System Identification of Non-Linear System Using Gentic Algorithm for Development of Active Vibration Control Algorithm

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Abstract

This work presented parametric linear estimation techniques for dynamic modelling of an extremely nonlinear flexible plate system for the development of active vibration control. In this research, a simulation study using Finite Difference method (FDM) was developed to create the vibration data of flexible rectangular plate structure with all edges clamped (C-C-C-C) boundary conditions. A finite duration step input force was then applied to excite the system at excitation point and the dynamic responses of the system at detection and observation points were investigated. An autoregressive with exogenous inputs (ARX) model with the order of 10 was proposed as a suitable model and the corresponding parameters were predicted using Genetic Algorithm (GA). The algorithm attained a suitable mean square error of 0.00028 in the 117th generation. Finally, the validity of the obtained model was investigated using prediction and statistical measurements. The parametric identification algorithm thus developed forms a suitable platform for the development of an active vibration control strategy for vibration suppression in the future work.

Keywords: System Identification, Genetic Algorithm, Active Vibration Control, Flexible Plate, Finite Difference method.

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1. Introduction

Flexible structures are of a large practical importance to marine, civil, aerospace, mechanical engineering and other significance applications, for example solar panels and slabs on columns. Beams, frames, shells and plates represent the essential members for flexible structure system. In recent years the significance of flexible plate structure has emerged owing to its broad application in the industries and also areas where precise operation performances are vital. The plate materials are now larger than before, lighter and thinner. However, large, light and thin structure leads to high vibration. The vibration of the structure is lightly damped due to the low internal damping of material used. Many scientists and researchers are attracted to investigate the effects of vibration on flexible structure systems and thus present techniques to control the vibration. In practice, many plate structures such as bridge decks, solar panels and etc. are always exposed to forces that results structural and components damage and lead to high vibrations. This is a major reason why the vibration of flexible structure needs to be controlled [1].

The purpose of vibration control in flexible structures is to reduce the response of the structure to external excitation. In the case of flexible plate structures, and due to time-varying phenomena in practical applications, adaptive control methods are preferred. Adaptive systems are proposed to adjust their behaviour in accordance with the changing properties of controlled processes and their signals. An adaptive mechanism is characterised by two complementary processes; identification and control. In the process of identification a suitable model is developedthat exhibits the same input/output characteristics as the controlled process (plant).

Generally, the procedure of system identification involves four steps:

1. Acquiring data.
2. Selection of a suitable model structure.
3. Estimation of model parameters.
4. Validate the model.

In the process of control a control process is determined, implemented and tested on the plant on the basis of the identified model and control/performance objective [2].

In numerous engineering applications and science it is not constantly possible to have entire knowledge of all the parameters of a dynamic system. So, system identification is one of the most essential requests for many engineering and scientific fields. The aim of is to obtain approximate or exact models of dynamic systems based on observed input and output data. The input and output data can be obtained through simulation, experimental work or directly collected from the plant [3].

The finite difference method (FDM) is considered as one method to develop simulation algorithms characterising the dynamic behaviour of the flexible structure. The result of the simulation is then utilized in the modelling stage, and then in development of suitable controllers for the flexible structure [4].

To provide accurate modelling, the unknown parameters must be estimated during real-time operations. Adaptive algorithms are able to provide a complete model of a system based on known parameters and previous history (e.g., inputs, outputs). Many researchers devised a number of adaptive techniques to determine models that best describe input-output behaviour of a system. GA algorithm considered as an example of intelligent techniques thatcan describe the system in the best possible way [5]. Recently, vast applications have been devised using GA [5, 6 and 7].

In this paper, dynamic modelling of the highly nonlinear flexible plate structure is considered using intelligent technique, namely Ga. The objective of the identification is to estimate a model of the flexible plate structure without any prior system knowledge was pertaining to the exact mathematical model structure or parameters relating to the actual system, i.e. black-box modelling. The model thus developed and validated will be used in subsequent investigations for vibration suppression and control strategies for the flexible plate structure.

The purpose of this study is to develop a model characterizing the vibration of a 2-D flexible rectangular plate structures using soft computing method through GA. In this work, a thin, rectangular plate with a cantilever configuration is considered. A dynamic model of the plate structure based on simulation characterizing the flexible plate structure is developed.

2. Finite Different Algorithm

In the finite difference method, the entire solution domain of the problem is divided into a grid of cells. Then, the derivatives in the governing partial differential equations are written in terms of the difference equations. Considering the boundary and initial conditions, a unique solution can be obtained for the overall system equation. The purpose of finite difference discretization on the governing differential equation of motion of rectangular plate is to develop an algorithm for the implementation in MATLAB environment. In the case of a flexible plate, the governing differential equation of rectangular plate is:

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial y^2 \partial x^2} + \frac{\partial^4 w}{\partial y^4} + \frac{\rho h}{D}\frac{\partial^2 w}{\partial t^2} = \frac{q}{D} \quad (1)$$

where $\boldsymbol{w}$ is the lateral deflection in $\boldsymbol{z}$ direction, $\boldsymbol{\rho}$ the density of plate with dimension mass per unit volume, $\boldsymbol{h}$ the thickness, $\boldsymbol{D = (Eh3)/(12(1-v^2))}$ is the flexural rigidity, $\boldsymbol{q}$ the transverse external force with dimensions of force per unit area, $\boldsymbol{E}$ the modulus of elasticity and $\boldsymbol{v}$ the Poisson ratio.

Finite difference method is used to solve the partial differential equation in (1). The differential equation and its initial and boundary conditions are replaced with equivalent difference equations. To apply this method, a rectangular plate is divided into a rectangular mesh, as shown in Fig.1.

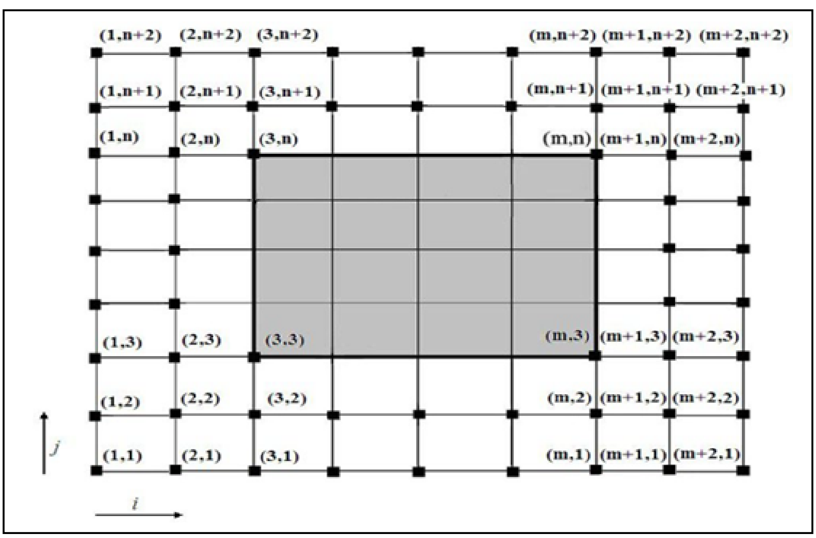


Fig.1. A schematic showing the plate mesh numbering

As can be seen in Fig.1, The x-axis is represented with the reference index $\boldsymbol{i}$, the y-axis with reference index $\boldsymbol{j}$ and for a flexible plate, time dimension is added to the system, and thus becomes a three dimensional coordinate system, where $\boldsymbol{t}$ represents the time-axis and $\boldsymbol{k}$ the reference for time-axis . where, $x = i\Delta x$, $y = j\Delta y$ and $t = k\Delta t$.

For each nodal point in the interior of the grid (x_i, y_j, t_k), a Taylor series expansion was used to generate the central difference formulae for the partial derivative terms of the deflection, w (x, y, t) = $w_{i,j,k}$, of the plate at point x = ix, y = jy and t = kt. Thus, a general solution of the partialdifferential equation (PDE) in the discrete form is shown in equation (2), where $w_{i,j,k+1}$ is the deflection of nodal point (x_i, y_j) of the plate at time step k+1[4].

$$w_{i,j,k+1} = -\frac{D\Delta t^2}{\rho h}\Big(Pw_{i,j,k} + Q\big(w_{i+1,j,k} + w_{i-1,j,k}\big) + R\big(w_{i,j+1,k} + w_{i,j-1,k}\big) + S\big(w_{i+1,j+1,k} + w_{i-1,j+1,k} + w_{i-1,j-1,k} + w_{i+1,j-1,k}\big) + T\big(w_{i+2,j,k} + w_{i-2,j,k}\big) + U\big(w_{i,j+2,k} + w_{i,j-2,k}\big)\Big) + 2w_{i,j,k} - w_{i,j,k-1} + \frac{\Delta t^2}{\rho h}F(i_o, j_o, k_o) \quad (2)$$

Where,

$$P = \frac{6}{\Delta x^4} + \frac{8}{\Delta x^2 \Delta y^2} + \frac{6}{\Delta y^4}, \quad Q = -\frac{4}{\Delta x^4} - \frac{4}{\Delta x^2 \Delta y^2}$$

$$R = -\frac{4}{\Delta y^4} - \frac{4}{\Delta x^2 \Delta y^2}, \quad S = \frac{2}{\Delta x^2 \Delta y^2}, T = \frac{1}{\Delta x^4}, \quad U = \frac{1}{\Delta y^4}$$

3. Model Structure

A suitable model structure should be selected after acquiring the data. Several model structures are accessible to assist in modelling a system. In order to determine the class of models to which the target system may belong, a prior knowledge is used. Therefore, if there is no a priori knowledge available, the structure realization might be done by a trial-and-error method. The autoregressive moving average model with exogenous inputs (ARMAX) model is one of the most popular linear models [1], [8].If the model is good enough to identify the system without incorporating the noise term or considering the noise as additive at the output, the model can be represented in the ARX form [8].

Since the simulated data is collected by the sampling process from the simulation stage; then it is easier to relate the detected and observed data to a discrete time model. The schematic of ARX model is shown in discrete domain as in Fig.2.

Mathematically the ARX model is given by the following equation:

$$y(k) = \frac{B(z^{-1})}{A(z^{-1})}u(k) + \frac{1}{A(z^{-1})}\xi(k) \quad (3)$$

$$A(z^{-1})y(k) = B(z^{-1})u(k) + \xi(k) \quad (4)$$

whereas,

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-1} + \cdots .. + a_n z^{-1} \quad (5)$$

$$B(z^{-1}) = b_1 z^{-1} + b_2 z^{-1} + \cdots .. + b_n z^{-1} \quad (6)$$

Substitute (5) and (6) into (4) will get:

$$y(k) = -a_1 y(k-1) \ldots - a_n y(k-n) + b_1 u(k-1) \ldots + b_n u(k-n) + \xi(k) \quad (7)$$

where $A(z^{-1})$ is Polynomials parameters of autoregressive and $B(z^{-1})$ is Polynomials parameters of exogenous. $u(k)$ is the detection data, $y(k)$ is the observation data, $\xi(k)$ is the zero mean white noise. z^{-1} is a back-shift operator, n is order of the model and a_1 until a_n and b_1 until b_n are the model parameters. The aim of is thus to estimate the model parameters as best as possible.

4. Genetic Algorithm (GA)

Building of mathematical model of a dynamic system depending on measured data is accomplished using parametric techniques. After determining the model structure, the main task of identification is to estimate the model parameters, which are usually determined on the basis of a global minimum criterion function. Parametric identification techniques are methods to calculate approximately parameters in given model structures to get the best agreement between the measured output of the system and the predicted one [1]. Many methods of identification can be found in the literature. One of these methods is Genetic Algorithm (GA).

GAs is regarded as global search heuristics. GAs is categorized as a particular class of evolutionary algorithms that utilize methods enthused by evolutionary biology such as selection, crossover, inheritance, and mutation. A Genetic Algorithm is used in computing to find an approximate or an accurate solution to search problems and optimization [8].

In various science and engineering applications, there has been rising attention amongst engineers and scientists in the use of GA. The working principle of GA, as described by Mat Darus et.al, [7], is shown in Fig.3.

In this research, GA methodology is utilized to predict the parameters in ARX model structures. Fig.4 shows the principle of plate system identification via GA. As can be noted, GA uses error function to estimate the model parameters [5]. The predicted error $e(t)$ between the system output $y(t)$ and one step ahead (OSA) estimated model output $\hat{y}(t)$ at time t is:

$$e(t) = y(t) - \hat{y}(t) \qquad (8)$$

The mean square error is defined as:

$$mse = \frac{1}{N}\sum_{t=1}^{N}(y(t) - \hat{y}(t))^2 \qquad (9)$$

where N is the number of sampled data. An obvious approach is then to estimate the model parameters so as to fit the predicted output $\hat{y}(t)$ as best as possible to the real output $y(t)$. In other words, the parameters should be estimated so that the mean square error mse converges to zero. Therefore, the mean square error was employed as the fitness function of the GA and the optimization process of the GA was conducted to estimate the model parameters so that the value of mean square error was reduced to a distinct level. Control parameters of the GA comprise number of individual, selection strategy, crossover probability and mutation probability. The performance and behaviour of the GA could be affected by the selection of the control parameters of the GA. Therefore, running a successful GA involves having to find settings for a number of control parameters which is not a trivial task.

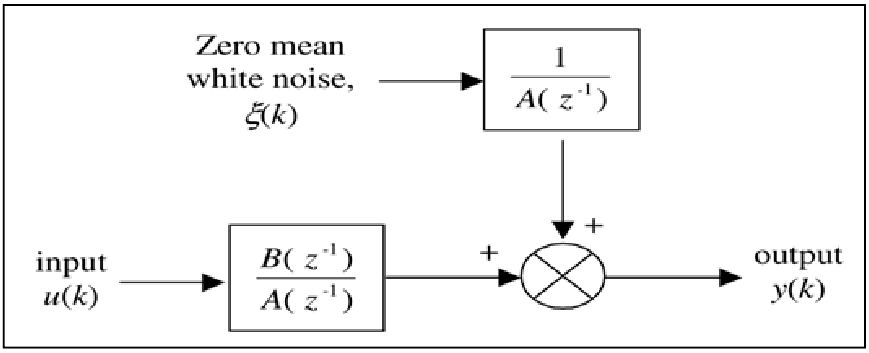


Fig.2. Schematic of ARX model

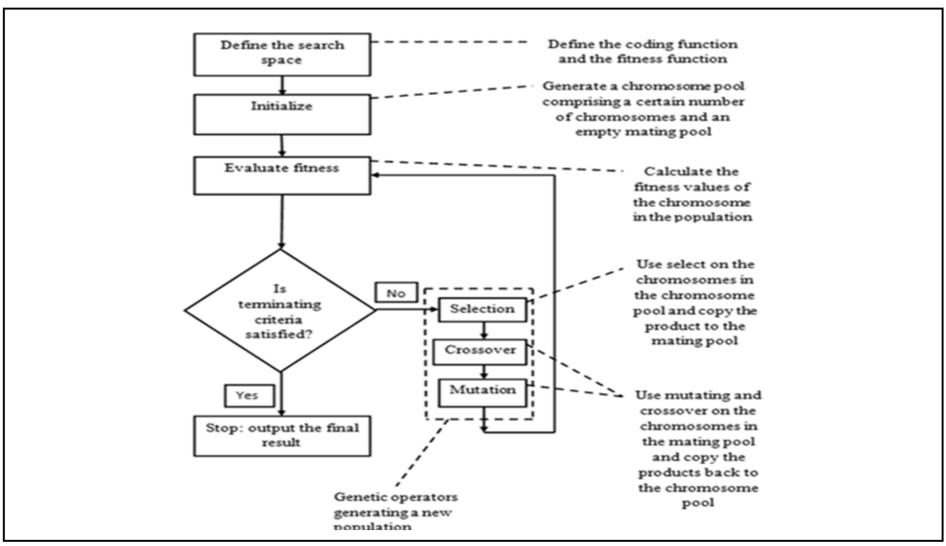


Fig.3. Working principle of GA

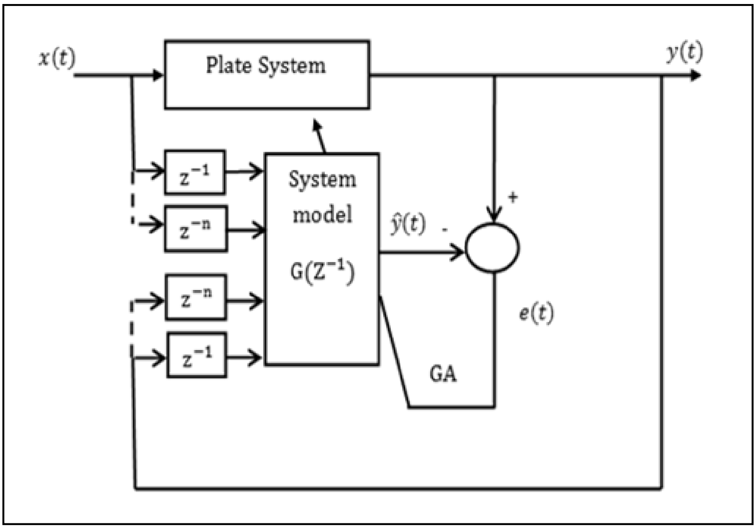


Fig.4. Diagrammatic representation of the GA algorithm

4.1. Population Representation and Initialization

Genetic algorithm operates on a set of potential individuals (population) concurrently. The members of the population are called individuals (chromosomes) and their number could be more than 100 or less than 10, depending upon the nature of the problem and type of GA. The initial population for a GA search is usually selected randomly [10].

In all GA implementations, appropriate selection of population size is extremely significant. The GA will usually converge too fast if the number of individuals is chosen too small, and in many cases it will achieve a poor solution due to inadequate information in the population. Conversely, if the number of individuals is chosen too large a population will take long time to converge to the true solution. Therefore, balancing between the requirement for a large information capacity in the population and the need to produce a solution within the limited amount of time should be considered [5].

Normal binary string is the classical approach of representing individuals in the GA. In this case, each decision variable in the parameter set is encoded as a binary string and these are concatenated to form a chromosome. It can be seen that the use of Gray coding is claimed to provide slightly better results than normal binary representation. Researchers is widely used this type of coding. However, there is too a growing attention in alternative encoding strategies, such as integer and real-valued representations. Real-coded GA has been used to solve a number of practical problems despite the opinion that a real-coded GA would not necessarily yield good results in some situations [9].

4.2. Fitness Functions

The fitness function is the main link between the GA and the problem to be solved. It evaluates the performance of each chromosome in the problem domain and helps in selecting the best ones for further reproduction. It takes chromosomes as input and produces a fitness value [5].

The key element in the development of a successful GA is the specification of an appropriate fitness function. The fitness function has a great effect on the convergence speed of a GA process. The fitness function should be able to reflect the key properties of the model, to drive the GA search process towards the location of the best solution. The fitness function will not be able of identifying a chromosome (solution) with superior characters, if it contains insufficientinformation about the model. Therefore, it would take a longer time to advance in the evolution. As described above, this will reduce the convergence speed of the process. The search process will not be able to find the best solution in an acceptable time period, if the convergence is too slow. According to the rule of the GA, the fitness value should be no less than zero, and it should index the fitness of chromosomes and rise during the evolution [11].

4.3. Selection Operator

Selection means a new population is selected with respect to probability distribution based on fitness values to be parents to crossover. Relative to Darwin's evolution theory the best individuals in population should survive and produce new offspring. Many methods are advised to choose the best individuals, for instance Boltzman selection, tournament selection, roulette wheel selection, rank selection, steady state selection and some others. An effective parent selection mechanism is required to generate good offspring. A “Roulette wheel” mechanism was employed by many selection methods to choose chromosomes probabilistically rooted in some measure of their performance. The roulette wheel is constructed as follows:

1. Calculate the fitness value for each chromosome.

2. Calculate the total fitness for the population.

3. Calculate selection probability for each chromosome.

4. Calculate cumulative probability for each chromosome.

5. Real-valued interval, *Sum*, is determined as the sum of the cumulative probability for all chromosomes.After that a random number is generated in the interval [0, *Sum*] and the selection of the individual will be achieved such that individual segment spans the random number. This step is repeated until the required number of individuals has been selected [12].

4.4. Crossover Operator

The essential operator in the GA for producing new chromosomes is crossover. It allows individuals to swap information like to a natural organism undergoing sexual imitation. Crossover operator creates new chromosomes that have some parts of both parent's genetic material in away similar to its counterpart in nature. A certain percentage of the individuals undergo crossover based on a predefined probability. Typical values of crossover probability are 0.4 to 0.9. The simplest form of crossover is that of single-point crossover in which a pair of solution randomly selects one cut-point and exchanges the right parts of two parents to generate offspring.

4.5. Mutation Operator

Mutation is the operator randomly alters one or more genes with a probability equal to the mutation rate. Mutation is typically used very sparingly. According to some probabilistic rule, Mutation leads to change theindividual genetic representation. Mutation will cause a single bit to change its state, $0 \Rightarrow 1$ or $1 \Rightarrow 0$, in the binary string representation.

4.6. Termination Strategy

When the genetic algorithm completes one iteration, the iteration is repeated until one of the termination conditions is satisfied. Two termination conditions were applied to the GA simultaneously. Firstly, the allowable number of generations and secondly, the algorithm was allowed to break the generation loop if a suitable solution was found earlier.

5. Model Validation

The events that are designed to measure the adequacy of a fitted model are called model validity tests. When a model of the system is obtained, it is vital to validate whether the model is good enough to represent the system. Several validation tests are obtainable in the literature, some of which are correlation error, one step-ahead prediction, mean squared error, model predicted output, etc. In this project research mean squared error, one step-ahead prediction and correlation test are used to validate the model [1].

6. Implemeaton and Results

Simulation study was conducted to investigate the vibration of a flexible, flat, rectangular plate system. The properties of the plate are listed in Table 1. In this study a rectangular plate with four edges clamped (C-C-C-C) boundary conditions as shown in Fig.5 was considered. The number of segments along the length and width of plate were taken as 24 and 16, respectively, which were found to be sufficient to simulate the system with an acceptable accuracy. The locations of excitation point, detection point and observation point were assigned as shown in Fig.5 for the development of active vibration control (AVC), which will be conducted in the future work. The location of input force is point (X). The location of detection signal at point (Y) and the location of observation signal at point (Z) are chosen so that it is far enough from the nodal lines defined by the first five natural frequencies of the plate as described by Tavakolpour[13]. Therefore, simulated studies were carried out using a finite duration step input force (per unit area), F with a magnitude of 100 N/m^2 was applied to point (X) located at x = 0.25a and y = 0.25b (a and b are the length and width of the plate respectively) from t = 0.01 s to t = 0.02 s and the dynamic response of the plate system was investigated for a period of 0.5 s as shown in Fig.6. The simulated lateral deflection of the plate at detection point (Y)located at $x = 0.75a$, and $y = 0.75b$, in time domain response is plotted in Fig.7. The simulated lateral deflection of the plate at observation point (Z) located at $x = 0.75a$, and $y = 0.25b$, in time domain response is plotted in Fig.8. The value for stability of the algorithm c was chosen as 0.11, which is less than half of its maximum allowable value. One should keep in mind that selecting a smaller value of c results in the increase of prediction accuracy of the model as well as the reduction of sampling time in the presented FDM algorithm.

Table.1. Plate specifications

Parameter	Value
Length (a)	1.5 m
Width (b)	1.0 m
Thickness (*h*)	0.003 m
Density (*ρ*)	2690 Kg m^{-3}
Modulus of elasticity (E)	6.83 1010 N m^{-2}
Poisson ratio (*υ*)	0.34

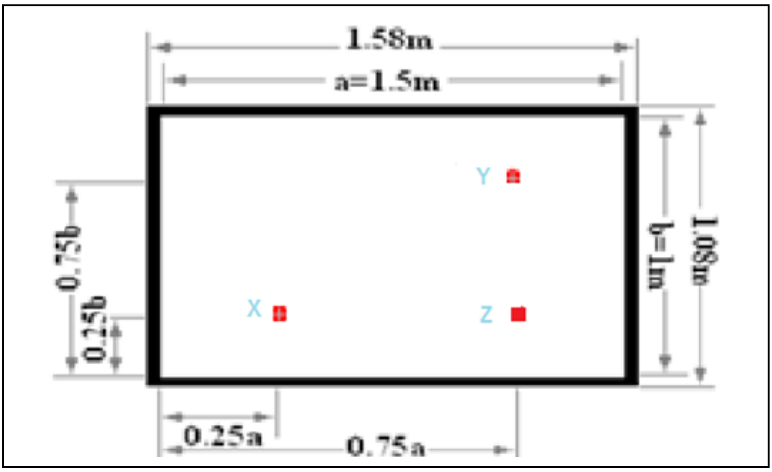


Fig.5. Schematic of the plate with cantilever configuration for the purpose of development of AVC

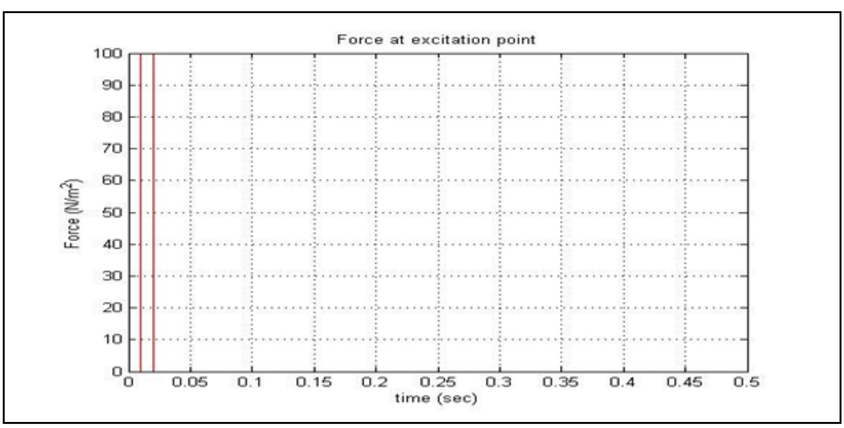


Fig.6. Applied force at x = 0.25a, y = 0.25b point X (excitation point)

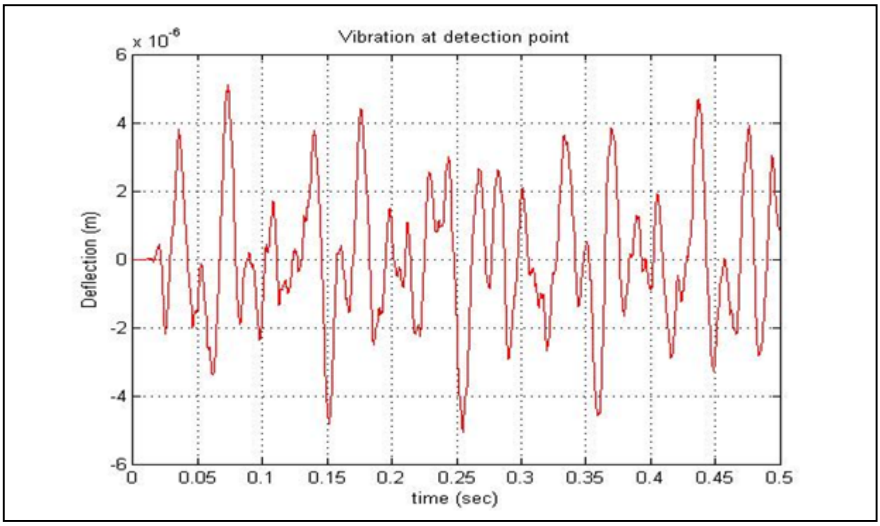


Fig.7. Lateral deflection detected at x=0.75a, y =0.75b point Y (detection point)

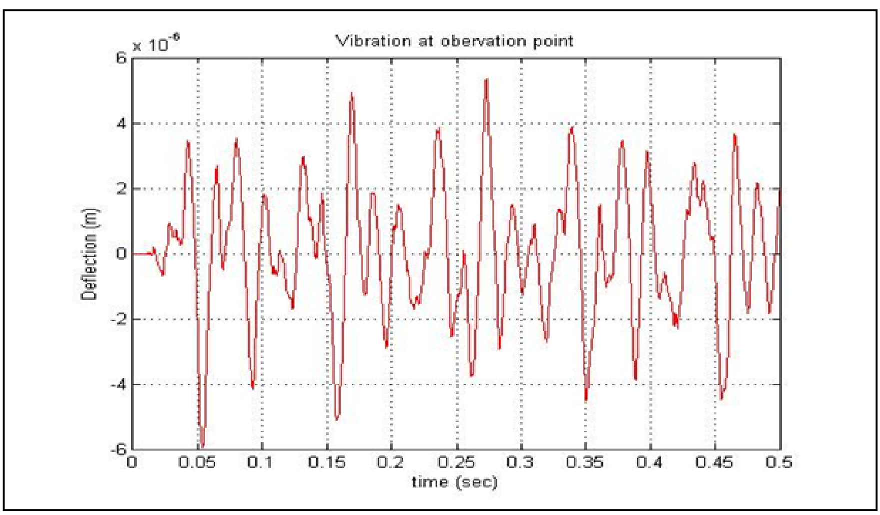


Fig.8. Lateral deflection detected at x=0.75a, and y=0.25b point Z (observation point)

6.1 Modelling using Genetic Algorithm (GA)

A MATLAB program has been implemented based on the GA using ARX model. The GA modelling is used with detection and observation data obtained from the experimental study of the rectangular plate developed earlier. Since there was no a priori knowledge regarding the suitable order of the model for the flexible plate system, the structure realization was performed by a trial-and-error method. Randomly selected parameters were optimized for different, arbitrarily chosen order to fit into the system by applying the working mechanism of GA as described before based on one step a head (OSA) prediction. Investigation was carried out by realizing the GA with different initial values and operator rates. From the work carried out it is found that satisfactory results were achieved with the following set of parameters:

Population Initial Range: [-1; 1]

Number of Generations: 600

Population Size: 60

Crossover Fraction 0.6

Stall Generation Limit: 5000

Stall Time Limit: 5000

Selection Function: roulette

Crossover Function: single point

Mutation Function: Gaussian

The data set, comprising 3500 data points, was divided into two sets of 2500 and 1000 data points respectively. The first set was used to find the parameters and the second set was used to validate the model. Both output and estimated output are plotted in Fig.9. The error between actual and predicted GA output is plotted in Fig.10 and the best mean fitness values in each generation are shown in Fig.11. The deflection model was investigated with different model orders. The best result was achieved with an order 4, which means that, $n_u = n_y = 2$ for 2500 data length is being used to find the parameter and the best mean squared error for GA algorithm is 2.0026*10^{-5}. Using the proposed identification procedure, the parameters a_1, a_2 $a_3$and b_1, b_2 b_3 of the model were estimated as follows:

$$a_1 = -0.1981, a_2 = -0.5706, \ a_3 = 0.7714$$

$b_1 = -0.0088,\ b_2 = 0.0048,\ b_3 = -0.0005,$

And therefore, the model is:

$$y(k) = 1.1981y(k-1) + 0.5706y(k-2) - 0.7714y(k-3) + 0.0088u(k-1) + 0.0048u(k-2) + 0.0005u(k-3) + \xi(k)$$

The correlation tests were carried out to determine the effectiveness of the GA-based model. Fig.12 shows the results of the correlation tests. The results were found to be within 95% confidence level thus confirmed the accuracy of the results.

7. Conclusion

The flexible plate structure has been modelled with genetic modelling technique and validated through input/output mapping, mean square error and correlation tests. It is noted that the GA based modelling technique has performed well in approximating the system response. The parametric models of the flexible plate structure thus developed and validated will be used in subsequent investigations for the development of control strategies for vibration suppression in flexible structures

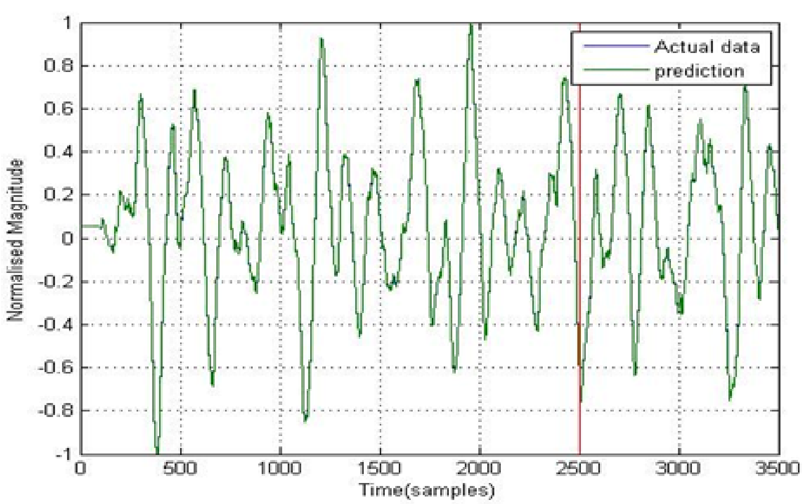


Fig.9. Actual and predicted GA output

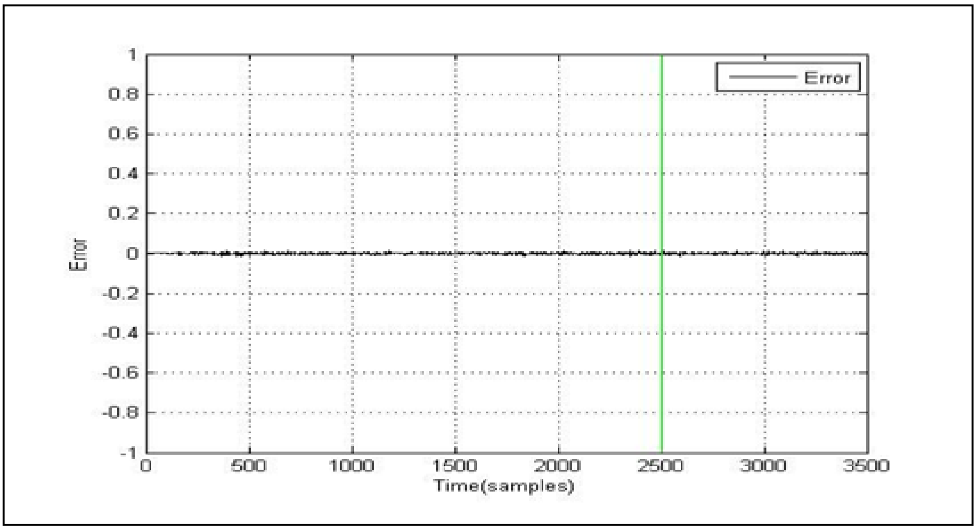


Fig.10. Error between actual and predicted GA output

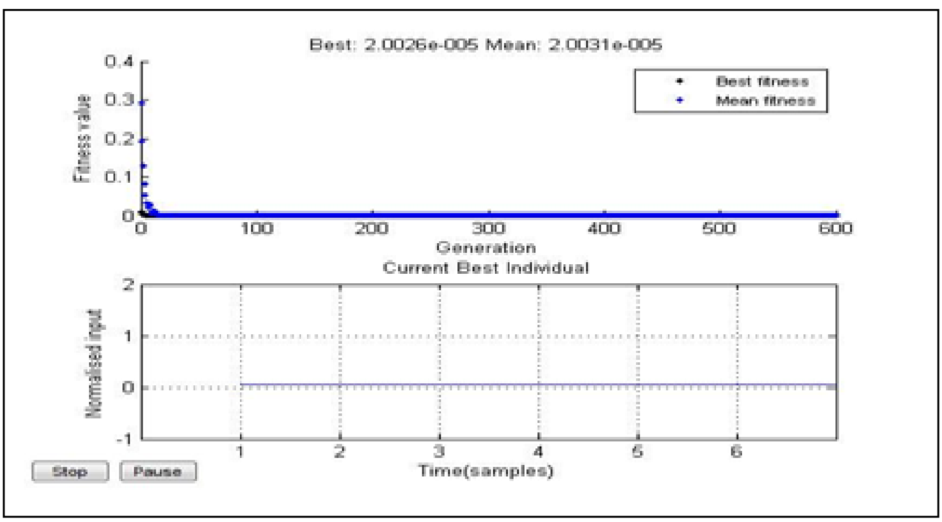
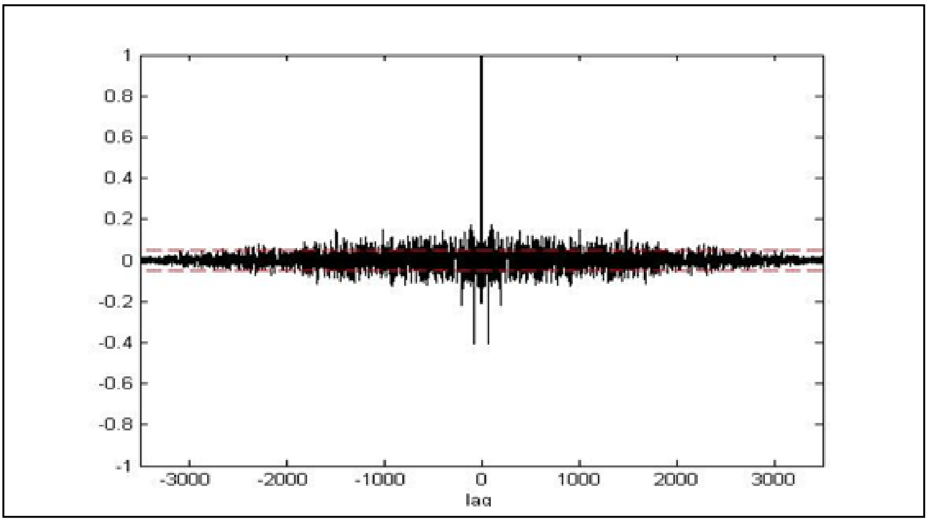
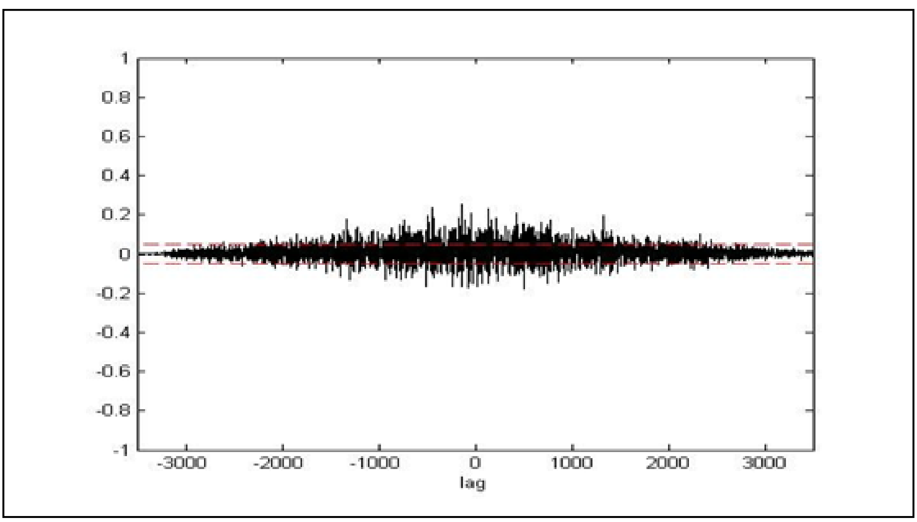


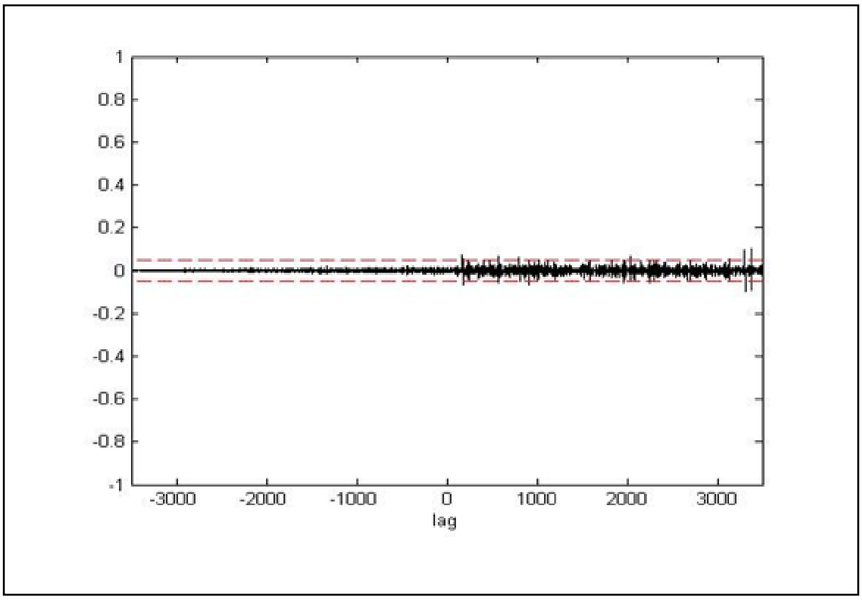
Fig.11. The best and mean fitness values in each generation



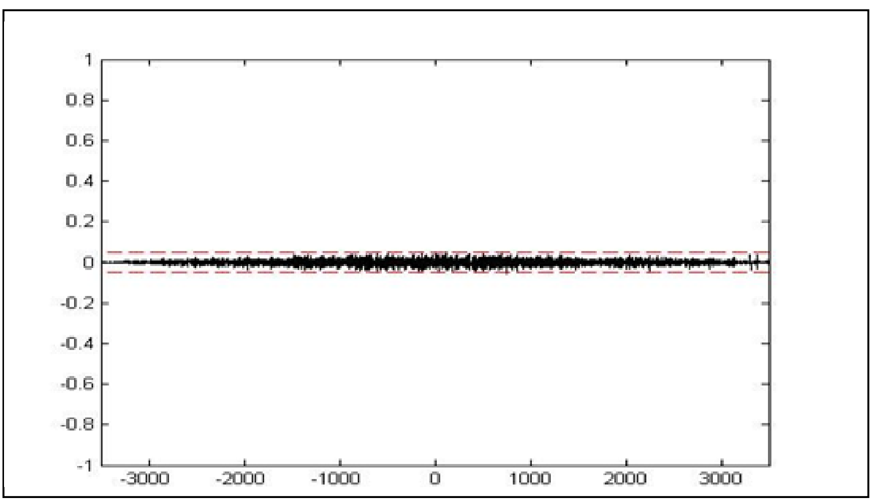
(a) Correlation of the error



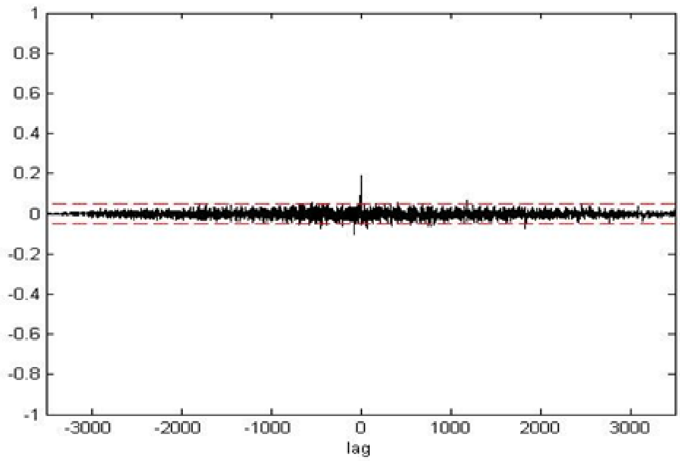
(b) Correlation of the input and the error



(c) Correlation of the square of input and the error



(d) Correlation of square of the input square of the error



(e) Correlation of multiplication of the input by the error and the error

Fig.12. Correlation tests of GA

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تميز النظام غير الخطي باستخدام الخوارزمية الجينية لتطوير خوارزمية السيطرة للاهتزاز الفعال

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هذا البحث يعرض طريقة تخمين خطية للتمثيل الحركي لنظام صفيحة مرنة لاخطية لغرض تطوير سيطرة اهتزازات فعالة. أن البحث يمثل دراسة محاكاة باستخدام طريقة الفرو قات المحددة طورت لتوليد قيم الاهتزاز لصفيحة مستطيلة مرنة مثبتة بجميع الاتجاهات. أن القوة الداخلة هي عبارة عن دالة خطوة محددة سلطت لإثارة النظام عند نقطة الإثارة و الاستجابة الحركية للنظام عند نقطة الكشف والملاحظة قد تم ملاحظتها. أن نموذج ARXبرتبة 10 قد اقترح كأنسب نموذج وقد تم استنتاج متغيراته باستخدام الخوارزمية الجينية. أن الخوارزمية الجينية قد وصلت إلى معدل مربع خطأ يساوي 0.00028 عند الجيل 117. وأخيرا أن صحة النموذج المتحصل عليه قد تم فحصها باستخدام قياسات تخمينيه و إحصائية. أن خوارزمية تعريف المتغيرات تمثل سطح مناسب لتطوير إستراتيجية سيطرة اهتزازات لتخمد الاهتزاز في العمل المستقبلي.

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