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〈논 문〉

Real-Time Tuning of the Active Vibration Controller by the Genetic Algorithm

유전자 알고리즘을 이용한 능동진동제어기의 실시간 조정

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ABSTRACT

This paper is concerned with the real-time automatic tuning of the positive position feedback controller for smart structures by the genetic algorithms. The genetic algorithms have proven its effectiveness in searching optimal design parameters without falling into local minimums thus rendering globally optimal solutions. The advantage of the positive position feedback controller is that if it is tuned properly it can enhance the damping value of a target mode without affecting other modes. In this paper, we develop for the first time a real-time algorithm for determining a tuning frequency of the PPF controller based on the genetic algorithms. To this end, the digital PPF control law is downloaded to the DSP chip and a main program, which runs the genetic algorithms in real time, updates the parameter of the controller in real time. Hence, any kind of control including the positive position feedback controller can be used in adaptive fashion in real time. Experimental results show that the real-time tuning of the positive position feedback controller can be achieved successfully, so that vibrations are suppressed satisfactorily.

요 약

이 논문은 지능구조물의 실시간 적응진동제어를 위해 유전자 알고리즘을 이용하여 Positive Position Feedback(PPF) 제어기를 조정하는 것과 관련이 있다. 유전자 알고리즘은 최적변수를 찾는데 있어 국소 최소점이 아닌 전체적인 최적점을 찾을 수 있는 능력이 있다. PPF 제어기는 다른 진동모드에 영향을 주지 않으면서 특정 진동모드의 감쇠를 증가시킬 수 있는 장점을 가지고 있는 반면에 효과적인 진동제어를 위해서는 제어하고자하는 진동모드의 고유진동수를 정확히 알아야하는 단점이 있다. 본 연구에서는 유전자 알고리즘을 이용하여 실시간으로 PPF 제어기가 필요로 하는 변수값을 추적할 수 있는 알고리즘을 개발하여 그 타당성을 실험으로 증명하였다. 실험결과는 PPF 제어기의 실시간 조정이 성공적으로 이루어져 진동제어가 효과적으로 이루어졌음을 보여주고 있다.

1. Introduction

The smart structure is defined as the one that consists of distributed sensors, actuators and the

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controller that achieves vibration suppression with them. Conceptually, the smart structure should be able to cope with the external disturbances and internal changes. There are many materials, which have been tested for actuators and sensors. They are piezoelectric materials, shape memory alloys, electrostrictive materials, magnetostrictive materials, electro-theological fluids, and fiber optics. These materials can be inserted into or bonded with structures thus acting as either sensor or actuator. Among them, piezoelectric materials have been popularly used because of high strength, temperature insensitivity, and ease of implementation. If the voltage is applied to the piezoelectric materials, then it undergoes deformations. On the contrary, the charge is produced when deformation occurs. Hence, it can be used both sensor and actuator. The most popular piezoelectric material is the piezoceramic material consisting of lead zirconate titanite. In particular, the piezoceramic plate can be easily glued to the surface of structures. The analysis on the smart structure equipped with piezoelectric sensors and actuators was initially performed on the beam structures. Crawley et al.(1,2) discussed on the modeling technique applicable to the beam structure bonded with piezoceramic sensors and actuators. Hanagud et al.(3) used the finite element method to model the smart structure and suppressed the vibration with rate-modal feedback and optimal controls. Fanson and Caughy(4) proposed the use of the Positive Position Feedback (PPF) control based on the modal displacement signal. Poh and Baz(5) improved the PPF controller for the multi-degree-of-freedom system using the independent modal space control concept. Many researchers extended the smart structure theory to different types of structures(6~13). The PPF controller is very effective in suppressing the specific vibration mode, which maximizes the damping in target frequency band without destabilizing other modes. The PPF control circuit is equal to the simple low-pass filter circuit so that it can be realized by operational amplifiers. Hence, the PPF controller appears to be practically attractive for smart structure applications. However, the natural vibration characteristics should be known a priori either theoretically or experimentally in order to successfully apply the PPF controller. This process is called the tuning process.

The random search technique can be employed for the tuning of control parameters such as the filter frequency of the PPF controller for active vibration suppression. However, it may take time to find the optimal solution if the parameter domain is large. The genetic algorithm (GA) is the alternative to the root-finding technique. The GA seeks the optimal solution based on the biological genetic law in which only adaptable genes survive, i.e., survival-of-the-fittest(14). Using the GA, the first generation is formed with arbitrary number of genes and the next generation is produced by crossovering the fittest group. The process is repeated until the optimal solution is obtained. The performance of the GA can not be easily proved mathematically. However, the GA shows its effectiveness in many problems(14~24). The main characteristics and advantage of the GA is the simple operation without falling into local minimum. The GA can seek the optimal solution without any information on the system and environment thus its adaptability is far superior to other techniques. The solution obtained by the GA is not the exact optimal solution but the optimal solution group. However, it is more realistic in engineering sense to find the near optimal solution without falling into local minimum than finding the exact optimal solution. Hence, the GA is preferred in engineering problem solving.

The GA was applied to simple mathematical problems initially but it has extended the application area(14). Recently, the GA has proved its effectiveness in the tuning of fuzzy neural net controller (15), the determination of control gains(16~21), active vibration controller design(22, 23), and the simultaneous optimization of structures and controller(24). The possibility of using the GA for smart structures was extensively studied in (25). Kwak and Han(25) introduced the essence of the GA briefly and proposed the use of the GA for the parameter tuning of the PPF controller. Their numerical and experimental results show that the GA can be effectively used for the parameter tuning of the PPF controller. However, the tuning of the PPF controller in (25) was carried out on the theoretical model. This motivated us to pursue the real-time tuning of the PPF controller for the realization of a real-time adaptive PPF controller.

In this paper, we propose a new algorithm for the real-time tuning of the active vibration controller design for smart structure by the GA. The real-time tuning of the PPF controller is realized by running two computer programs at the same time. The digital PPF control law is downloaded to the DSP chip and the memory block which contains the control parameter values is accessed by the main GA program. All the developments are proved experimentally.

2. Digital PPF Controller

Let us explain briefly the PPF control(4) expressed as

$$H(s)=\frac{\omega_f^2}{s^2+2\zeta_f\omega_f s+\omega_f^2} \tag{1}$$

where ζ_f and ω_f are the damping factor and filter frequency of the PPF controller, respectively. It is well known that the damping can be increased because of 90-degree phase shift if we tune the filter frequency of the PPF controller to the target natural frequency of the structure. This equation in fact represents the transfer function for the low-pass filter, so that the controller can be realized by a simple electronic analog circuit. The PPF controller can be used effectively when vibration modes of the structure are well separated. In that case, we can control a specific mode without affecting other modes. However, the natural vibration characteristics of the structure to be controlled should be known a priori to apply the PPF controller. This can be achieved either theoretically or experimentally. In this paper, we use the GA to find an appropriate PPF filter frequency.and

The analog expression of the PPF controller given by Eq. (1) should be converted to a digital form to implement it on a digital computer(13). To convert Eq. (1) into the digital form, we use the bilinear transform.

$$s=\frac{2}{T}\frac{z-1}{z+1} \tag{2}$$

where T is the sampling period and should be fast enough not to cause instability in higher modes. Inserting Eq. (2) into Eq. (1) yields

$$H(z)=\frac{b_2z^2+b_1z+b_0}{z^2+a_1z+a_0} \tag{3}$$

where

$$b_2=\frac{\omega_f^2}{\Delta},\ b_1=\frac{2\omega_f^2}{\Delta},\ b_0=\frac{\omega_f^2}{\Delta}$$
$$a_1=\frac{2\omega_f^2-8/T^2}{\Delta},\ a_0=\frac{4/T^2-4\zeta_f\omega_f/T+\omega_f^2}{\Delta}$$
$$\Delta=\frac{4}{T^2}+\frac{4\zeta_f\omega_f}{T}+\omega_f^2 \tag{4}$$

The digital PPF controller given by Eq. (3) is downloaded to the DSP board, DS1102 of dSpace Inc. which has the maximum sampling rate of 20 kHz. A cantilever beam with piezoceramic sensor and actuator is considered for the technology demonstration. The fundamental frequency of the beam is found to be around 11 Hz so that the sampling rate of 10 kHz is more than enough for active vibration control. The real-time GA is used to locate a suitable filter frequency of the PPF controller, for a given environment. The damping factor of the PPF controller, is set 0.3. The lower damping factor gives better performance because it increases the amplitude of the feedback control but becomes sensitive so that the PPF controller should be tuned accurately.

3. Real-time Tuning of the Digital PPF Controller using Genetic Algorithm

Compared to other optimization algorithms which deals with the parameter, the GA deals with the coding of the parameter set thus finds the concentration of the optimal points(14). The GA is not deterministic but probabilistic in nature. If we use the GA, we should make the parameter set to be optimized into the string of finite length. The simple GA consists of reproduction, crossover, and mutation. The reproduction represents the process of making a new generation based on the fitness. Hence, the global fitness value increases naturally as generation proceeds. The simple crossover means exchanging arbitrary number of binary numbers between two superior genes. In this way, the fittest to a given environment may survive. The mutation improves the global convergence characteristics. The mutation indicates the sudden change in genes.

For example, let us consider the optimization problem consisting of 4 parameters and assume that each of these parameters consists of 5 bits as shown in Fig. 1. The GA represents all parameter values with a single parameter. Hence, the binary number becomes 20-bit number in this case. We assign arbitrary binary number into 16-bit number and plugged into the performance function and choose the fittest. The roulette wheel selection is used in choosing proper genes for the reproduction. Of course, the transformation of the binary number into real numbers is necessary to compute the fitness. We then crossover the good genes and repeat the same process. Hence, the genes exchange information through crossover. The GA can be regarded as an iteration process based on changing generation with crossover. We can easily find that the binary numbers are densely populated at a certain point as the generation proceeds. This amounts to the biological survival of fittest and differs from other optimization technique. While most of optimization techniques search the maximum or minimum point starting from an initial point, the GA searches the maximum set starting from many arbitrary points. Hence, the convergence laws in other optimization techniques are deterministic but the convergence law in the GA is probabilistic. The performance of the GA is in general measured by the on-line performance and the off-line performance; The on-line performance is the average performance value of the all values and the off-line performance is the average of each generation's best performance value. We use the best fit among all the generations as the tuning parameter and the performance of the GA is measured by the average fit of the population.

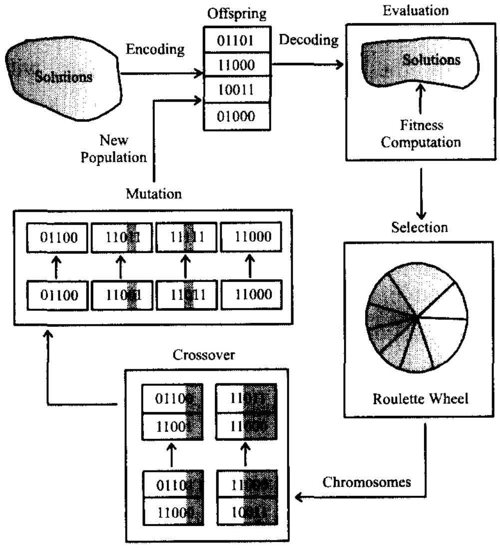


Fig. 1 The operation of genetic algorithms

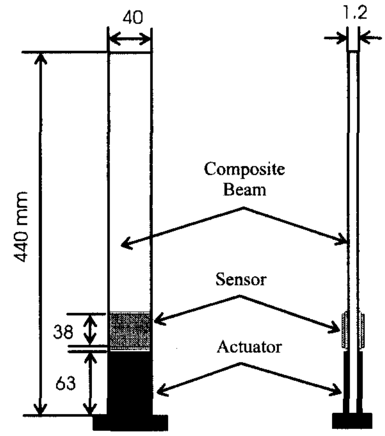


Fig. 2 Smart cantilever beam

To demonstrate the real-time tuning of the PPF controller, a smart beam with piezoceramic sensor and actuator was built as shown in Fig. 2. The sensor output was connected to charge amplifier and the actuator was connected to the output of the power amplifier and the outputs of the charge amplifier and power amplifier were connected to the A/D and D/A converters of the DSP board as shown in Fig. 3. The gain of the power amp was set 10. The output of the charge amplifier was stored as a block unit (3s×1 kHz). The block data was then transferred to a main PC to estimate the fitness. The digital PPF controller was running in 10 kHz but the data-sampling rate was reduced to 1 kHz to minimize the memory use. The Digital PPF controller given by Eq. (3) was realized using TMS320 Floating-Point DSP Optimizing C compiler. The main program stored in the PC updated the PPF filter frequency based on the sensor data and uploaded to the DSP memory block.

The GA program starts with random initial values and obtains the fitness value for each gene, which in fact represents the PPF filter frequency. To calculate the fitness value, the beam was excited with a sine

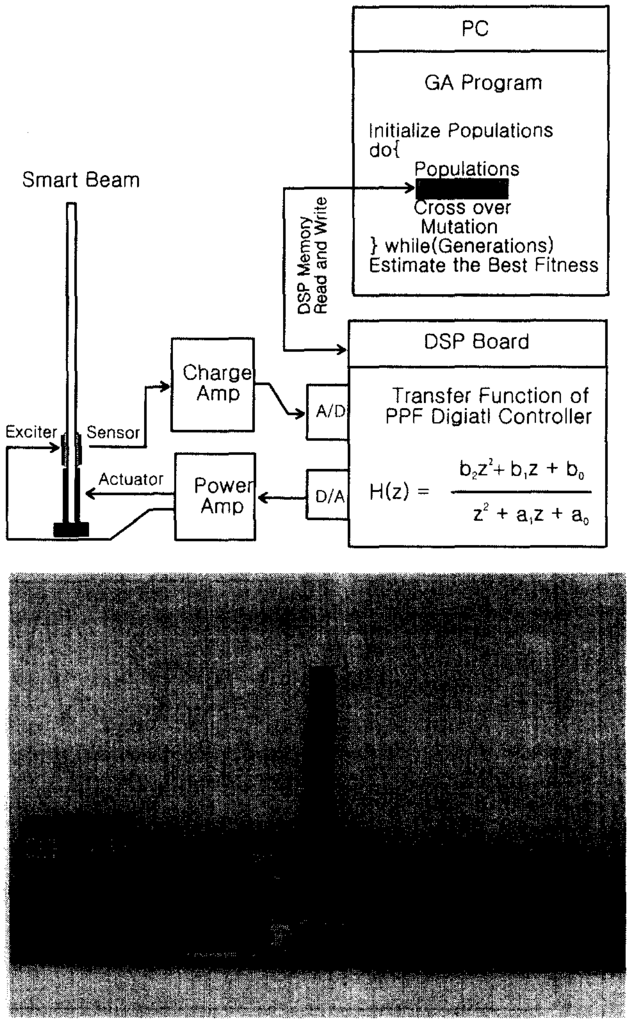


Fig. 3 Experimental setup

wave having the frequency of 10 Hz and the peak-to-peak amplitude of 10V for 1 second. Then the controller with the filter frequency which was uploaded from the main genetic program was turned on and the sensor data was collected for 3 seconds. Hence, the computation time for the performance values of one generation consisting of 20 genes takes about 80 seconds. In addition, the GA takes about 5 seconds in 486 PC. The sensor data is used to estimate the fitness value given by the following equation.

$$Fintness = \left(1000 / \sum_{i=0}^{3000} v_s^2\right)^5 \tag{5}$$

where v_s is the sensor output obtained from the charge amplifier. As indicated by Eq. (5), the fitness value increases as vibrations of the beam are suppressed. Hence, the proposed algorithm eventually finds the suitable PPF filter frequency based on the genetic algorithm. To compare the fitness values of genes to each other, the same condition should be given to the system. This is possible in numerical simulations but impossible in real world. Experimental results show that the fitness value varies even for the same gene value. However, it still shows that GA is capable of tracing the optimal value for the PPF filter frequency.

To investigate the effect of the population size, the crossover probability, the mutation probability on the convergence of the genetic algorithm, the series of experiments as shown in Table 1 were carried out. The maximum and minimum values of the PPF filterfrequency are 5 and 25 Hz, respectively. Any of combinations shown below results in almost the same optimal PPF filter frequency. However, it is necessary to determine the best combination.

Figure 4 shows the effect of the population size on the average fitness. The time required for evaluating each group is proportional to the population size. If the population size is too small, the convergence may become slow down. On the other hand, if the population size is too big, then the computing the performance values for each generation takes too long. As can be seen from Fig. 4, the convergence of the GA does not depend on the population size. As the population size grows, the performance of the GA improves. However, the case P-3 results in excessive running time compared to the case P-2. Hence, it can

Table 1 Case studies

Case	Population Size	Maximum No. of Generation	Crossover Probability	Mutation Probability
P-1	10	50	0.7	0.05
P-2	20			
P-3	50			
C-1	20	30	0.1	
C-2			0.3	
C-3			0.5	
C-4			0.7	
C-5			0.9	
M-1			0.7	0.01
M-2				0.04
M-3				0.07
M-4				0.10

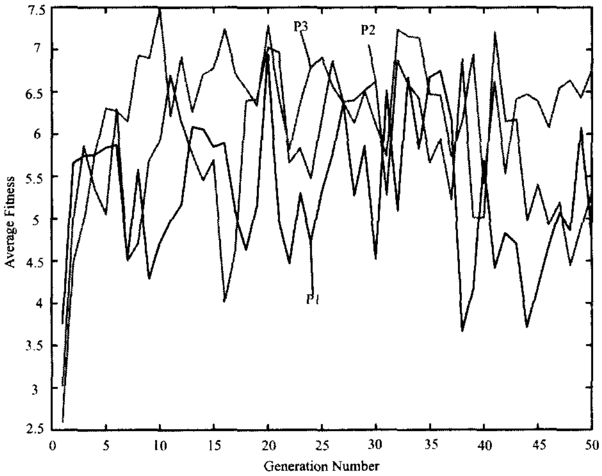


Fig. 4 Average fitness vs. generation(case P-1, P-2, P-3)

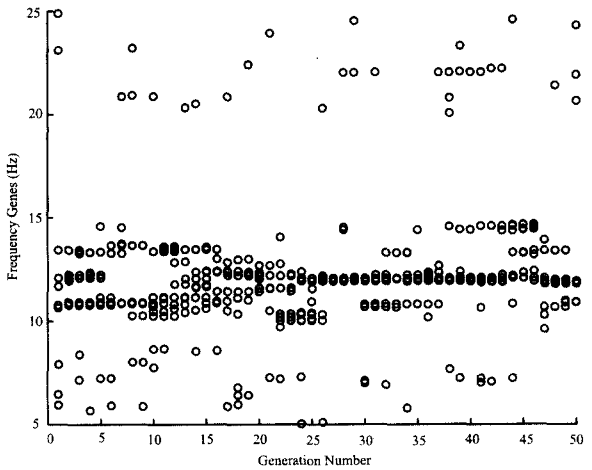


Fig. 5 Distribution of frequency genes vs. generation (case P-1)

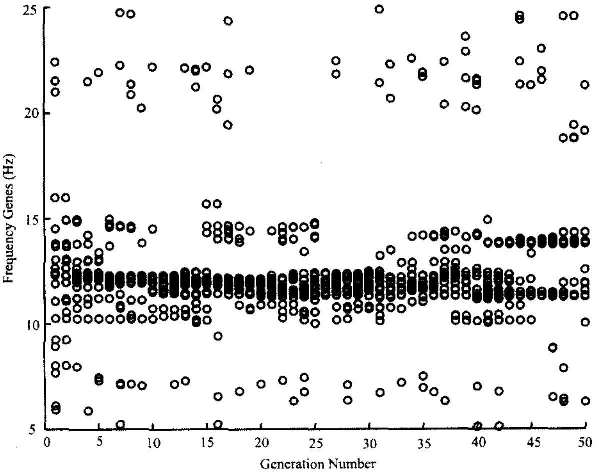


Fig. 6 Distribution of frequency genes vs. generation (case P-2)

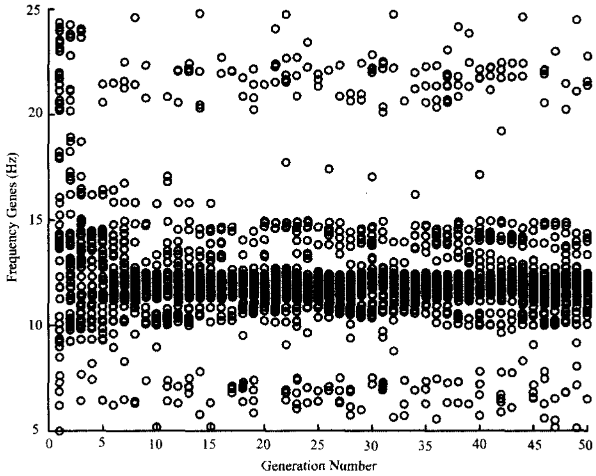


Fig. 7 Distribution of frequency genes vs. generation (case P-3)

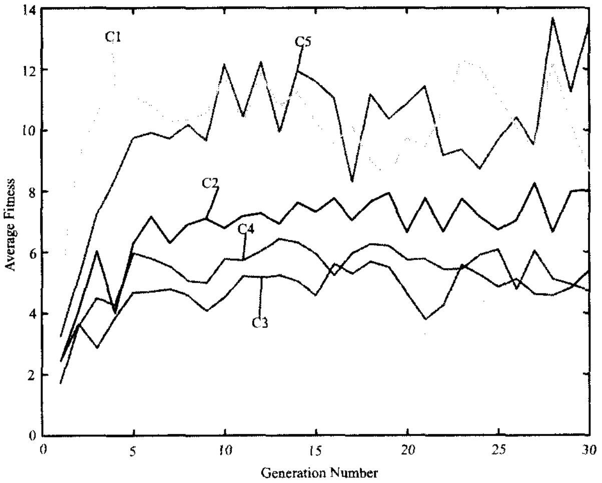


Fig. 8 Average fitness vs. generation(case C-1, C-2, C-3, C-4, C-5)

be said that the population size of 20 is practical for the current vibration suppression experiment. Figures 5 through 7 show the distribution of genes for each case. As can be seen from the figures, genes are loosely populated in Fig. 5 and densely populated in Fig. 7.

The performance of the genetic algorithm depends on the crossover probability. We changed the crossover probability from 0.1 to 0.9 and observed the effect of the crossover probability on the average fitness. It is interesting to see in Fig. 8 that the average fitness reaches the highest value when the crossover probability is either 0.1 or 0.9. Theoretically speaking, if the crossover probability is low, then there exists the possibility of falling into local minimum. On the contrary, if the crossover probability is high, then the genetic algorithms spend time to explore unnecessary region so that the overall convergence may suffer. However, as indicated by Figs. 9 through 13, the crossover probability does not affect the convergence of the GA for the addressed experiment. The distribution patterns of genes are similar for all cases as can be seen from Figs. 9 through 13.

The mutation plays a role of producing a new generation totally different from parents, so that it gives an opportunity of testing a new gene for the fitness. If the mutation probability is low, then the possibility of testing new genes becomes low so that the fittest may be missed. If the mutation probability is

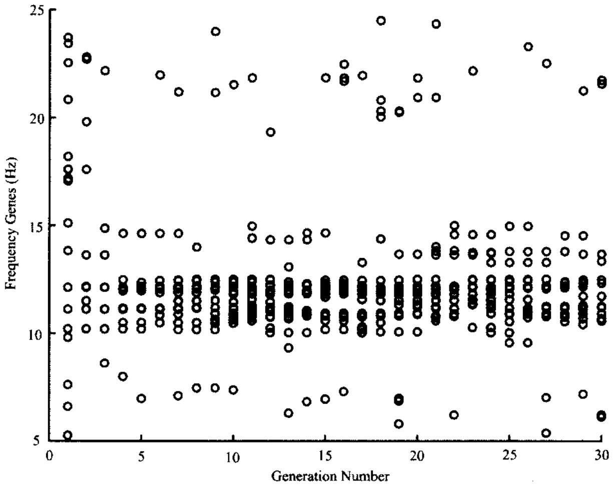


Fig. 9 Distribution of frequency genes vs. generation (case C-1)

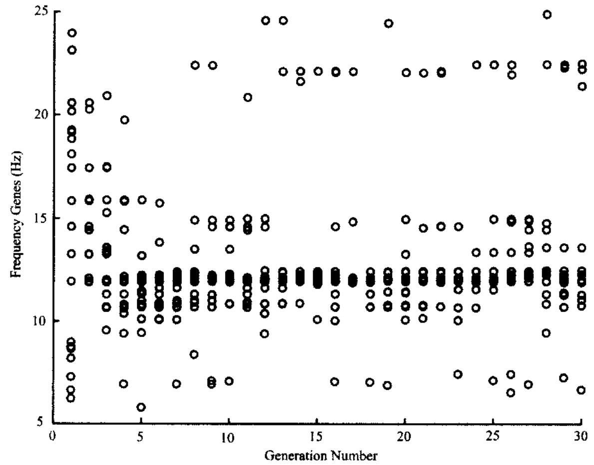


Fig. 10 Distribution of frequency genes vs. generation (case C-2)

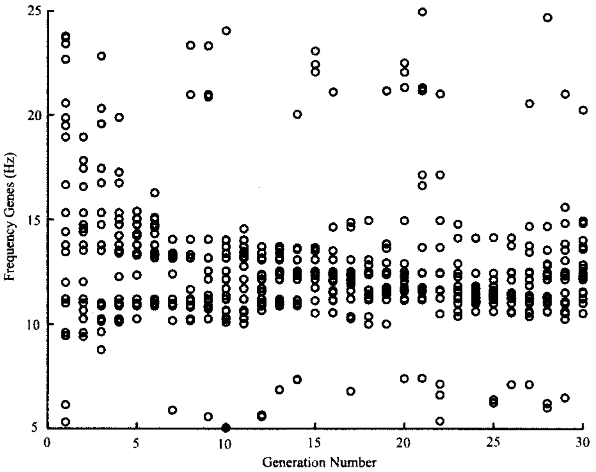


Fig. 11 Distribution of frequency genes vs. generation (case C-3)

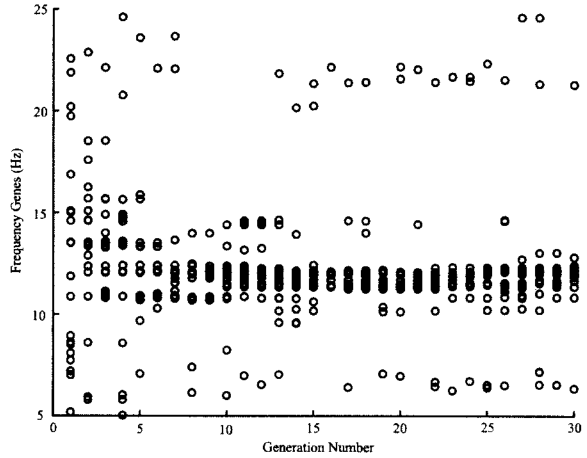


Fig. 12 Distribution of frequency genes vs. generation (cases C-4)

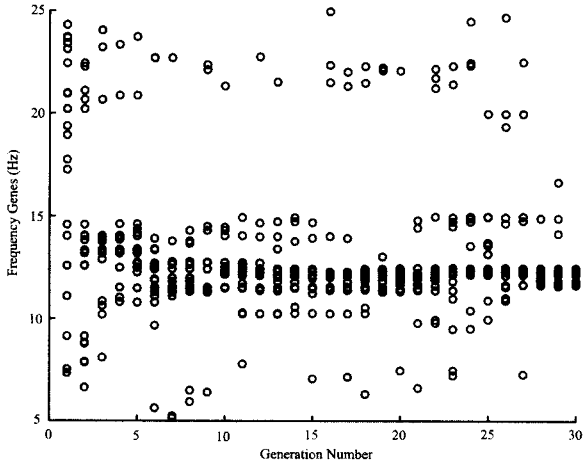


Fig. 13 Distribution of frequency genes vs. generation(case C-5)

high, then the next generation will lose the similarity to the parents so that the convergence may suffer. Figure 14 shows the average fitness values for the cases M-1 through M-4. It is found from Fig. 14 that the case M-2 is the optimal choice. Figures 15 through 18 show that the genes get widely spread as the mutation probability increases. This is the same as expected theoretically.

It can be readily seen from Figs. 5 through 7, 9 through 13, and 15 through 17 that genes get densely populated around 11 Hz as the generation proceeds. The experimental results show that the maximum fitness value was achieved at 10.8755 Hz. The fundamental

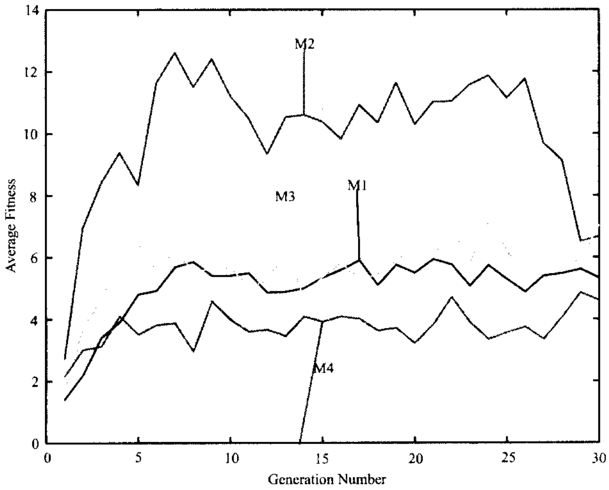


Fig. 14 Average fitness vs. generation(case M-1, M-2, M-3, M-4)

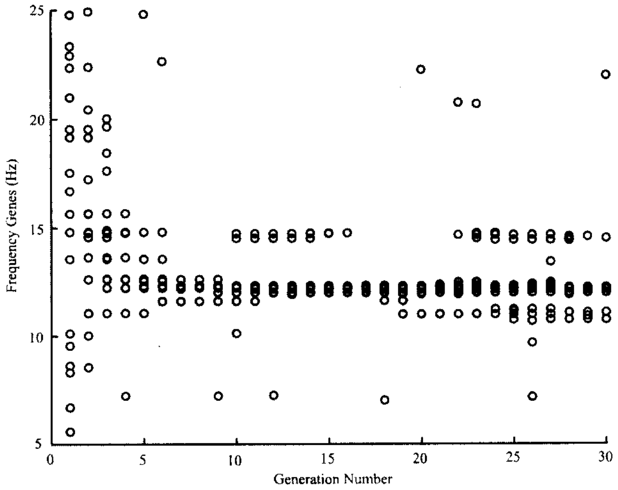


Fig. 15 Distribution of frequency genes vs. generation (case M-1)

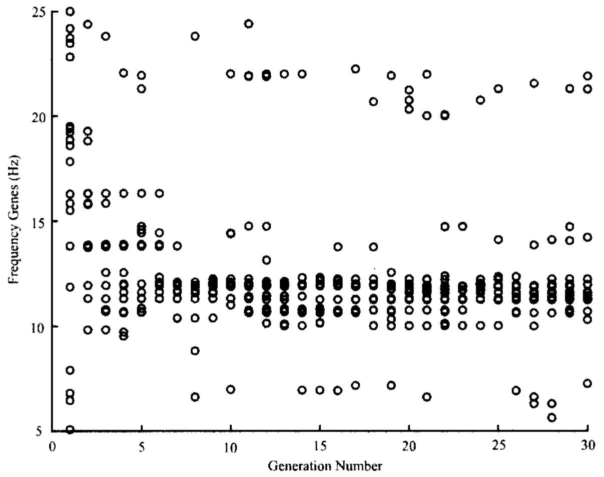


Fig. 16 Distribution of frequency genes vs. generation (case M-2)

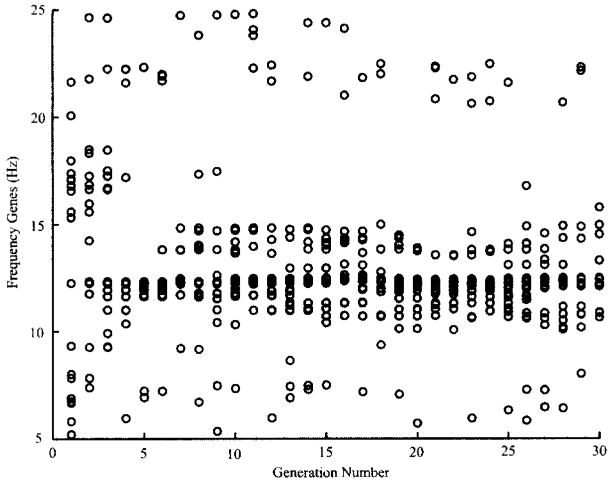


Fig. 17 Distribution of frequency genes vs. generation (case M-3)

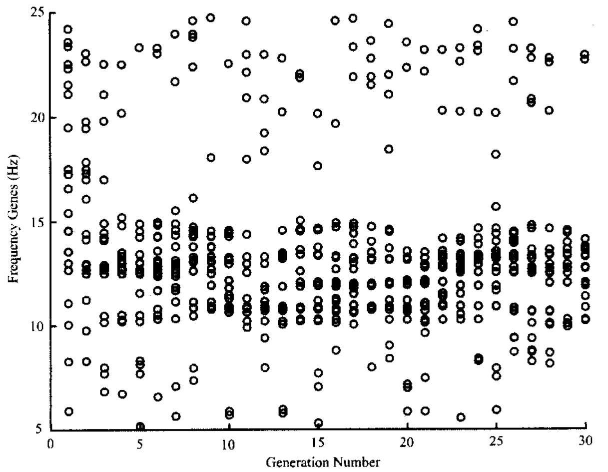
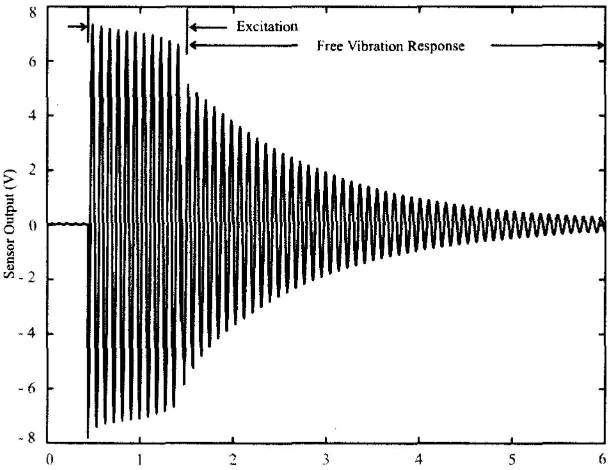


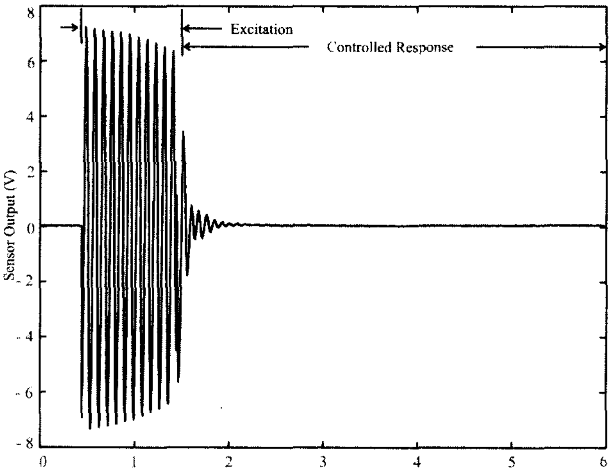
Fig. 18 Distribution of frequency genes vs. generation(case M-4)

frequency of the beam is found to be around 11 Hz, so that the PPF filter frequency obtained by the GA is found adequate.

Figure 19 shows the free-vibration and controlled responses of the beam after the excitation for 1 second, where the PPF filter frequency was set 10.8755Hz. This filter frequency is the best fit over all generations. It can be readily seen in Fig. 19 that the active vibration suppression was successfully.



(a) Uncontrolled case



(b) Controlled case

Fig. 19 Uncontrolled and controlled free vibration responses

4. Discussion and Conclusions

This paper is concerned with the real-time tuning of the PPF controller by the GA. We considered the smart structure equipped with piezoceramic sensor and actuator and tested the effectiveness of the algorithm developed in this paper using the test article. The main advantage of the PPF controller is that it can be easily implemented with analog circuit and the target mode can be controlled separately. However, the PPF controller should be tuned properly to obtain the maximum performance. Hence, the natural vibration characteristics of the structure should be determined a priori either theoretically or experimentally. In this paper, we propose the use of the GA for tuning the PPF controller. The PPF controller is chosen because one control parameter governs the performance of the PPF controller, which is the filter frequency of the PPF controller. The digital PPF controller is stored in the DSP chip and its control parameter is changed in real time by accessing the memory block of the DSP chip.

It is generally accepted in the area of active vibration control that the fundamental mode is the mode of prime interest to be controlled since it dominates the free vibration characteristics. Hence, a single PPF controller is normally tuned to the fundamental frequency of the target structure. The main objective of this paper is to examine the applicability of the GA in real time even though there is only one control parameter to be tuned. The real-time tuning experiments show that the GA is capable of finding a optimal tuning frequency in a few generations. The controlled response confirms that the PPF controller tuned by the GA can effectively suppresses the vibration of the smart beam.

The main problem in applying the GA in real time is that it is difficult to impose the same initial condition on each gene. Hence, the fitness values obtained from the experiment show probabilistic distribution for the same gene, which is the main obstacle in applying the GA on smart structures in real time. However, it was observed from the series of experiments that we were able to find the optimal PPF filter frequency at every attempt since the fitness value peaks around the fundamental frequency of the beam.

Another problem in applying the GA is the determination of the lower and upper bounds of the gene value. If the range of the gene value is too wide, then the convergence becomes slow. Hence, the range of the gene value should be determined carefully. Testing the genetic algorithm on the theoretical model, which is close to the real structure, is a good way of reducing efforts.

Even though the proposed real-time algorithm tunes only one control parameter in the experiment, it can be easily extended to the multiple control parameter-tuning problems. As indicated by the experimental results, the PPF controller tuned by the real-time genetic algorithm successfully suppresses vibrations.

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