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Active Vibration Control of Flexible Beam using Differential Evolution Optimisation

Mohd Sazli Saad, Hishamuddin Jamaluddin and Intan Zaurah Mat Darus

***Abstract*—**This paper presents the development of an active vibration control using direct adaptive controller to suppress the vibration of a flexible beam system. The controller is realized based on linear parametric form. Differential evolution optimisation algorithm is used to optimize the controller using single objective function by minimizing the mean square error of the observed vibration signal. Furthermore, an alternative approach is developed to systematically search for the best controller model structure together with it parameter values. The performance of the control scheme is presented and analysed in both time and frequency domain. Simulation results demonstrate that the proposed scheme is able to suppress the unwanted vibration effectively.

***Keywords*—**flexible beam, finite difference method, active vibration control, differential evolution, direct adaptive controller

I. INTRODUCTION

VIBRATION control has been widely applied in many applications including automotive, aircraft, electrical machinery and civil structures. Vibration occurs whenever a mechanical mechanism is moved intentionally or unintentionally. The unwanted vibration may cause damage to structures or degradation to system's performance. Therefore, many attempts have been proposed to reduce this unwanted disturbance by considering passive and active controls. Passive vibration control methods work well at high frequencies or in a narrow frequency range but often have the disadvantage of added weight and poor low frequency performance. Meanwhile, the potential of Active Vibration Control (AVC) to solve the problem has been demonstrated [1].

The concept of AVC was initially proposed by Lueg [2] for noise cancellation. AVC works based on artificially generating the cancellation signal to absorb the unwanted disturbance force that can reduce the effect of vibration to the system. Vibration suppression in AVC can be achieved by detecting and processing via suitable control schemes, thus the superimposed disturbance signals will cancel out the actual disturbance force. Several strategies based on closed-loop control scheme have been proposed in AVC system such as sliding mode control (SMC), fuzzy control (FC), self-tuning control and intelligent algorithms [3]-[4].

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AVC problem of flexible beams has attracted significant interest due to its generic nature and easily applied in many practical problems such as robot manipulators, aircrafts, electrical machines and civil structures. The development of various control strategies has been widely studied where the performance of the control schemes has been analyzed via simulation and experimental studies. Haichang and Song [5] proposed robust model reference controller and shown the robustness and effectiveness of the proposed method even in the presence of varying modal frequency due to changes in the mass of the flexible beam. Itik *et al.* [3] employed sliding mode control and H infinity control schemes using state space modeling approach. By performing experimental identification method, an estimated transfer function which represents the system was formed. The two control strategies were applied to the same system and the experimental results showed the success of the control approaches. Fei [6] also revealed that, the used of adaptive feed-forward sliding mode control and model reference adaptive sliding mode control are effective in vibration suppression problem.

Evolutionary algorithms have proven to be one such popular alternative in active vibration control optimization since the last two decades [7]-[8]. The evolutionary algorithm (EA) is a robust search and optimization methodology that is able to cope with ill-behaved problem domains, exhibiting attributes such as multimodality, discontinuity, time-variance, randomness, and noise. Recently, a group of researchers have come out with direct adaptive control using EA as controller optimization method. This controller has been created based on the indirect controller optimization initially proposed by Tokhi and Hossain [9]. For indirect controller optimisation method, controller is designed based on the identified model. The performance of this controller depends on how accurate the model is identified. But, for direct controller optimisation, it's performance depends on the ability of optimisation algorithms to produce the best global minimum of the fitness value. The effectiveness of indirect and direct optimization controller in suppressing the unwanted vibration has been demonstrated in simulation platform using FD methods. Hashim *et al.* [10] investigated the development of direct adaptive controller used genetic algorithm (GA) as the optimisation algorithm in AVC of flexible beam system. A significant amount of vibration cancellation over a broadband of frequencies has been achieved. Julai *et al.* [11]proposed active vibration control (AVC) of a flexible plate structure using continuous ant system algorithm (CASA). Julai *et al.* [12] also developed a direct PSO-AVC mechanism which involves direct optimization of the controller parameters based on minimization of the error signal (observed signal). This approach does not require knowledge of the input/output characterization of the system for controller design. Mohamad *et al.* [13] presented the utilization of continuous ant colony optimization algorithm intended for active vibration control of flexible beam structures. The performance of the system was presented in both time and frequency domains and the simulation results reveal that good performance is achieved using this approach.

Recently, differential evolution (DE) has been found to be a promising algorithm in numerical optimization problems. DE has been designed to fulfill the requirement for practical minimization technique such as consistent convergence to the global minimum in consecutive independent trials, fast convergence, easy to work with, as well as ability to cope with non-differentiable, non-linear and multimodal cost functions [14]. Therefore, the algorithm has gained a great attention since it was proposed. Ruijun [15] studied the performance of DE and particle swarm optimization (PSO) in optimizing PID controller for first order process. DE has found to be more robust (with respect to reproducing constant results in different runs) than PSO. Pishkenari [16] utilized DE algorithm to optimize the membership functions of a fuzzy controller for mobile robot trajectory tracking where the performance of the optimized controller is better than the traditional fuzzy controller. Yousefi *et al.* [17] applied DE algorithm to find the best values for the unknown parameters of a servo-hydraulic system with a flexible load. Results have revealed that DE algorithm accurately identified the time delay, structure and parameters of the system with a fast convergence rate. Youxin and Xiaoyi [18] has applied DE algorithm in tuning the PID controller for electric-hydraulic servo system of parallel platform. Simulation results show that the optimized PID controller has improved the performances of the electric-hydraulic servo system.

This research aims to provide an alternative control scheme using direct optimisation controller based on differential evolution algorithm in attenuating the unwanted vibration of flexible beam system. The parameters in linear parametric controller structure is optimize based on mean square error of the observed signal. In this method, the control design does not require knowledge of the input/output characteristics. The proposed control scheme used the random search capability of DE to directly update the required controller characteristic based on measurement the observed signal and is very likely to achieve the global minimum in the performance index surface. Furthermore, an alternative method has been proposed in order to select the best controller model structure and its parameter using optimization EA algorithm.

The rest of the paper is structured as follow: Section 2 briefly describes the fundamental theory of DE , Section 3 describes a flexible beam system and the development of a simulation environment characterising its dynamic behavior for use as a platform for test and verification of the proposed control approach, Sections 4 and 5 respectively introduce the proposed DE based active control system design and presents the implementation of the proposed strategy, Section 6 presents the associated results in a flexible beam system, and finally the paper is concluded in Section 7.

II. Differential Evolution Algorithm

Differential evolution (DE) algorithm is a stochastic, population-based optimization algorithm recently introduced. Unlike simple GA that uses binary coding for representing problem parameters, DE uses real coding of floating point numbers. The crucial idea behind DE is a scheme for generating trial parameter vectors. Basically, DE adds the weighted difference between two population vectors to a third vector.

The key parameters of control are: *NP* - the population size, *CR* - the crossover constant, *F* - the weight applied to random differential (scaling factor). It is worth noting that DE's control variables, *NP*, *F* and *CR*, are not difficult to choose in order to obtain promising results. The proposer of DE has come out with several rules in selecting the control parameters. The rules are listed below:

1) At initialization the population should be spread as much as possible over the objective function surface.
2) Frequently the crossover probability $CR \in [0,1]$ must be considerably lower than one (e.g. 0.3). If no convergence can be achieved, $CR \in [0.8, 1]$ often helps.
3) For many applications $NP=10\times D$ is a good choice. *F* is usually chosen at [0.5, 1].
4) The higher the population size *NP* is chosen, the lower one should choose the weighting factor *F*.

These rules of thumb for DE's control variables which is easy to work with is one of DE's major contribution [14]. The detailed Differential Evolution algorithm used in the present study is explained in section 5.

III. Modeling of the Flexible Beam System

A flexible beam of length, *L*, in fixed-free mode is considered. A schematic diagram of the flexible beam is shown in Fig. 1. Force is applied at distance, *x*, from the fixed end at time, *t*, and the resulting deflection from it's stationary position is denoted by $u(x,t)$ and $y(x,t)$ respectively. The motion of the beam in transverse vibration is formulated by fourth-order partial differential equation (PDE) that yields the following equation[9]:

$$\mu^2 \frac{\delta^4 y(x,t)}{\delta x^4} + \frac{\delta^2 y(x,t)}{\delta x^2} = \frac{1}{m} u(x,t) \qquad (1)$$

where $u(x,t)$ is the actuating force applied at a distance, *x*, from its fixed end at time, *t*, $y(x,t)$ is the beam's deflection at a distance, *x*, from its fixed end at time, *t*, μ is the beam constant represented by $\mu^2 = \frac{EI}{\rho A}$, with *E*, *I*, ρ and *A* representing Young's modulus, moment of inertia, mass density and cross-sectional area respectively, and *m* is the mass of the beam. The model in (1) does not have damping, so there is no energy loss in the model mathematically. The boundary conditions at fixed and free end of the beam are given by:

$$y(0,t) = 0$$

$$\frac{\delta y(0,t)}{\delta x} = 0$$

$$M(L,t) = \frac{\delta^2 y(L,t)}{\delta x^2} = 0$$

$$V(L,t) = \frac{\delta^3 y(L,t)}{\delta x^3} = 0 \qquad (2)$$

where M and V represent shear and bending moments of the beam respectively.

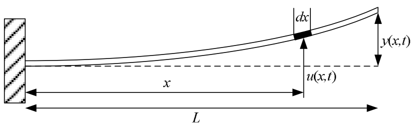


Fig. 1 Schematic diagram of a flexible beam system

Finite difference (FD) method is chosen to obtain the numerical solution of the PDE in (1). Simulations of flexible plate and beam via FD method are easy to implement and the method has been proven effective in investigating dynamics behavior of structures [4], [19]-[20] . The beam is discretized into a finite number of equal-length sections (segments), each of length, Δx, and the deflection of beam at the end of each segment is sampled at a constant time, Δt. By using first-order central finite difference, the PDE in (1) becomes:

$$Y_{j+1} = -Y_{j-1} - \lambda^2 S Y_j + \frac{\Delta t^2}{m} U(x,t) \qquad (3)$$

where $U(x,t)$ is an $n\times 1$ matrix which represents the actuating force applied on the beam, Y_k, ($k = j-1$, j, $j+1$) is an $n\times 1$ matrix which is the deflection of the beam at segment 1 to n at time step k and S is known as stiffness matrix, which give the characteristic of the beam and $\lambda^2 = \left[\frac{(\Delta t)^2}{(\Delta x)^4}\right]\mu^2$. The dynamic behavior of the beam can be simulated using (3), which can be programmed easily via any digital programming software. In this research, Matlab software was used to model (3). The simulation platform is designed so that user can easily study the cases of any number of segments, length of the beam, different excitation signals and other simulation requirements.

Before executing the simulation model, the parameters of the beam given in Table 1 were set into the Matlab script. Then the sampling time was set to be 0.3 ms in order to satisfy the convergence requirement for the simulation in which λ^2 must be properly chosen between $0 < \lambda^2 \leq 0.25$ [21]. The above sampling time is also sufficient to cover a broad range of dynamics of the flexible beam.

TABLE I
BEAM SPECIFICATIONS

Parameter	Value
Number of segment	20
λ	0.3629
Mass	0.037 kg
Length	0.635 m
Beam constant	1.351

IV. Direct Adaptive Control Scheme

Direct adaptive controller scheme using differential evolution algorithms is used in active vibration control for flexible beam. The aim of this controller is to suppress the unwanted vibration of the beam by means of optimisation method. Fig. 2 illustrates the block diagram of active vibration control using differential evolution direct optimisation controller scheme. An unwanted disturbance signal emits broadband disturbance into the structure which is detected by a detector. Then, the detector senses the disturbance signal and feed to a controller. The controller will determine the amount of actuator signal to reduce the level of vibration at an observation point along the structure.

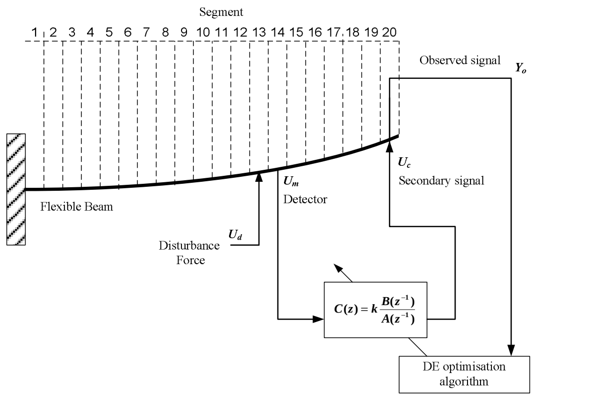


Fig. 2 DE AVC of flexible beam using DE direct adaptive controller

In this study, the aim of the controller design is to minimize the deflection Yo via the actuator forcing signal, U_C for generating anti-phase control signal to counteract the vibration produced by U_D. Optimal vibration reduction can be achieved by DE optimisation method based on the observed signal Y_O. The controller is realized in a linear parametric form as:

$$U_C(t) = -a_1 U_C(t-1) - a_2 U_C(t-2) - \cdots - a_n U_C(t-n) + b_0 U_M(t) + b_1 U_M(t-1) + \cdots + b_0 U_M(t-m) \qquad (4)$$

where n and m are the order of lags for the denumerator and numerator of the controller model order structure.

DE optimisation method is designed in such that it can be used to find the best controller structures as well as its parameter in order to yield optimum cancellation of broadband vibration at the observation point along the beam. The fitness function used in the optimisation algorithm is based on the mean square error of observed deflection signal, Y_O which is formulated as:

$$f(e) = \frac{1}{N}\sum_{i=1}^{N}(|Y_o|)^2 \qquad (5)$$

where N represents the number of output samples. With the fitness function, the global search technique of the DE is utilized to obtain the best parameters and order structures of the controller.

V. Implementation of DE Controller Optimisation

Differential evolution (DE) algorithm is a heuristic optimization algorithm recently introduced. Unlike simple GA that uses binary coding to represent the parameters, DE uses real coding of floating point numbers. The crucial idea behind DE is a scheme for generating trial parameter vectors. Basically, DE adds the weighted difference between two population vectors to a third vector.

The key parameters of control are: *NP* - the population size, *CR* - the crossover constant, *F* - the weight applied to random differential (scaling factor). It is worth noting that DE's control variables, *NP*, *F* and *CR*, are not difficult to choose in order to obtain promising results. Storn [22] have come out with several rules in selecting the control parameters. The rules are listed below:

1) The initialized population should be spread as much as possible over the objective function surface.
2) Frequently the crossover probability $CR \in [0,1]$ must be considerably lower than one (e.g. 0.3). If no convergence can be achieved, $CR \in [0.8, 1]$ often helps.
3) For many applications $NP=10\times D$, where D is the number of problem dimension. F is usually chosen at [0.5, 1].
4) The higher the population size, *NP*, the lower the weighting factor *F* should choose.

These rules of thumb for DE's control variables which is easy to work with is one of DE's major contribution [14].

The detailed Differential Evolution algorithm used in tuning the PID controller is presented below:

A. Setting DE Parameter Optimisation

All the DE optimization parameter required for optimization process is listed below:

- *D* – problem dimension
- *NP*, *CR*, *F* – control parameters
- *G* – Number of generation/stopping condition
- *L*,*H* – boundary constraints

In this study, population size, NP = 65, crossover constant, CR = 0.8, mutation constant, F = 0.5, and the number of generation G = 100. The problem dimension, D is set based on the number of controller parameters, numerator order, denumerator order and controller gain, k, used in the objective function. In the previous study, controller model order selection has been done by a trial-and-error method. Now, an alternative approach has been developed to systematically search for the best controller model structure together with it parameter values. The range for controller model order has been set from 0 to 5 (m = n = 0 to 5) which mean the problem dimension, D = 13. Fig. 3 illustrates the individual of solution space in problem dimension. Individual in problem dimension, D:

k	a_1	a_2	a_3	a_4	a_5	b_1	b_2	b_3	b_4	b_5	m	n

Fig. 3 Problem dimension

The boundary constraint is set based on the individual parameter range. For example, controller parameters a and b are set at the interval of [-1, 1], it means that low boundary, L = -1 and high boundary, H = 1. Details information about DE initial setting is shown in Fig. 4.

```
D=13; %dimension of problem
NP=65; %Population size
F=0.5; %differentiation constant
CR=0.8; %crossover rate
GEN=100; %generations
%order
Lm=1; %low boundary constraint 1Kp
Hm=5; %high boundary constraint 1
Ln=1; %low boundary constraint 2a1
Hn=5; %high boundary constraint 2
%parameter
L1=0; %low boundary constraint 1Kp
H1=1000; %high boundary constraint 1
L2=-1; %low boundary constraint 2a1
H2=1; %high boundary constraint 2
L3=-1; %low 0boundary constraint 3 a2
H3=1; %high boundary constraint 3
L4=0; %low 0boundary constraint 4 b1
H4=1; %high boundary constraint 4
```

Fig. 4 DE parameter setting

B. Vector Population Initialisation

Initialize all the vector population randomly in the given upper and lower bound and evaluate the fitness of each vector.

$$Pop_{ij} = L + (H - L).\mathrm{rand}_{ij}(0,1), \quad i = 1,...,D, j = 1,...,NP. \qquad (6)$$

$$Fit = f(Pop_j) \qquad (7)$$

Before the optimization is launched the population needs to be initialized and its fitness function needs to be evaluated. The population is initialized randomly within its boundary constraints is done using (6). Each of the individual in the population is used to compute the fitness value which referred as MSE. The fitness value is computed by the fitness function as in (7) which is referring to active vibration control of flexible beam. Fig. 5 shows the block diagram of population and its corresponding fitness value. For example, if control parameters, a and $b \in [-1, 1]$, controller gain, $k \in [0, 1000]$, and controller model order, m and $n \in [1, 5]$, population and fitness values are calculated as:

For controller gain, $k \in [0, 1000]$,
$$Pop_{1,1} = 0 + (1000 - 0)rand_{1,1}(0,1)$$
$$Pop_{1,1} = 688.8 = k$$

For parameter, $a_1 \in [-1, 1]$,
$$Pop_{1,2} = -1 + (1 - (-1))rand_{1,2}(0,1)$$
$$Pop_{1,2} = 0.5944 = a_1$$

For controller model order, m $\in [1, 5]$,
$$Pop_{1,12} = 1 + (5 - 1)rand_{1,12}(0,1)$$
$$Pop_{1,12} = 10.4714 = m$$

Then, the value of individuals are sent to the objective function which is the AVC of flexible beam system to compute for fitness value (refer to Fig. 5 below).

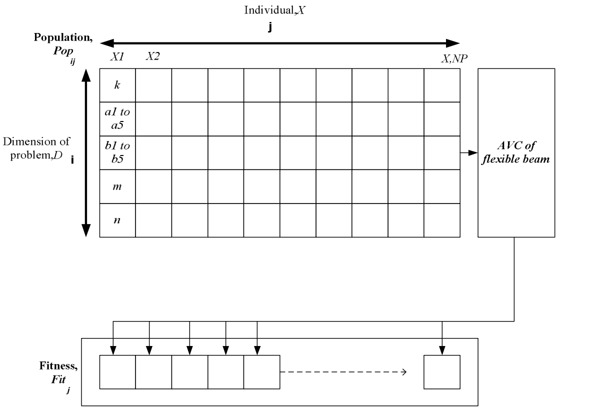


Fig. 5 The block diagram of population and its corresponding fitness value

C. Perform Mutation and Crossover

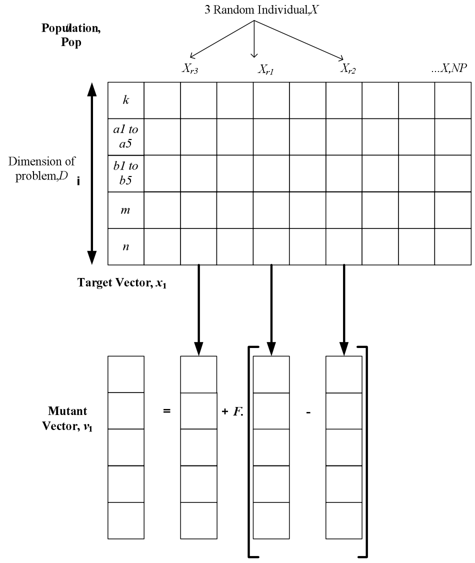
Whenever initialization process is done, the optimization process is executed. The optimization process will run iteratively until the end of generations. By referring to Fig. 6, the first individual fitness value from the current population is set to be the target vector. Then the trial vector is created by selecting three individuals randomly from the current population, mutate using (8) and crossover with the target vector. The fitness value (MSE) of the trial vector is computed by sending its individuals to the fitness function.

i) Mutant vector

For each vector $x_{j,G}$ (target vector), a mutant vector is generated by:

$$v_{j,G+1} = x_{r3,G} + F.(x_{r1,G} - x_{r2,G}) \tag{8}$$

Where the three distinct vectors x_{r1}, x_{r2} and x_{r3} randomly chosen from the current population other than target vector $x_{j,G}$. The detail example how the mutant vector is determined is shown in Fig. 6.



$$v_{j,G+1} = x_{r3,G} + F.(x_{r1,G} - x_{r2,G})$$

Fig. 6 Mutation process

ii) Crossover

Perform crossover for each target vector with its mutant vector to create a trial vector $u_{j,G+1}$.

$$u_{j,G+1} = (u_{1j,G+1}, u_{2j,G+1}, \ldots, u_{Dj,G+1})$$

$$u_{ij,G+1} = \begin{cases} v_{ij,G+1} & \text{if } (\text{rand}_i \le CR) \vee (\text{Rnd} = i) \\ x_{ij,G} & \text{otherwise} \end{cases}$$

$$i = 1, \ldots, D$$

Crossover is done in order to increase the diversity of the perturbed controller parameters for each individual in the population. The block diagram on how this process is done is shown in Fig. 7.

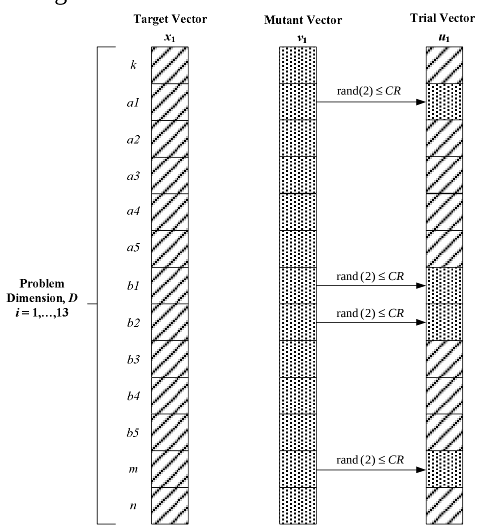


Fig. 7 Crossover process

D.Verifying the boundary constraint

If the bound (i.e. lower & upper limit of a variable) is violated then it can be brought in the bound range (i.e. between lower & upper limit) either by forcing it to lower/upper limit (forced bound) or by randomly assigning a value in the bound range (without forcing).

$$\text{if } x_i \notin [L, H], \quad x_i = L + (H - L).\text{rand}_i(0,1) \qquad (9)$$

Equation (9) is purposely used in order to make sure that all the parameter vectors are within its boundary constraints.

E. Selection

Performance of the trial vector and its parent is compared and the better one is selected. This method is also known as greedy selection. Selection is performed for each target vector, $x_{j,G}$ by comparing its fitness value with that of the trial vector, $u_{j,G}$. Vector with lower fitness value is selected for next generation. Fig. 8 shows how the selection process is performed. The process is repeated until a termination criterion is met. The flowchart shown in Fig. 9 summarizes the DE algorithm.

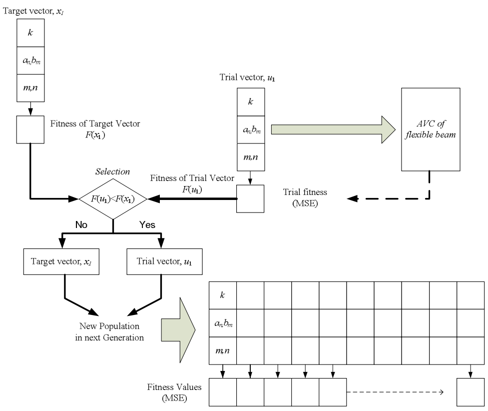


Fig. 8 Selection process

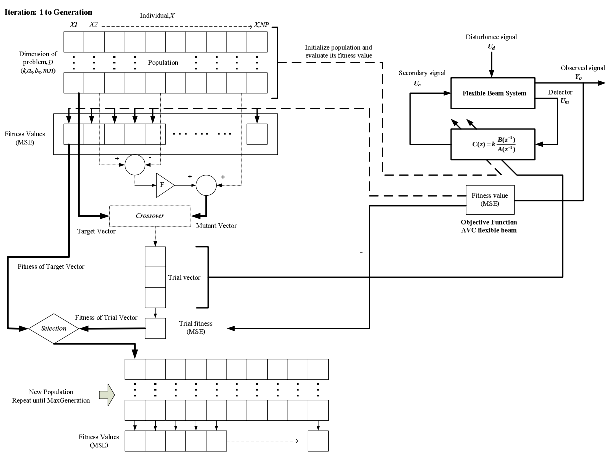


Fig. 9 Flowchart of differential evolution direct adaptive controller of AVC flexible beam system

VI. Simulation Results

In this section, fixed free flexible beam with specifications in Table 1 was simulated. The beam was divided into 20 segments and a sampling time of 0.27078 ms that satisfies the stability requirement of the FD simulation model and is effectively to cover the resonance frequencies of vibration of the flexible beam. In order to study the performance on the proposed controller, sine disturbance signal with amplitude of 10V and frequency of 15 Hz was applied at segment 13 of the beam, and the control actuator signal was applied a segment 20. The detector and observed signal were placed at segment 14 and 20 respectively.

The proposed controller is design based on DE direct adaptive control. Differential evolution optimisation method is used to search for the best controller parameters including its optimum controller model structure. All these can be done in single optimisation approach. The search space for controller gain, controller parameters and controller model order is set based on Fig. 4. Since there was no prior knowledge about a suitable order of the controller, thus in this research an automated approach is proposed to search for the best controller model order within 1 to 5. The selection of DE optimisation parameters has great effect on the performance of the DE search algorithm, thus some guidelines are available [14]. Normally, *NP* should be chosen between 5 to 10 times the dimensions of problem. The value of *F* lies between 0.4 to 1.0 and for *CR* is from 0.1 to 1.0, but in general *CR* should be as large as possible for quick solution. In this study the number of generation, *GEN*, *NP*, *F* and *CR* were set to 100, 65, 0.5 and 0.8 respectively. The complete parameters setting can be seen in Fig. 4.

As shown in Fig. 10, DE optimisation achieved the best MSE levels of 2.424×10^{-10} m in the 96th generation with sine disturbance force signal. The optimum values for controller gain, controller parameters and controller model order are shown in Table 2. All these values have been search randomly using DE optimisation method in a way that a global minimum of MSE is achieved. This result reveal that the proposed method can be used to automatically search for the best controller model order by eliminating trial and error method proposed by previous studies [10], [13], [23].

The system performance with sine disturbance is shown in Figs. 11 and 12 which illustrate the time and frequency responses of the beam deflection respectively before and after control where a significant reduction of vibration level is achieved. It is observed that the spectral attenuations achieved at the first five resonance modes of the beam are 61.13 dB, 23.37 dB, 24.39 dB, 9.16 dB and 8.559 dB respectively (see Fig. 13). It shows that the power spectral density of the system reduces sufficiently at the first mode because the first vibration mode of system has large impact on overall system performance as it consist most of the vibration energy.

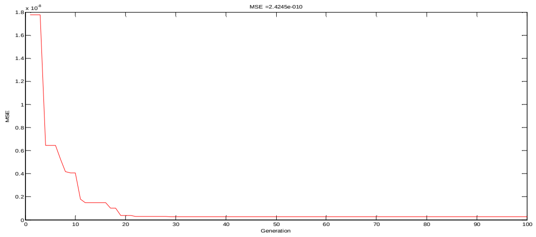


Fig. 10 DE convergence profile

TABLE II
IDENTIFIED CONTROLLER PARAMETERS

Controller gain, k	353.2				
Numerator order	3				
Denumerator order	4				
	a1	a2	a3	a4	a5
Numerator parameter	-0.6524	-0.3644	-0.3393	-	-
	b1	b2	b3	b4	b5
Denumerator parameter	-0.6373	-0.2260	0.2881	0.0923	-

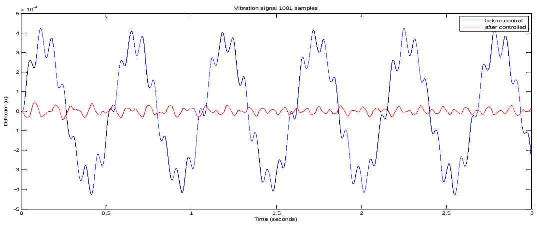


Fig. 11 Time domain responses

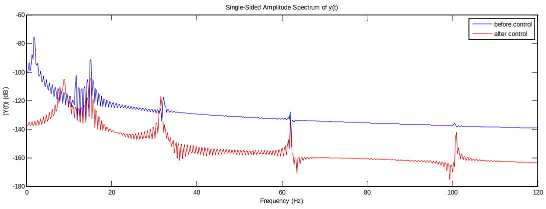


Fig. 12 Frequency domain responses

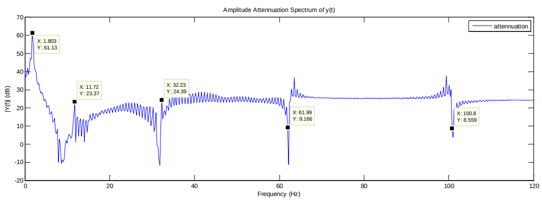


Fig. 13 Amplitude attenuation

VII. CONCLUSION

The design and implementation of an adaptive active control mechanism using DE optimisation algorithm has been presented and verified through simulation exercises in a flexible fixed-free beam system. The performance of the control system in vibration reduction with sine disturbance force signal has been assessed. It has been demonstrated that, a significant amount of vibration reduction over the full range of frequencies of the input signal has been achieved. The methodology proposed in this paper utilised DE optimisation to directly adjust controller parameters based on the MSE of observed signal at the tip of a flexible beam. The motivation gained with this approach is that no knowledge of the dynamic characterisation of the plant is needed for controller adaptation. The proposed method to automatically search for the best controller model order structure is able to work successfully without trial and error method.

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