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Active vibration control of flexible beam system based on cuckoo search algorithm

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ABSTRACT

A flexible beam is recognized as a lightweight structure that is prone to excessive vibration, resulting in poor performance. Thus, controlling unwanted vibration is necessary to maintain the system's performance. Therefore, this study presents a technique to suppress undesired vibration in a flexible beam structure by introducing active vibration control (AVC). However, to develop an effective controller, an appropriate flexible beam model must first be obtained. In recent times, one of the best methods employed to model a flexible beam structure is system identification via a swarm intelligence algorithm. In this study, an intelligent algorithm acknowledged as cuckoo search (CS) was acquainted. The capability of the proposed algorithm was verified using three robustness techniques which were correlation test, pole-zero diagrams and mean square error (MSE). The simulation result showed that the CS algorithm achieved superior performance by achieving the lowest MSE of 6.1547×10^{-9}, a correlation test between a 95% confidence level and high stability. Next, a proportional-integral-derivative (PID) controller tuned by the Ziegler-Nichols method was developed using the transfer function accomplished from the CS model. Two types of interference, namely single and multiple sine waves were introduced to validate the effectiveness of the controller. The controller successfully achieved a 30.2 dB of attenuation level for both disturbances.

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1. INTRODUCTION

The use of flexible beam structures has been rising in many engineering applications such as spacecraft and large communication antennas [1]. The characteristics of a flexible beam is well understood among engineers as it is a fundamental element when designing a system. Although the usage of flexible beam resulted in lightweight devices, nonetheless, its long-term stability has become a vital issue. This system often undergoes large and undesirable displacement when subjected to load which induces high vibration levels [2]. Hadi *et al*. [3] stated that industries face many problems due to the excessive vibration and resonance in the plant which inhibits the system from achieving the desired level of performance. Therefore, by incorporating a good controller, it will improve the performance of the system. In order to design an effective controller, the development of a proper model should be done to portray the real features of the flexible beam structure.

Researchers have proposed numerous modeling techniques in the literature, namely finite difference method (FDM), finite element method (FEM), and system identification (SI) to model a system. In the early

1950s, FDM was used to model a regular geometry, specifically for rectangular or block-shaped models [4]. The employment of this method was implied in solving the neutron transport equation which is in an equilibrium state. The aforementioned method modeled the equation for both 1D and 2D systems on Cartesian geometry for spatial discretion. Since FDM ignored the boundary layer and was limited to model rectangular geometries only, FEM was used as an alternative in solving differential equation problems. Khot *et al.* [5] implemented a simplified system obtained from FEM to be used in proportional-integral-derivative (PID) based output feedback. However, huge numbers of mathematical equations meant computational calculation to model a system consumed a large amount of time [6]. FEM method was found to be inaccurate [7].

Recently, system identification (SI) techniques have exhibited the potential to model a flexible beam structure. System identification can be categorized into two, which are parametric and non-parametric identification. Parametric identification is where a model structure and its parameter are known while non-parametric identification has missing information on the structure or parameter [8]. Modeling using parametric and non-parametric models has been conducted by many researchers to compare their accuracy. Sovardi *et al*. [9] used large eddy simulation (LES) for both parametric and non-parametric identification in their study which was known as nonlinear acoustic scattering at duct discontinuities. The prediction of a physical system's behavior can be identified by creating the system model using this approach. Two methods have been identified to model a system, which are conventional and intelligence algorithms.

Nowadays, metaheuristic algorithms which are inspired by nature are emerging and becoming popular. Some examples include algorithms based on bats, fireflies, and cuckoo search (CS). Two key features of these algorithms are that they are based on environmental adaptation and selection of the fittest. Yang and Deb [10] utilized CS via Levy flights in their research. The study focuses on the combination of the Levy flights behavior for both fruit flies and birds with CS characteristics on the obligate brood parasite. Numerous academics have developed experiments employing this method for its intriguing breeding activity. Ghose [11] published a journal on speech recognition based on CS, inspired by the disruptive reproductive strategy of cuckoos. In addition, the estimated desired location by implementing CS positioning algorithm has been documented by Jiang *et al.* [12].

Control of excessive vibration can be achieved using various techniques, such as passive and active vibration control. Previously, countless studies have employed passive vibration control (PVC) to resolve vibration concerns. PVC is effective to reduce the response of rigid structures while active vibration control (AVC) can attenuate vibrations level in low-frequency systems [13]–[16]. Due to this, AVC has gained a lot of attention among researchers. The implementation of AVC in systems has increased rapidly in the past decades. The development of a hybrid controller based on fuzzy-PID was done by Hadi and Darus [3] to reduce the vibration on a horizontal flexible plate structure. Furthermore, Yiqi and Yiming [17] investigated the nonlinear dynamic responses on the piezoelectric functionality graded plate using the same controller. The employment of such controllers in smart devices such as piezoelectric further enhances the reputation of AVC techniques.

The purpose of this research is to develop a flexible beam model by utilizing swarm intelligence algorithm (SIA) via cuckoo search algorithm (CSA). These techniques are known as system identification (SI), which uses real input and output data collected from laboratory work. In pursuance of the superior efficiency of the developed model, three validations were applied to the system, which are mean squared error (MSE), correlation tests, and pole-zero diagram stability. Finally, the developed model using the proposed algorithm was utilized to design a controller for vibration suppression. The robustness of the controller was verified by exerting single and multiple disturbances.

2. EXPERIMENTAL SETUP FOR VIBRATION DATA COLLECTION

For this research, the input-output vibration data was extracted from an experiment conducted by Eek *et al*. [18]. A beam type cantilever which is made of aluminum with width, thickness, and length of 53, 1, and 600 mm, respectively was chosen as the model flexible beam structure, as presented in Figure 1. Twenty segments were evenly divided to represent the sensors' and actuators' positions as highlighted in Figure 2. Two actuators, namely disturbance actuators were placed in between segments 8^{th} and 9^{th}, and control actuators were placed in between segments 10^{th} and 11^{th}. The disturbance actuators were used to create a vibration on the flexible beam and the vibration created is controlled and reduced by the control actuator based on the output given by the controller.

Furthermore, two sensors known as observation and detection sensors were clamped onto the flexible beam structure. The input experienced by the beam was detected by the detection sensor. Meanwhile, the vibration and movement of the beam structure at the selected segments were observed by observation sensors. The detection sensors were placed on the segments between 9^{th} and 10^{th}, while the observation sensors were located at segments 19^{th} and 20^{th}. In addition, both sides of the beam structure were clamped with actuators and sensors using electrical components, namely piezoelectric patches.

Figure 1. The cantilever beam system [18]

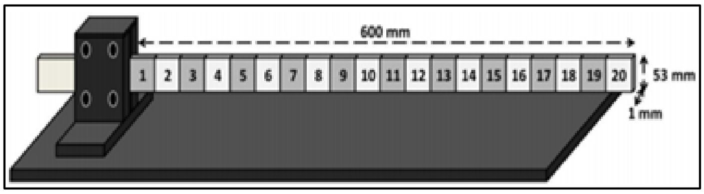


Figure 2. Segment division of cantilever beam [18]

Initially, the disturbance signal was generated from the personal computer to actuators after passing through the data acquisition (DAQ) system for digital-analog conversion. Next, the sine wave signal resulting from disturbances was transmitted to the amplifier in the form of voltage for amplification and moved along to the piezoelectric actuator. Then, piezoelectric patch starts to bend once the vibration was created from the voltage signal at the disturbance point on the beam. At the observation and detection nodes, the piezoelectric sensor measured the vibration and passed it to the DAQ system. Once the amplification using E-413 was completed, the extracted signal was analyzed by the computer. Finally, the storage of input-output data was saved in the MATLAB Simulink.

3. CUCKOO SEARCH ALGORITHM

Yang and Deb [10] introduced another swarm intelligence algorithm known as CS algorithm. This methodology was driven by cuckoos' tendency of laying their eggs in different nests from other bird species for survival. Normally, parasitic cuckoos locate their eggs in the nest belonging to other bird species that recently produced eggs for disguise purposes. Generally, the cuckoo eggs will hatch before the host nest eggs, increasing the likelihood of cuckoo offspring receiving food from the host bird. Furthermore, the ability of cuckoo offspring to mimic the host nest voice provides a significant benefit in securing sufficient food.

The technique from cuckoo breading behavior can be applied to solve optimization tasks, where each cuckoo egg laid in the host nest indicates a potential solution. Following that, the cuckoo will lay a second egg in the same nest to suggest another solution. The new lay egg, on the other hand, will be compared to the previous egg based on the host bird's likelihood of recognizing different eggs at their nest. The initial egg will only be replaced with a new one if the host nest detects an alien egg, which is considered the worst solution. The aim of the new solution is to generate a larger feasible solution, assuring the best possible discovery. Additionally, the quantity of eggs in the host nest will be governed by the objective function required in the optimization problem. In this research, only one objective function was set namely MSE, hence each nest will only consist of one egg.

The cuckoo's behavior can be standardized for execution strategy by three guidelines [19]. First, each cuckoo lays and throws one egg at a time into a random host nest. Second, the best nest, consisting of high-quality eggs, will be carried to the following generation. Third. the number of available host nests is fixed, and a host bird has a probability of $pa \in [0,1]$ of recognizing an alien egg. Due to this likelihood, the host bird has two options: either eliminate the egg or abandon the nest and construct a new one in a different region.

Each decision parameter for the initial position of the nests received a set of random values in the lower and upper bounds. Following that, the fitness was assessed by calculating the initial position of each nest, *n* using the objective function (1) [19]:

$$X_{ij} = LB + rand_{ij}.(UB - LB); i = 1, \dots, n; j = 1, \dots, mo \tag{1}$$

where X_{ij} is a number of nests representing the solution between the lower and upper bounds. Furthermore, a range of 0 and 1 was assigned to the expression and indicated as *rand*. The solution to the optimal task was performed in the following stage by generating a new generation of cuckoos. In this research, only one solution is needed, hence the number of cuckoos is equal to the number of nests. Two techniques namely, Levy flight and random walk were applied for the search space exploration. Levy flight, which consists of a probability distribution with random step lengths, is well-known as an efficient strategy for finding new solutions. It comprises of a sequence of straight-line flights followed by a sharp 90-degree turn. In CSA, Levy flights are accomplished using (2) [19]:

$$x_i^{(t+1)} = x_i^t + \alpha.S.(x_i^t - x_{best}^t).r \tag{2}$$

where x_i^t is the current individual position, α is a constant value of step size; r is a random number generated by a normal distribution, x_{best}^t is the current best nest; and S is a random walk employing Levy flights. As illustrated in (3), the step length S is calculated using a Mantegna algorithm [19].

$$S = \frac{u}{|v|^{1/\beta}} \tag{3}$$

where β is a variable that ranges from 1 to 2 and is held constant in this study at 1.5. The values of u and v can be calculated using normal distribution formula as stated in (4).

$$\sigma_u = \left\{\frac{\Gamma(1+\beta)\sin(\frac{\pi\beta}{2})}{\Gamma[\left(1+\frac{\beta}{2}\right)]\beta 2^{(\beta-1)/2}}\right\}^{1/\beta}, \sigma_v = 1 \tag{4}$$

Existing eggs were replaced by comparing their quality with a new egg generated from their present position using random walks with a step size using (5):

$$S = rand.(nests(randperm1(n), :) - nests(randperm2(n), :))$$
$$nest^{t+1} = nest^t + S.* P \tag{5}$$

where *randperm1* and *randperm2* are random permutation functions used for different rows, permutation is applied on nest's matrix, and P is the probability matrix.

4. RESULTS AND DISCUSSION

In this section, the results of modeling using CSA are discussed. Firstly, 3,334 data collected from the experiments were selected for model development. The data were divided into two groups, where both testing and training were assigned with 1,667 data. The best model was obtained by using the heuristic method. Lowest mean squared error testing (MSET), correlation test between 95% confidence level and good stability of root locus were used for best model selection. The best model of flexible beam structure was obtained by tuning the algorithm parameters accurately.

4.1. Modelling using cuckoo search algorithm

The numbers of nests, switching probability, lower and upper limit, model order, and iteration were tuned in this research. The first tuning was concentrated on the CSA parameters, then model order, and ultimately a number of iterations. For CSA parameters, the number of nests varied from 16 to 40, meanwhile, the other parameters were fixed to certain known values. For the number of nests, the values varied from 16 to 40, while other variables were kept constant. After that, numbers ranging from 0.01 to 0.5 were tuned to obtain the best results, followed by upper and lower limits ranging from [-1,1] to [-8,8]. Then, the model order values were varied from 2 to 10 and were tuned for model order. Finally, the iteration parameter was adjusted starting from 1,500-5,500 with 1,000 increments. The initial tuning values were decided based on previous research as a benchmark to speed up the tuning process and obtain the best model [20]–[25].

Table 1 summarizes the set of variables that were fine-tuned using the heuristic method to generate the optimum model for a flexible plate system using CSA. These parameters have met the required specification of the best model. Figure 3 shows the convergence graph of CSA in accomplishing the best model. The model managed to imitate the real system because the actual and predicted outputs overlapped each other.

The actual and simulation outputs for the structure in the time and frequency domains are illustrated in Figures 4 and 5, respectively. The highest mode of vibration experienced by the flexible beam structure is 34.6 dB as depicted in Figure 5. In addition, the error between the real and simulation outputs via CSA is demonstrated in Figure 6.

Table 1. The parameters for the optimum flexible beam system developed using CSA

Parameter	Value
Number of nests	20
Switching probability	0.01
Lower and upper limit	[-1 1]
Model order	3
Maximum generation	3500
Parameter number	6

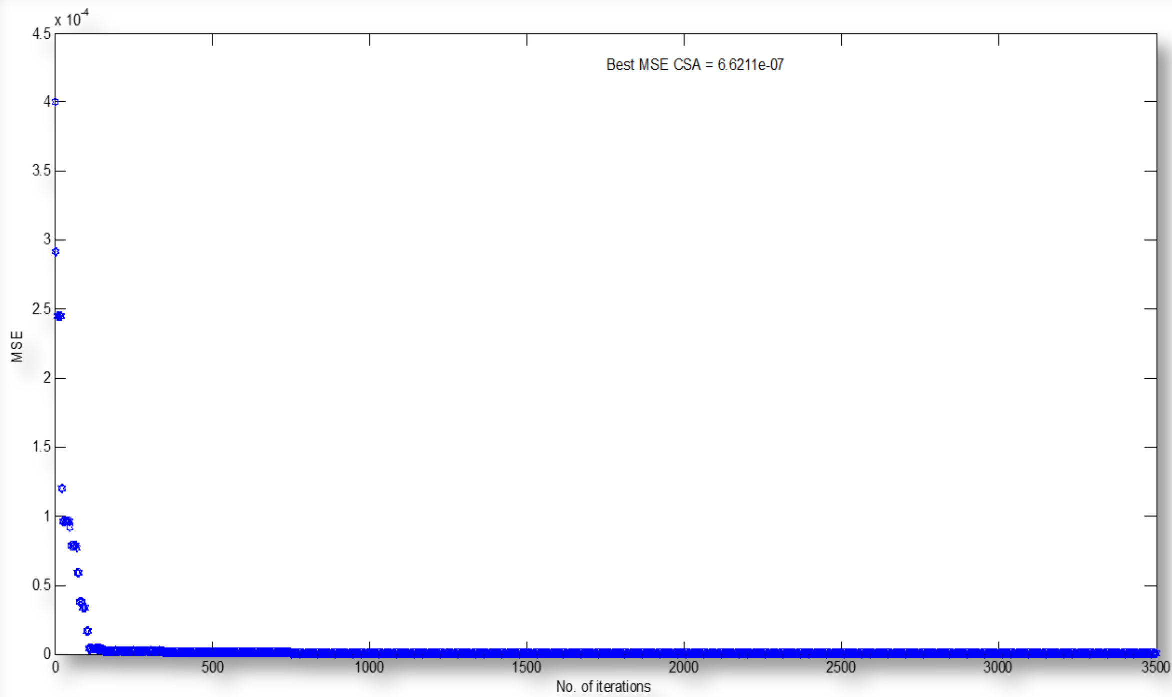


Figure 3. Mean squared error versus number of generations for CSA modelling

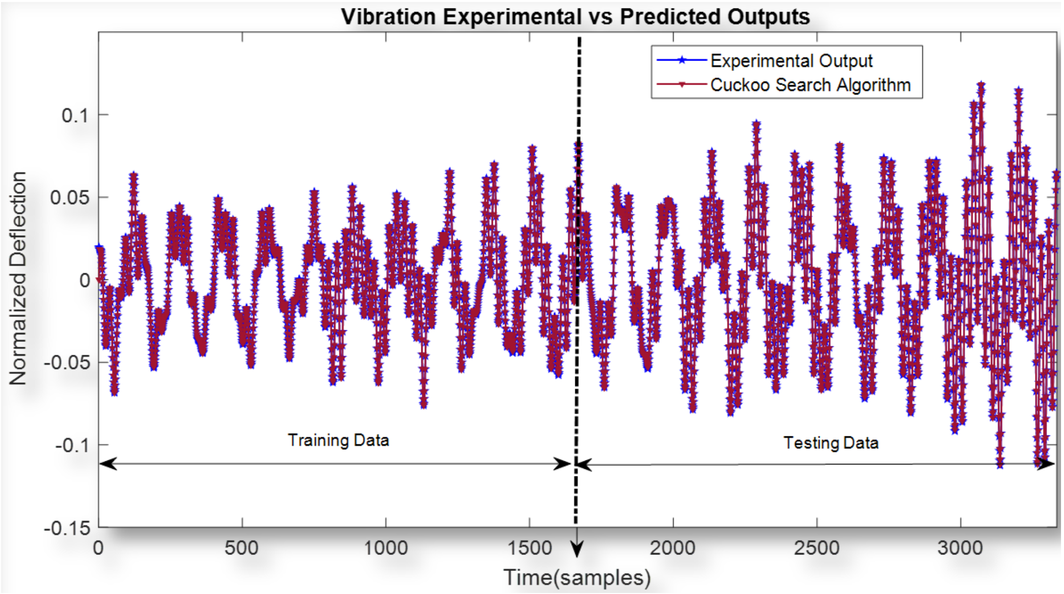


Figure 1. The flexible beam system using actual and CSA outputs in time domain representation

The pole-zero diagrams and correlation test for CSA modeling are shown in Figures 7 and 8, respectively. The correlation test in autocorrelation is shown in Figure 8(a), meanwhile cross-correlation is illustrated in Figure 8(b). The entire poles gained from model order 3 were visible inside the unit circle, indicating that the system is stable. The model appears to be unbiased in the correlation test as the confidence level is between the 95% interval. The optimum model of a flexible beam system developed via CSA modeling is stated in (6) in discrete transfer function form.

$$\frac{0.01802\, z^{-1} - 0.03256\, z^{-2} + 0.01555 z^{-3}}{1 - 2.917\, z^{-1} + 2.877\, z^{-2} - 0.9588 z^{-3}} \quad (6)$$

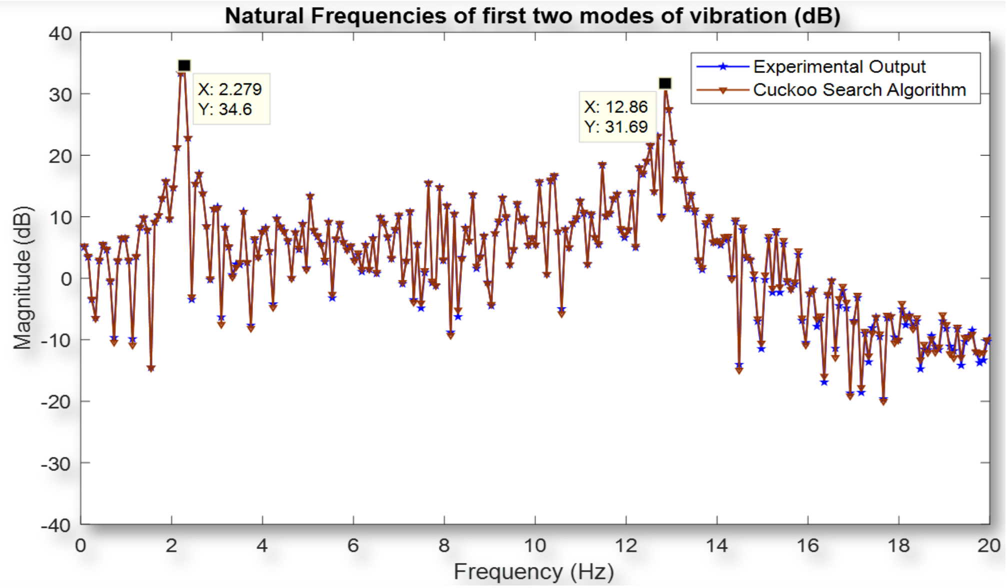


Figure 5. The flexible beam system using actual and CSA outputs in frequency domain representation

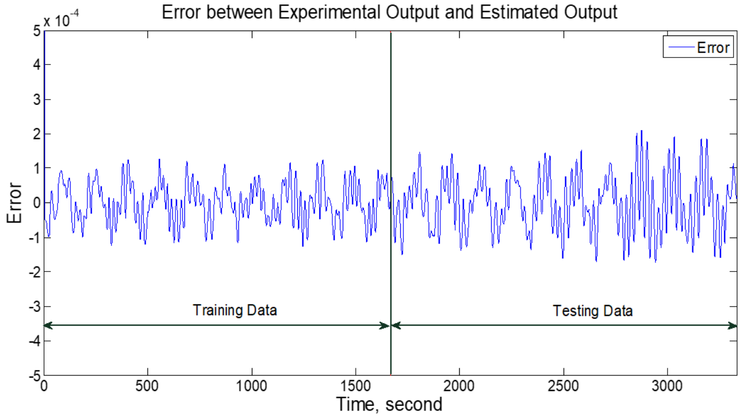


Figure 6. The errors between actual and estimated outputs for flexible beam system using CSA modelling

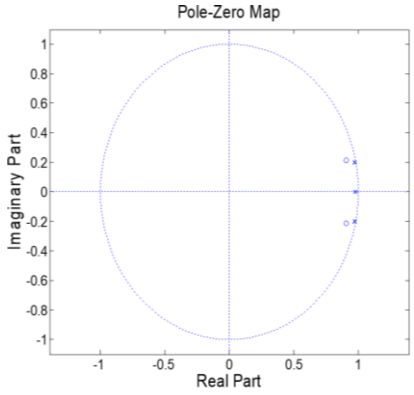
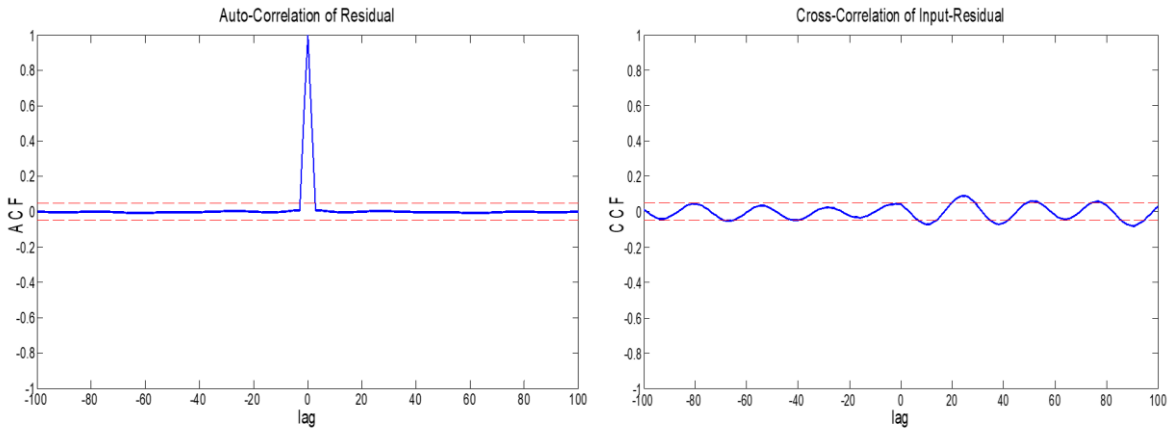


Figure 7. Pole-zero diagram stability for CSA modelling



(a) (b)

Figure 8. CSA model correlation test (a) autocorrelation and (b) cross-correlation

4.2. Development of PID controller using Ziegler-Nichols method

The development of a PID controller was introduced in this section after obtaining the discrete transfer function from the best model. The software used to analyze the robustness of the controller was MATLAB/Simulink 2018. Initially, a block diagram was created and the attenuation level was observed through the plotted graphs of time and frequency domains when the value of K_p, K_i, and K_d were inserted in the controller. The analysis started with a single sinusoidal disturbance in the system. Amplitude and frequency were set at 4 V and 2.279 Hz, respectively to represent the disturbance. After that, the system was introduced with multiple sinusoidal disturbances by using the same value of K_p, K_i, and K_d gained in the single sinusoidal disturbance.

The values of K_p, K_i, and K_d were tuned using Ziegler-Nichols (ZN) method. In the ZN method, the value of proportional gain, K_p was tuned by increasing the value from zero until it reaches the ultimate point. The ultimate point is referred to as the ultimate gain, K_{cr}, and period, P_{cr}. In particular, K_{cr} was the proportional gain, K_p before the system became unstable, and P_{cr} was the oscillation frequency period at this state. The period can be obtained from the peak-to-peak value in the time-domain graph as shown in Figure 9. Based on the tuning, the ultimate gain, K_{cr} was set to 110, and the period, P_{cr} achieved was 0.438 s. Next, these values were used in calculating the number of K_p, K_i, and K_d. The calculated values for K_p, K_i, and K_d are 66, 0.219 and 0.055, respectively. The results were mentioned in Table 2 and were used to suppress the vibration on the flexible beam structure under single and multiple sinusoidal disturbances.

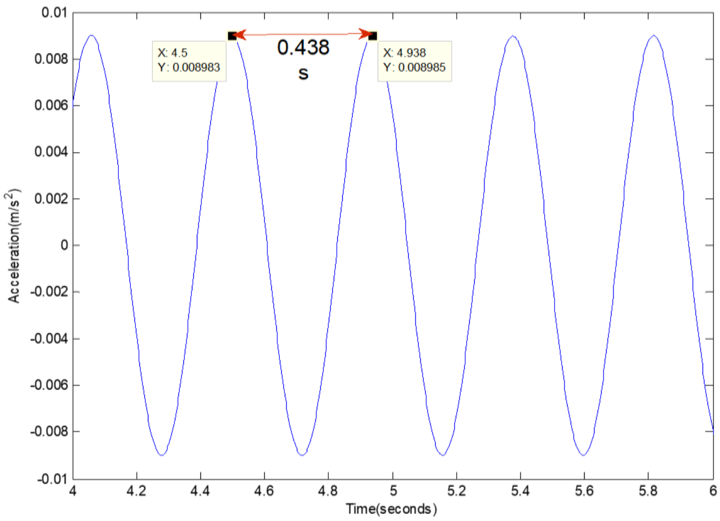


Figure 9. The sustained oscillation with period, P_{cr}=0.438 s when K_{cr} is set to 110

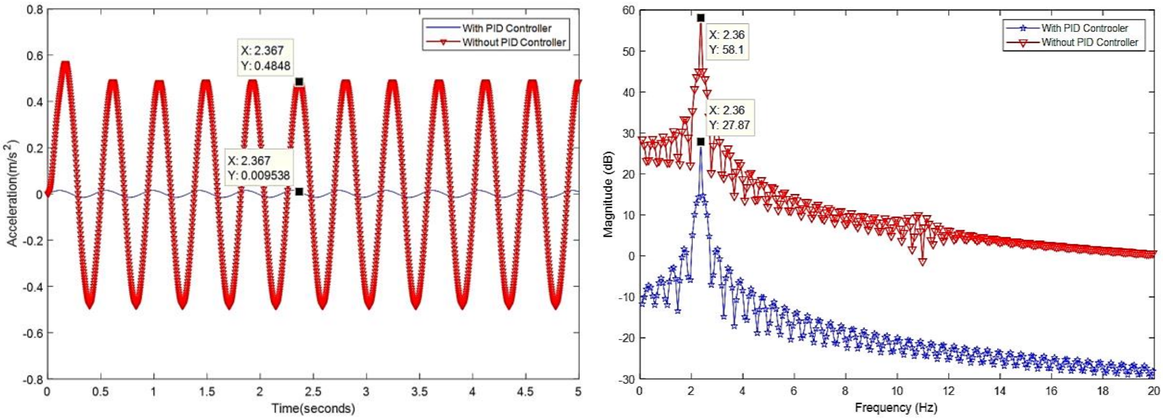
Table 2. The PID parameters obtained using ZN method

Controller	K_p	K_i	K_d
Without PID Controller	-	-	-
PID-ZN Controller	66	0.219	0.055

Initial studies were carried out with single sinusoidal disturbance for 10 s simulation run time to determine the attenuation level at the first mode of vibration using PID-ZN controller. The analysis reported that the PID-ZN controller successfully achieved superior attenuation at the first mode of vibration by 30.2 dB which is approximate to 52% percentage reduction from the uncontrolled system. The flexible beam has an attenuation value of 58.1 dB before the controller was introduced. The system managed to achieve an attenuation value of 27.87 dB after the implementation of the PID-ZN controller. The attenuation results of the PID-ZN controller under single sinusoidal disturbance in time and frequency domains are shown in Figures 10(a) and 10(b), respectively.

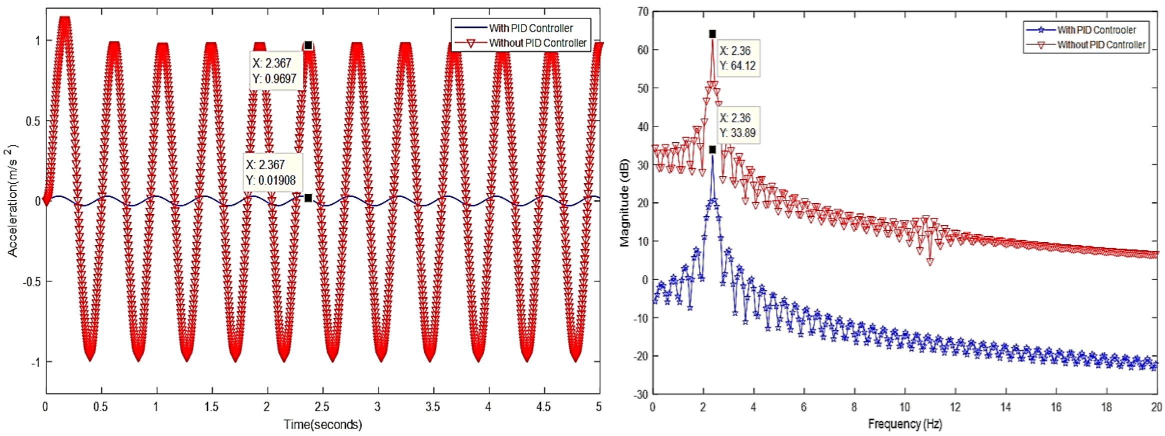
The simulation was then repeated under multiple disturbances to validate the capability of the developed controller. Figure 11 demonstrates the attenuation results of the PID-ZN controller under multiple sinusoidal disturbances in time and frequency domains as highlighted in Figures 11(a) and 11(b), respectively. The results further strengthened the ability of the PID-ZN controller because it managed to reduce the first mode of vibration from 64.12 to 33.89 dB. The percentage of reduction obtained was 47.1%.

The comparison between the decibel magnitude, the attenuation level in dB, and the percentage of reduction achieved by the controller at the first mode of vibration under single and multiple disturbances are tabulated in Table 3.



(a) (b)

Figure 10. The PID controller under single sinusoidal disturbance in (a) time domain (b) frequency domain



(a) (b)

Figure 11. The PID controller under multiple sinusoidal disturbance in (a) time domain (b) frequency domain

Table 3. The attenuation level achieved by PID controller at first mode of vibration using Ziegler-Nichols method

Disturbance	Controller	Decibel Magnitude (dB)	Attenuation Level (dB)	Percentage of Reduction (%)
Single Sinusoidal	No controller	58.1	reference	reference
	PID-ZN controller	27.87	30.2	52%
Multiple Sinusoidal	No controller	64.12	reference	reference
	PID-ZN controller	33.89	30.2	47.1%

5. CONCLUSION

CSA was developed to model a flexible beam structure. The purpose of modeling was to obtain the real characteristics of the flexible beam structure for vibration suppression. Thus, in this study, the transfer function from the best model was used as a platform for controller development. The performance of the developed models was validated using three criteria, which are correlation tests, pole-zero diagrams, and MSE. The algorithm that achieved the lowest MSE, correlation test within a 95% confidence level, and great stability in the pole-zero diagram was selected to represent the flexible beam characteristics. The validation results revealed that CSA model has an acceptable MSE and superior stability. In addition, this technique shows a clear difference in terms of correlation tests where it can be concluded that the developed model meets the overall validations set. Thus, the accomplishment of modeling a system via CSA successfully justified the first objective of this research. The transfer function obtained from the best model was used for the vibration suppression using a PID controller. The performance of the PID controller was validated by exerting two types of disturbances, namely single and multiple sinusoidal to the system based on the identified model. The simulation results demonstrated that the PID-ZN was found to present a remarkable attenuation level at the first mode of vibration with 30.2 dB. Therefore, the findings from the controller implementation have met the second objective of this study.

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