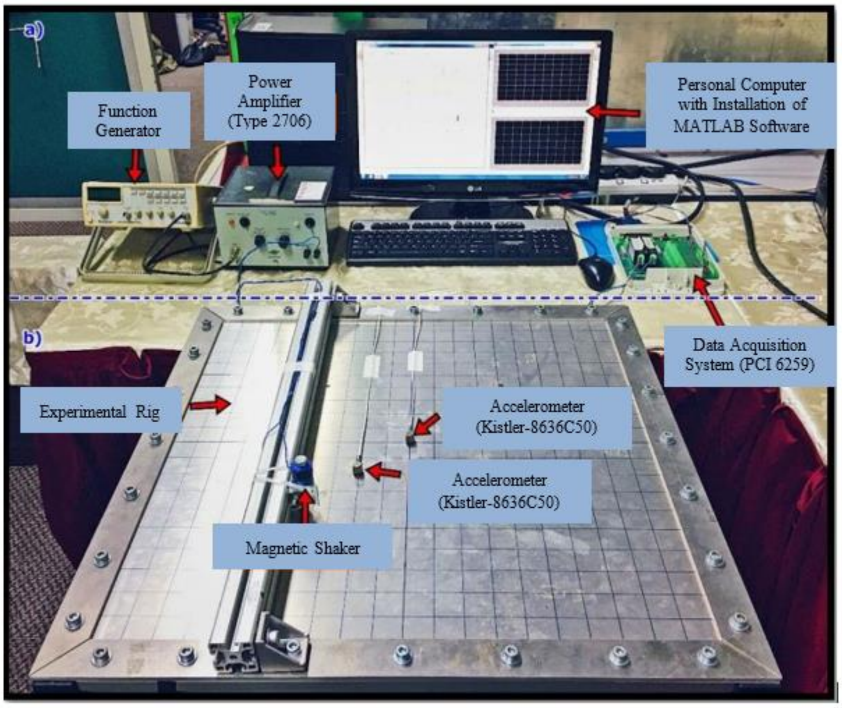


Figure 1. The data collection experimental setup (a) the experimental rig with the DAQ system and instrument system and (b) the sensor position on the plate

3. CONTINUOUS ANT COLONY OPTIMIZATION

The initial application of the ant colony optimization (ACO) algorithm was used for discrete problems only [18]. Thus, the application of ACO has been improved for continuous optimization problems. There are various types of ACO for continuous optimization known as continuous ACO (CACO) [19], the API algorithm [20] and continuous interacting ant colony (CIAC) [21]. Nonetheless, most of these methods are inspired by the ideas of ACO but do not implement the actual ACO structure [22]. The most recent improvement was introduced in [23], where the proposed algorithm used the basic structure of the original ACO known as continuous domain ACO (ACO_R) [24].

The continuous ACO (ACO_R) algorithm was extended from ACO metaheuristic algorithm without changing the basic structure of ACO. The fundamental of ACO_R provided multiple solutions that depend on biased solutions. In addition, ACO_R was performed by adjusting the discrete probability to continuous probability density function (PDF). ACO_R used the formula of Gaussian kernel and weighted summation of certain Gaussian functions as PDF. The formula of weight of the Gaussian kernel is described in (1).

$$\omega_l = \frac{1}{qk\sqrt{2\pi}} . e^{-\frac{(l-1)^2}{2q^2k^2}} \tag{1}$$

The Gaussian function weighted, ω value was presented with ranking l, standard deviation qk and mean 1.0. q is the locality of search that acts as the parameter which adjusts the weight in solution archive. The lower value of q indicated that the probability of the outcome being generated is biased to the current best result while the larger q provided uniform solution probability among solutions in solution archive [23]. The l^{th} Gaussian function probability formula is described in (2).

$$p_1 = \frac{\omega_1}{\sum_{r=1}^{k} \omega_r} \tag{2}$$

In addition, standard deviation, σ and mean, μ were required for this process. The actual Gaussian function sampled was different at each dimension of the chosen solution were set as the mean of the distribution, $\mu_l^i = s_l^i$ and σ was calculated dynamically using the (3) [24].

$$\sigma_1^i = \xi \sum_{e=1}^{k} \frac{\left|s_e^i - s_l^i\right|}{k-1} \tag{3}$$

where $S_l^i = \mu_l^i$ and $\xi > 0$ are the same for all dimensions. For each dimension of the solution, the sampling Gaussian function using (4) will randomly generate a new different value from chosen PDF. ξ is the algorithm parameter that affects the Gaussian function standard deviation size. Standard deviation was used for radius search space for the sampling process. A higher value of ξ (> 1.0) expands the search space while lower $\xi(< 1.0)$ shrinks the search space. Hence, the previous studies reported that the value of ξ has an effect on the algorithm convergence rate [23]. The larger the input of ξ, the slower the algorithm convergence rate. After that, the Gaussian kernel was developed based on the value of the weight, probability, and standard deviation. The formula of the Gaussian kernel is described in (4).

$$G^i(x) = \sum_{l=1}^{k} \omega_l \, g_l(x) = \sum_{l=1}^{k} \omega_l \frac{1}{\sigma_l^i \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma_l^{i2}}} \tag{4}$$

The l^{th} Gaussian function is derived based on the k population of the lth member. Besides, the σ is the standard deviation while the μ is the mean and ω is the weight of Gaussian function. The sampling of G^i was used to generate the new solution outcome x_i. The construction of the new solution is generated when an ant chooses probabilistically one solution from the solution archive, T proportional to the weight, ω [25].

4. RESULTS AND DISCUSSION

The flexible plate system model was developed using ACO algorithms with linear autoregressive with exogenous input (ARX) model. The 5000 vibration data sets of input-output collected throughout the experiment were split into two equal sections. The first part which comprised 2,500 datasets were utilized for model training while the remaining 2,500 data were implemented for model performance testing. After that, the generated model system was assessed on three criteria which were correlation tests, pole-zero plots and mean square error (MSE). The best model was selected depends on its good stability, 95% of the correlation test confidence level and lowest MSE. Then, the best model was used for controller development based on the AVC technique. The developed controller performance was verified by several types of disturbances to the system, including single and multiple sinusoidal disturbances.

For the modelling using ACO_R algorithm, the best model of the flexible plate system was achieved using the heuristic approach. Thus, the model was tuned heuristically as no clear information exists to tune this algorithm. There were six parameters that needed to be set in ACO_R algorithms such as model order, iteration, archive size (k), number of ants $(Nant)$, locality of search (q) and speed of convergence rate (ξ). Besides, the tuning process was achieved by tuning one parameter per function while the remaining parameter was fixed. It began with varying the number of ants, $Nant$ while the other parameters were fixed. As referred to by Mohammad *et al.* [24], the number of ants was set between 10 till 30. Other than that, the speed of convergence rate, $\xi = 0.85$ was used for all the runs in this system as it was able to provide the best result for optimization problems [23]. The locality of search, (q) were tuned based on the suggested value from the previous researchers which were 1, 0.5, 0.1, 0.05 and 0.01 [25]. The ACO_R algorithm iteration number was set at 500 to 2,500 with an increment of 500.

From the tuning result, the best flexible plate model was acquired when the model order was set to 4 with the sets of parameters described in Table 1. The MSE value for the best model acquired for the ACO_R algorithm was 6.7613×10^{-6} for testing data. Figure 2 presents the graph of MSE against the number of iterations of ACO_R modelling. Next, Figure 3 and Figure 4 reveal the performance of ACO_R in time and frequency domains for the actual and predicted outputs. In addition, Figure 3(a) portrays the entire sample data output of 5000, whilst Figure 3(b) highlights a narrow view of the sample ranging from 400 to 600. The model developed is capable to replicate the measured output successfully as the frequency of predicted outputs were overlapped with the actual experimental data. The actual and predicted outputs errors are plotted in Figure 5.

Table 1. The sets of the parameter used to achieve the best result of ACO_R modelling

Parameters	Values
No of ant, $Nant$	22
Archive size, k	40
The locality of search, q	0.05
Speed of convergence, ξ	0.85
Iteration	500
Model order	4

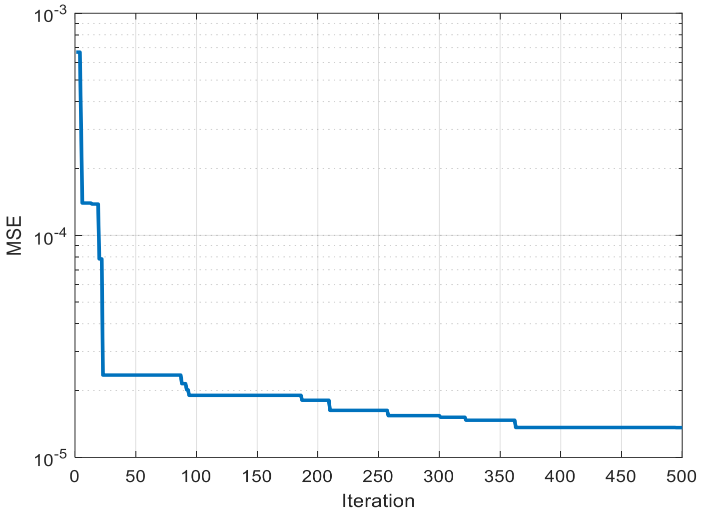
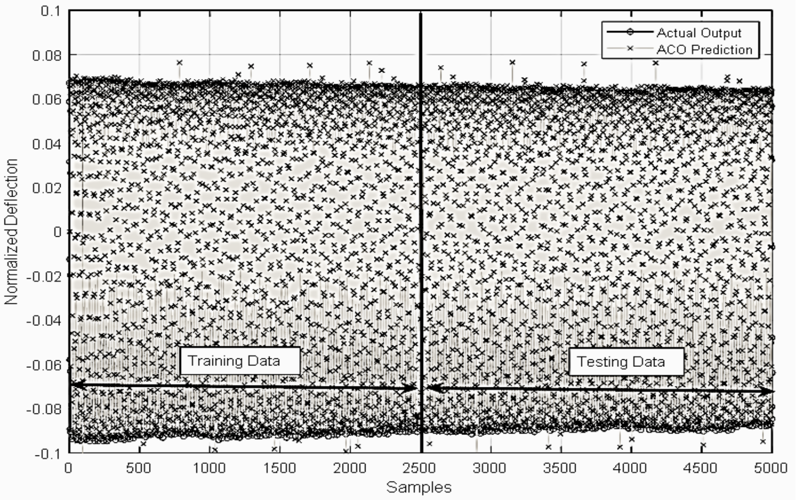
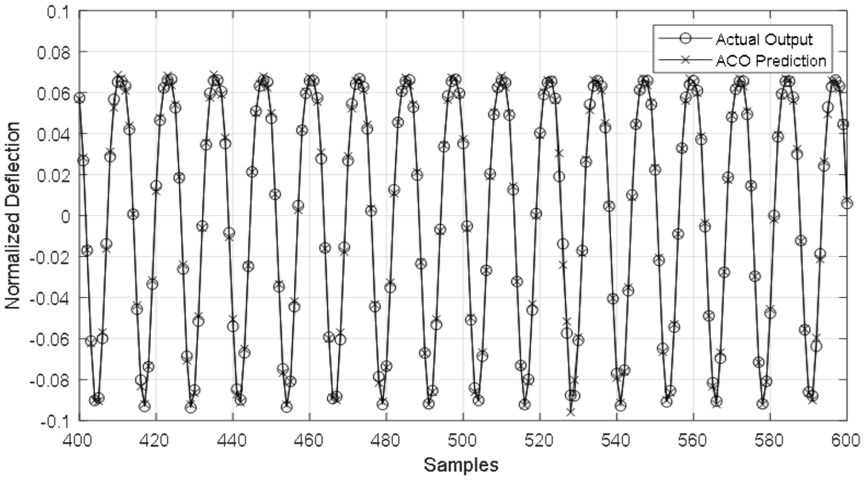


Figure 2. Convergence graph of ACO_R modelling



(a)



(b)

Figure 3. The time domain response of the actual and predicted outputs using ACO_R modelling (a) the sample data output for 5,000 and (b) the broaden view of the sample

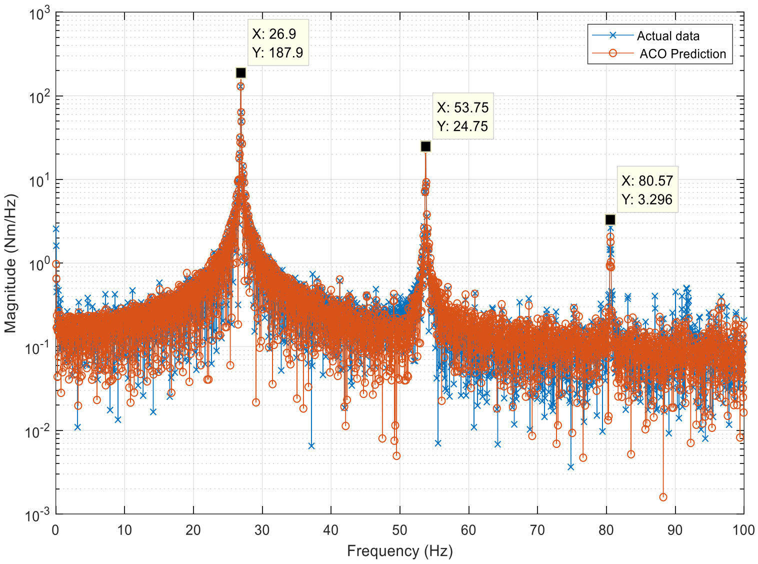


Figure 4. The frequency domain response for the actual and predicted outputs using ACO_R modelling

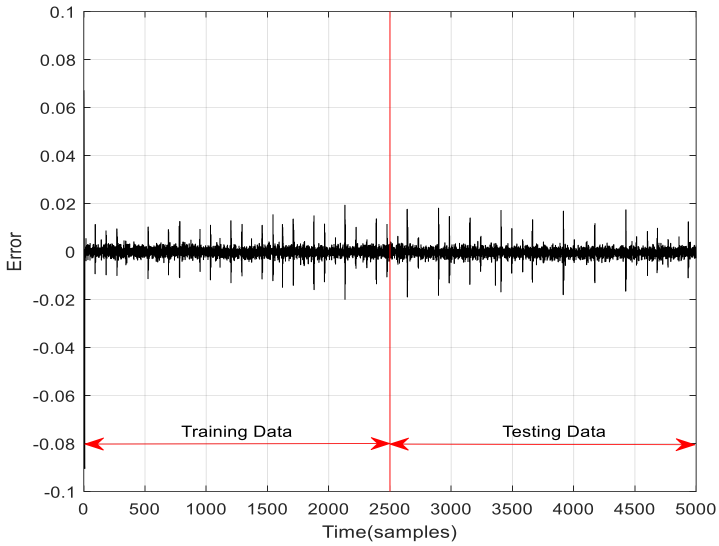


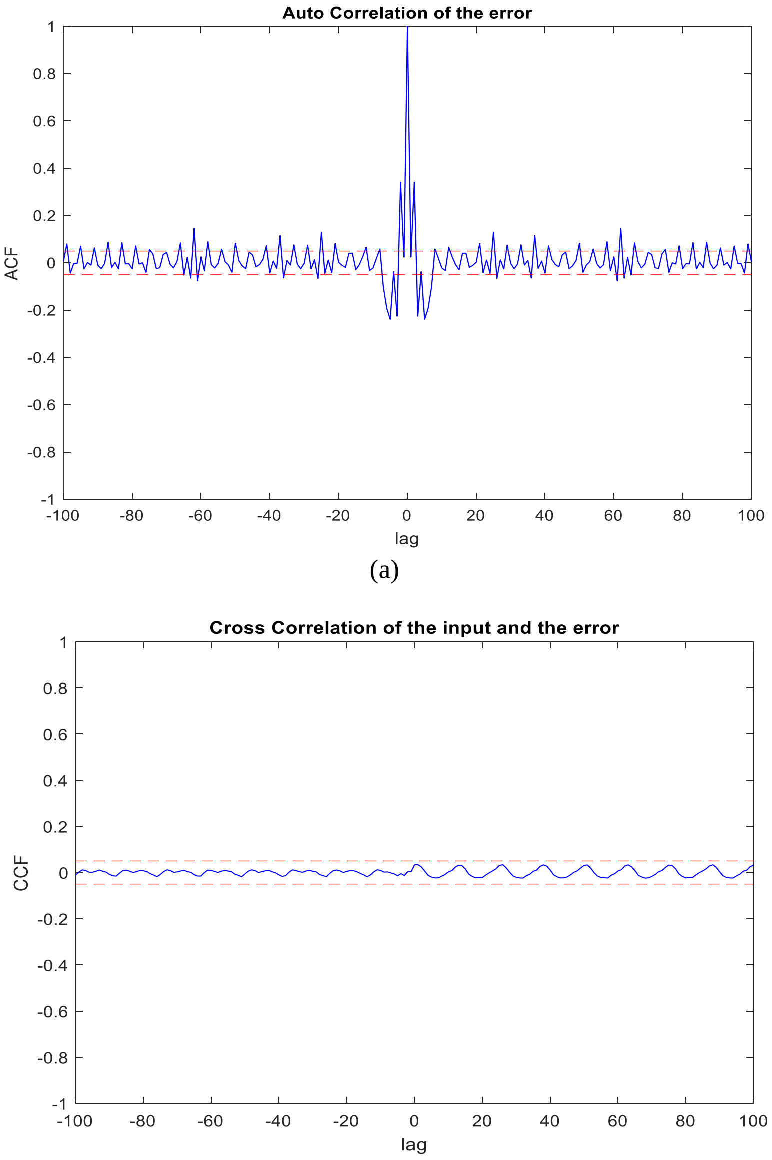
Figure 5. The error on ACO_R modelling

The correlation test and pole-zero plot stability for the best model in ACO_R modelling are illustrated in Figures 6 and 7, respectively. Two types of validations via auto and cross correlations are shown in Figure 6(a) and 6(b), respectively. The pole-zero plot indicated that the model was consistent when poles of transfer function were within the circle. The correlation test was performed to measure the developed model efficiency. The results of the correlation test in ACO_R modelling were unbiased as the responses are within the 95% of confidence level. The transfer function of the best model using ACO_R modelling is described in (5). This discrete transfer function of the ACO_R modelling is used for controller development.

$$\frac{y(t)}{u(t)} = \frac{0.07653z^{-1} - 0.05687z^{-2} + 0.6189z^{-3} - 0.5729z^{-4}}{1 - 1.032z^{-1} + 0.6442z^{-2} - 0.2162z^{-3} + 0.2859z^{-4}} \tag{5}$$

For the control strategy, the active vibration control (AVC) method was introduced to reduce vibration on the flexible plate system. The simulation of the AVC technique was utilized with a proportional integral derivative (PID) controller using the MATLAB/Simulink. The performance of the controller directly depended on the parameters of PID which is K_p,K_i and $K_{d.}$ Thus, these parameters were optimally tuned in order to achieve the desired system response. The heuristic strategy also known as the trial-and-error approach was used in the tuning process to get optimal values of PID parameters. The controller was tested by applying several types of disturbances including sinusoidal and multiple sinusoidal. Initially, the best model of a flexible plate system transfer function based ACO was used as the platform for the controller optimization process. After that, the parameter of PID was tuned until the maximum reduction of the first vibration mode on a flexible plate was obtained. The analysis of the PID controller was started using the sinusoidal disturbances to the flexible plate system. Figure 8 indicates the block diagram of the PID controller based on AVC with a single sinusoidal disturbance. The setting of the amplitude disturbance was set to 1 while the sample time was set to 0.003 s. Table 2 presents the optimum value of the PID parameter that was tuned heuristically. Based on the result, the value of kp, ki and kd are 0.9, 0.2 and 0.0010, respectively. The same set of PID parameters were applied to validate the performance of the controller for multiple sinusoidal disturbances.

For single sinusoidal disturbances, the findings obtained in Table 3 indicates that the PID controller has succeeded to attenuate the first vibration mode which is 6.19 dB. The controller has managed to reduce the attenuation value from 58.21 dB (before control) to 52.02 dB (after control), for which the percentage of vibration minimizing achieved by the controller was 10.63%. Figures 9(a) and 9(b) indicated the single sinusoidal disturbances on PID controller with the attenuation result in time and frequency domains.



(a)

(b)

Figure 6. Correlation test of ACO_R modelling (a) auto correlation and (b) cross correlation

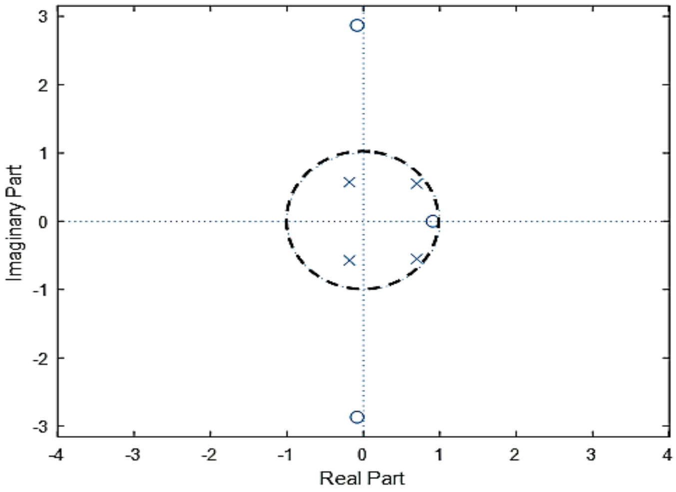


Figure 7. The result of the pole-zero plots of ACO_R modelling

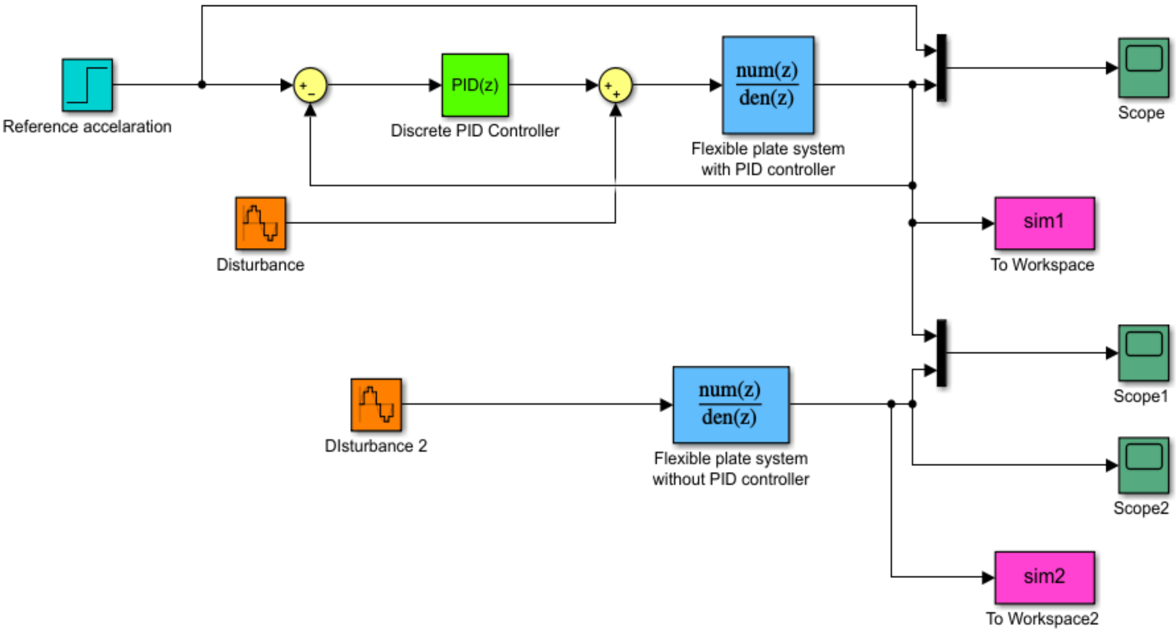


Figure 8. Block diagram of the PID controller based AVC under single sinusoidal disturbance

Table 2. The optimum value of the PID parameter tuned using heuristic method

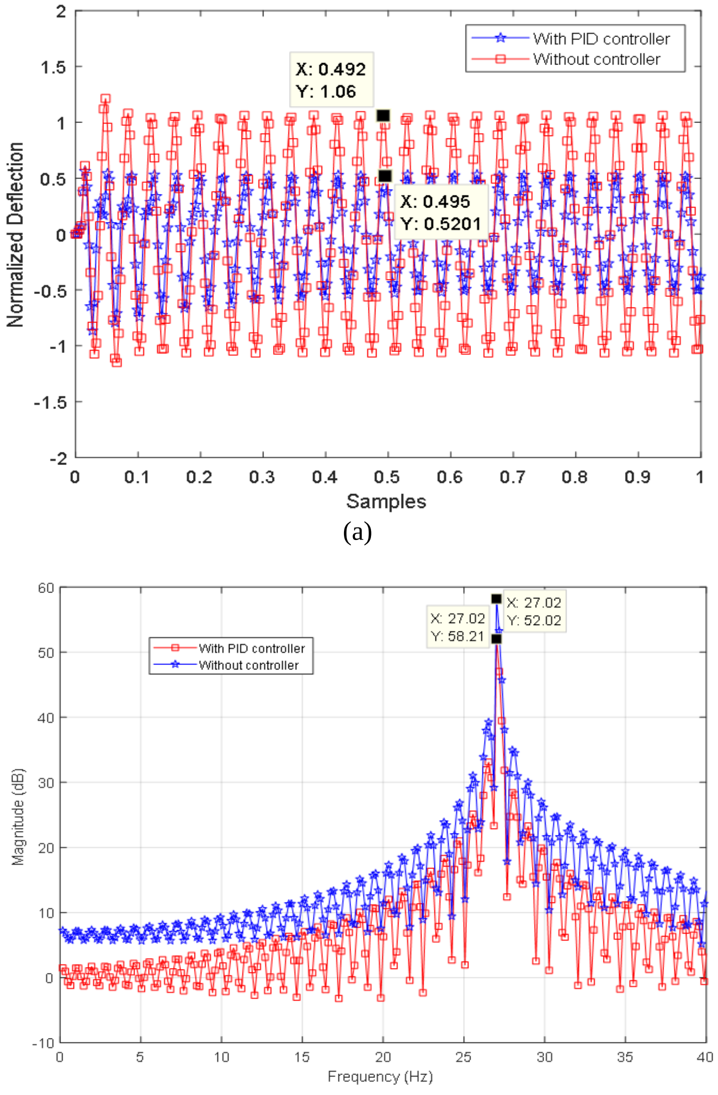
Controller	K_p	K_i	K_d
PID	0.9	0.2	0.0010

Table 3. The controller performance for single sinusoidal disturbances

Controller	Level of magnitude (dB) First mode	Reduction rate (dB) First mode	Reduction percentage (%) First mode
Without controller	58.21	-	-
PID	52.02	6.19	10.63

The study of the controller was continued by subjecting the system to multiple sinusoidal disturbances in order to verify the controller robustness. According to the objective of this study, the developed controller should be able to control the unwanted vibration under single and multiple sinusoidal disturbances by achieving the maximum reduction for the first mode vibration. From the result obtained in Table 4, the PID controller has achieved the maximum reduction level which is 6.19 dB.

The controller managed to suppress the magnitude of the first mode of vibration from 64.23 dB to 58.04 dB, for which the reduction percentage the controller achieved was 9.64%. Besides, the percentage of the reduction under multiple disturbances is found to be lower compared to the controller under a single sinusoidal disturbance. This shows that the controller performance under multiple disturbances is reduced when double disturbances were added to the system. However, the performance of the developed PID controller under multiple disturbances was still acceptable and logical. Figures 10(a) and 10(b) indicates the capabilities of the PID controller in time and frequency domains for multiple disturbances. The result of the PID controller with multiple disturbances was tabulated in Table 4.



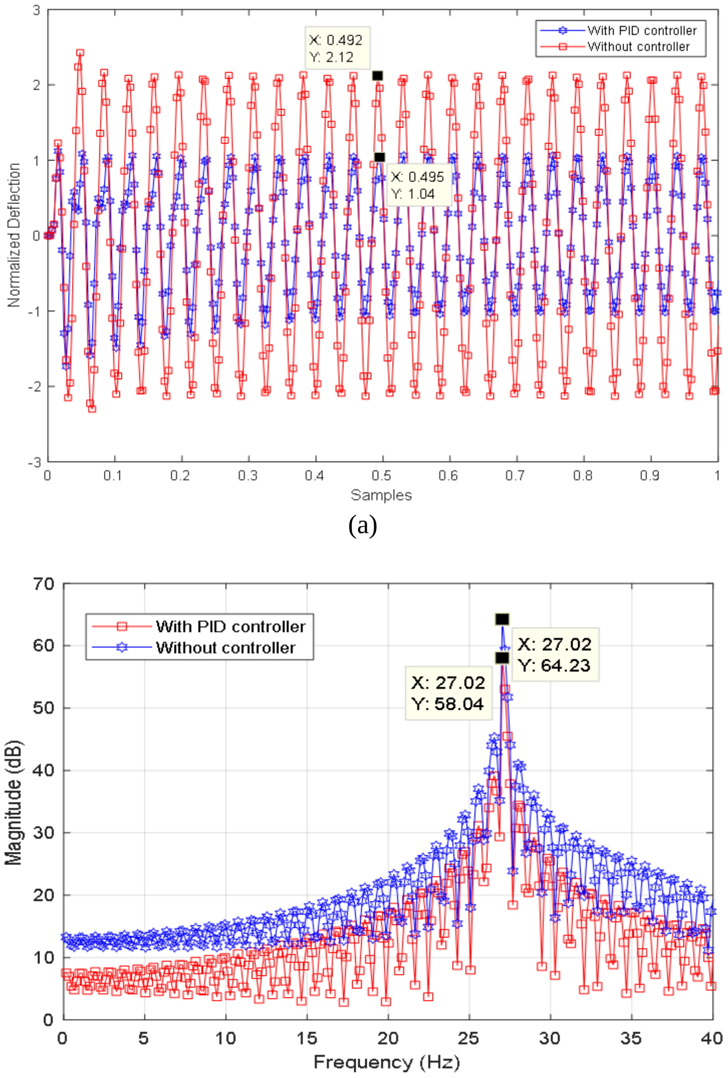
(a)

(b)

Figure 9. The PID controller response for single sinusoidal disturbance (a) time domain and (b) frequency domain

Table 4. The controller performance for multiple sinusoidal disturbances

Controller	Level of magnitude (dB) First mode	Reduction rate (dB) First mode	Reduction percentage (%) First mode
Without controller	64.23	-	-
PID	58.04	6.19	9.64%



(a)

(b)

Figure 10. The PID controller with multiple sinusoidal disturbances (a) time domain and (b) frequency domain

5. CONCLUSION

In this research, the dynamic system model was presented and discussed by utilizing a system identification technique via continuous ant colony optimization, ACO_R. The modelling results using ACO_R were achieved and evaluated for controller creation to minimize the undesired vibration on the flexible plate system. It showed that the flexible plate system was successfully modelled using the ACO_R algorithm by acquiring the minimum MSE, excellent correlation test, good stability of the pole-zero plot and simple model. The lowest MSE value was very essential for determining the precision of the developed model system and ensuring the robustness of the controller. Then, the best model based on ACO_R was implemented for the development of the PID controller. Other than that, the aforementioned controller based on the AVC technique has effectively reduced the undesired vibration on the flexible plate system by obtaining a decent reduction level for single and multiple disturbances at the first mode of vibration using MATLAB software. Nonetheless, the performance of the controller was affected as more disturbances were added to the system.

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