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Optimum placement of high-damping rubber dampers for vibration control of structures using genetic algorithm

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ABSTRACT

The optimal placement of a storey-installation type damper for vibration control of structures and building has not yet been established. Therefore, in almost cases, the dampers have been installed uniformly in each storey of the building for example. However, it is thought that this method is not efficient placement to produce the different energy dispassion between low and high storeys. This study attempts to apply the genetic algorithm (GA) to determine the proper distribution for the storey-installation type damper rapidly and easily. In this paper, we extended the fitness function that used before to satisfy multiple design targets and we describe the disposed results and effectiveness that is obtained by this function.

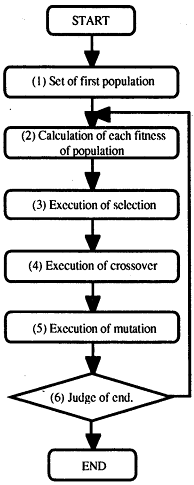
1. INTRODUCTION

In Japan, after 'the Great Hanshin Earthquake' disaster, passive vibration control technologies are becoming more necessary for either industrial or non-industrial facilities and structures than they had been because it was well recognised that the active vibration control technology such as active mass damper systems for high-rise buildings were not capable of reducing the structural responses due to destructive earthquake input. Reduction in the responses will be significantly obtained by installing passive energy absorption systems into the structural members of equipment, facilities or buildings in which the seismic safety against the large inputs is strongly required not only for the improvement of the seismic reliability of the structure but also for maintaining the operational functions during or after earthquakes. From the stand point of view mentioned above, the authors have been carried out the R&D of the high-damping rubber dampers for the industrial facilities and tall buildings [1] and consequently conducting the investigation regarding the proper placement or distribution of the dampers in the structures to obtain the most desirable performance in the limited conditions for a practical design; i.e., allowable locations, cost limitations, design requirements for the dampers and so on. In this study, the authors attempt to apply the genetic algorithm (GA) to determine the proper placements of the storey-installation type damper using a tall building model which representing the structures subjected to seismic inputs.

2. METHODS

2.1 Genetic algorithm

The genetic algorithm is the probability optimization method that simulates the evolution of living things. This method has attracted the attention by searching an optimization problem at high speed. Moreover, this algorithm is flexible method, and it can obtain the good performance against the problem that isn't established methodology to solve yet. The genetic



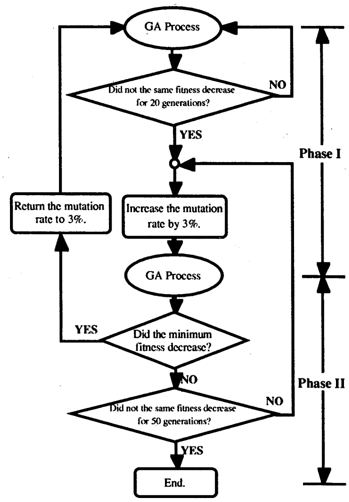


Fig. 1 Flowchart of SGA Fig. 2 Flowchart of the termination routine

algorithm set up the plural search points, and these points can obtain a better solution if the operations that simulate such as the selection, the crossover and the mutation are executed. The feature that GA is different from other algorithm is to have many search points in the search space.

These points also search the optimum solution by co-operating or competing each other. Then, if each search point converged, these points would search the search space in detail by exchanging the information with each other. Moreover, because GA isn't established the methodology, the various methods and parameters are an indefinite factor. However, the general methods execute the procedures that are shown in Fig. 1 . This algorithm is called "Simple Genetic Algorithm". In this study, this algorithm was used as the fundamental algorithm.

In first, the initial populations are generated at random because the search space is generally like a black box. However, if it was known a little in advance, the population probably would be generated around the place that the fitness is high.

Then, a user must decide the expression formality of the population as the option. However, a general method is expressed by the code of binary or decimal. Moreover, the population size is the option. In this study, the population was expressed by the binary code, and the population size was set to 20.

In the next step, the population are evaluated by the fitness function that is decided in advance. In this study, the response value of structure or the number of damper was applied to this function.

Since the evaluation, the main operations that simulate the selection, crossover and mutation are executed for this population. The selection is the operation that survives the individuals that have the good performance to the next generation. If only the individuals that have the good performance were survived, the speed of convergence would become faster, but it shows also the tendency that falls into the local minimum. In this study, the 40% of population survive to the next generation. The mutation is the operation that causes GA to search widely by changing the part of gene.

For these three operations, it is necessary to decide the occurrence probability. These probabilities that used in this study are shown later.

In all search algorithm, the convergence judgement is also one of important algorithm. Figure 2 shows the judgement method in this study. If the same minimum fitness value in the population continues within the 20th generation, the mutation rate is increased by 3 % in each generation on the assumption that the value is in a local minimum (Phase I). The algorithm will be accomplished when the minimum fitness value doesn't change during the following 30 generations. However, if the minimum fitness value changes, the mutation rate is returned to 3%, and the process return to Phase I, again. (Phase II) Therefore, this algorithm is regarded finally as the end when the minimum fitness does not change during the 50 generations.

2.2 Damper and building model

Figure 3 shows the building model and the storey-installation type damper model used for the simulation. The building model is 5DOF system. The natural frequency of the 1st mode of this model is set to 0.30 Hz, and the other is 0.82, 1.3, 1.6, 1.9 Hz respectively. Then, the damping ratio of the 1st mode is assumed as 0.7 %.

In this study, the genetic algorithm is used to decide the number of dampers that are arranged in each storey of the building model. In this time, the total installation number of the damper, ϕ_{total}, was assumed to be fifteen in total:

$$\phi_{total} = \sum_{n=1}^{5} \phi_n \leq 15 \tag{1}$$

where ϕ_n is the installation number of the damper in the n th storey. The gene of GA is defined so that it could choose the number of the dampers discontinuously from 0 unit to 15 units.

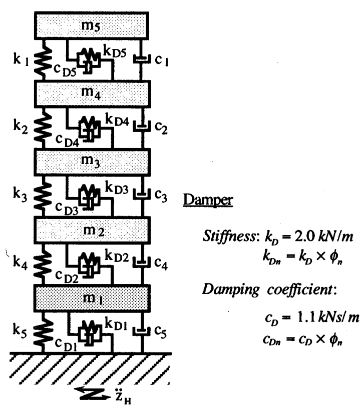


Fig. 3 5DOF structure model used for simulation

Therefore, the stiffness and damping coefficient of the damper in the *n* th storey is presented as the following:

$$c_{Dn} = c_D \times \phi_n \tag{2}$$
$$k_{Dn} = k_D \times \phi_n \tag{3}$$

where c_{Dn} is the damping coefficient of the damper in the *n* th storey, c_D is the damping coefficient per a damper assumed as the storey-installation type damper, k_{Dn} is the stiffness of the damper in the *n* th storey, k_D is the stiffness per a damper assumed as the storey-installation type damper. Besides, if the damper is arranged uniformly in each storey that is normal installation way in practical, three dampers will be installed respectively in a storey.

Moreover, two kinds of the input excitation waves were used in this simulation. El Centre NS (Imperial Valley earthquake , 1940) and Taft NS (Kern Country earthquake , 1952) were as an example of the short periodic seismic wave and Akita NS (Nihon-kai Chu-bu earthquake , 1983) was as an example of the long periodic seismic wave. The maximum accelerations of all seismic waves are adjusted to 1.0 m/s^2.

Table 1 shows the minimum fitness values and the damper arrangement shapes that are the proper arrangement shape for the building against each seismic wave. This result indicates the correct values because these values were calculated beforehand against 3876 total combinations in which 15 dampers were installed in the building model. Moreover, Table 2 shows the minimum fitness in the case that the dampers are installed uniformly to the building. These values become a performance index of the GA solution.

Table 1 Correct value and damper arrangement

Input Wave	Arrangement shape $\phi_1 \rightarrow \phi_5$	Minimum fitness m/s^2
El Centro NS	1 5 3 3 3	0.3689
Taft NS	1 5 5 3 1	0.1284
Akita NS	2 2 4 4 3	0.5357

Table 2 Minimum fitness value in case of the uniform arrangement

Arrangement shape		Minimum fitness value (m/s^2)		
	$\phi_1 \rightarrow \phi_5$	El Centro NS	Taft NS	Akita NS
Uniform arrangement	3 3 3 3 3	0.4123	0.1643	0.5443

2.3 Parameters for genetic algorithm

Because GA isn't established the methodology, all parameters and methods of GA must be decided by trial and error or by experience according to various problems. Especially, to decide the rate of crossover and mutation is very important for the convergence solution or the calculated frequency in GA. Therefore, the relation between a parameter and the search performance of GA were investigated before.[2] The parameters that were obtained by this investigation are shown in the following.

Population size: $N = 20$
Crossover rate: $c_r = 0.9$
Mutation rate: $M_r = 0.03$
Selection method: Elite strategy
Crossover method: One-point crossover

The elite strategy used in selection keeps some elite individuals unconditionally in the population with the optional rate at the next generation. The rate, which means priority existential rate to the next generation, was set to 40%.

Figure 4 shows a method to convert the gene of GA to the number of damper. These are expressed by binary codes. The numbers of damper that were installed in a floor are expressed by 4 bits of binary codes. Then, the last 4 bits of binary codes shows the total number of damper that are installed in this building. However, if the number of damper isn't the design condition in the fitness function, this part is disregarded and the total number of damper is 15 units. These code are converted from the binary code to the decimal code,N_{GA} , at first as shown in the figure. Then, in order that the total of N_{GA} doesn't exceed the upper limit of the total of damper, the correction value a is multiplied to N_{GA}.

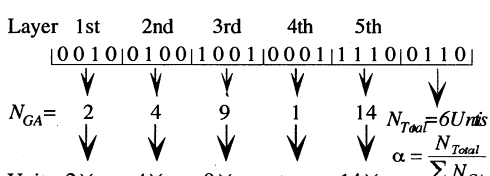


Fig.4 the convertsion method from the gene of GA to the number of damper

2.4 Fitness function

In generally, if a purpose is optimized on the several conditions, the searching area ought to be limited through the several processes. However, because the designer's opinion also influences that process, it is usually difficult to apply the mathematical programming. Therefore, in this study, "the weight method" that is one of the method of optimizing for many purposes were applied. This method is defined generally as following.

$$Minimize \sum_{k=0}^{n} w_k f_k(x) \tag{4}$$

where $f_k(x)$ is an optimization item, and w_k is weight values that show levels of priority among optimization items. This method's purpose is that the summation of the product of $f_k(x)$ and w_k makes minimum. Then, as Equation (5) indicates, the weight value w_k is defined as the optional positive real number that summation is 1. This method has a feature that can apply flexibly to variegated request by adjusting weight value.

$$w_k \geq 0, \quad \sum_{k=0}^{n} w_k = 1 \tag{5}$$

However, in this method, if the design condition's units are different each other, it is inconvenient for the optimization. Then, by comparing the target values and GA's solution, these values are transformed into the non dimensional number such as following.

$$f_k(x) = \frac{Response\ value\ (\ e.g.\ Solution\ of\ GA\ )}{Target\ value\ (\ e.g.\ Solution\ of\ Uniform\ disposition\ )} \tag{6}$$

In that result, even if the design condition's units are different, these conditions can be compared in the same standard.

The target values were set the solution of the uniform arrangement in this study.

3. RESULTS

In this study, the damper arrangements that show the fine performance against the plural design conditions were sought. This paper shows the damper arrangement against the two purposes. The purposes of these damper arrangements are that one is that the response accelerations of the structure are reduced against plural seismic waves, and the other is that the response acceleration of the structure and the number of damper are reduced.

3.1 Example 1 : Reduction of the response accelerations of the structure against plural seismic inputs

In this paragraph, the damper arrangement was sought that reduces the response accelerations of the structure against plural seismic wave inputs. Then, the feature of this damper arrangement shape is considered. As an example, the result when two kinds of seismic waves were induced is shown. The fitness function of this simulation is shown such as following.

$$f_k = \sum_{i=1}^{2} \left[w_i \times \frac{RMS(\ddot{x}_i)^{GA}_{wave\,i}}{RMS(\ddot{x}_i)^{Target}_{wave\,i}} \right] \tag{7}$$

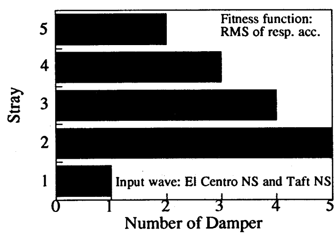
where $RMS(\ddot{x}_i)^{GA}_{wave\,i}$ and $RMS(\ddot{x}_i)^{Target}_{wave\,i}$ are the RMS of response acceleration of the structure and w_i is the weight value.

For simulation, two seismic waves were selected from 3 kinds of seismic waves derived before. The combination of the seismic wave inputs is the 2 cases as following.

- Case I: El Centro NS wave and Taft NS wave
- Case II: El Centro NS wave and Akita NS wave

In this simulation, the weight value was set to 0.5, and the target value is the response acceleration in case of the uniform arrangement against each seismic wave.

Figure 5 shows the damper arrangement shape in Case I, and Fig. 6 shows that the arrangement shape in Case II. Then, Fig. 7 shows the proper damper arrangement shapes against each seismic wave in order to compare the feature of these damper arrangement shapes. In this building model, in order to reduce a response acceleration, Fig. 5 and 6 shows that many dampers should be arranged around a peak of the 2nd mode. Then, these arrangement shapes are under the influence of the proper arrangement shape of each seismic wave.



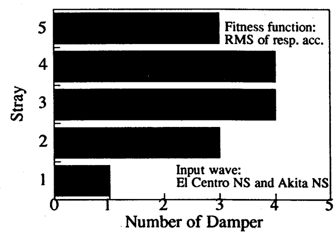


Fig. 5 Damper arrangement shape of CASE I   Fig. 6 Damper arrangement shape of CASE II

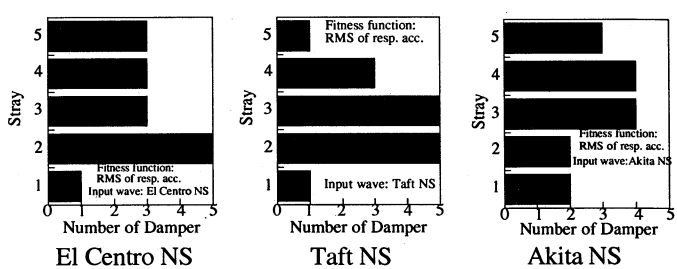


Fig. 7 Proper arrangement shape against each seismic wave

Table 3 shows the response results of these damper arrangements. In Case I, the response accelerations were reduced to about 90% against the El Centro NS and to about 78% against Taft NS compared with the uniform arrangement. From these results, to obtain the damper arrangement that reduces the response value against plural seismic waves was succeeded. In Case II, the response acceleration was reduced to about 93% against the El Centro NS inputs, however was increased to about 102% against the Akita NS inputs compared with the uniform arrangement.

Table 3 Response results

	Acc. with El Centro NS (m/s^2)		Acc. with TaftNS (m/s^2)		Acc. with AkitaNS (m/s^2)	
Input wave	GA solution	Target value	GA solution	Target value	GA solution	Target value
El CentroNS&TaftNS	0.3700	0.4123	0.1289	0.1643	-	-
El CentroNS&AkitaNS	0.3850	0.4123	-	-	0.6993	0.6836

3.2 Example 2 : Preservation of the response performance and reduction of the number of damper

From a requirement of a cost reduction, the total number of the dampers should be reduced as possible. However, since keeping a vibration control performance is the necessary condition, the damper arrangement to satisfy this conflicting condition was searched by GA. To execute this search, the number of dampers was added to one of the optimization condition of the fitness function. Then, the fittness function is shown as following.

$$f_k = w_1 \times \frac{RMS(\ddot{x}_{GA})}{RMS(\ddot{x}_{Target})} + w_2 \times \frac{D_{GA}}{D_{Target}} \tag{8}$$

where D_{GA}, D_{Target} is the number of damper. The target values in this equation also are the response acceleration and the total number of dampers that the damper installed uniformly in the building model. Moreover, it was considered that keeping the vibration control is more important than reducing the number of damper. Therefore, the weight values were established to attain this purpose. ($w_1 = 0.75$, $w_2 = 0.25$)

Figure 8 shows the damper arrangement shapes that were obtained by searching for the above condition. From these results, all arrangement shape is similar to the arrangement shape of Fig. 7.

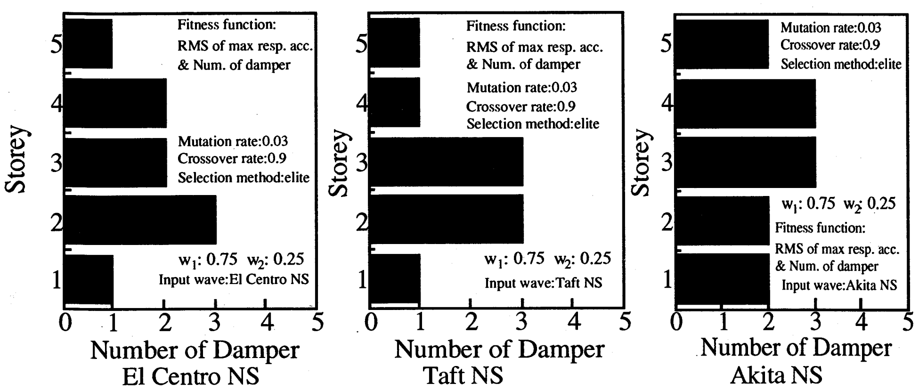


Fig. 8 Damper arrangement shape

Table 5 shows the results of the response acceleration and the number of dampers. This table shows that the response accelerations of the building were reduced to about 97% against El Centro NS and to about 85% against Taft NS. Moreover, these results also show that the number of damper was reduced to 9 units against 15 units of target.

The number of damper against Akita NS inputs was reduce to 80%. However, the response acceleration increased to about 102% compared with the target value. This reason was caused by being unsuitable of the setting of the weight value.

Table 5 Simulation results

	Max. response acc. RMS (m/s^2)		Number of Damper	
Input wave	GA solution	Target value	GA solution	Target value
El Centro NS	0.4000	0.4123	9	15
Taft NS	0.1395	0.1643	9	15
Akita NS	0.5565	0.5443	12	15

In such a case, we solved by being bigger a weight value that multiplies for the part of a building response than the number of damper. Figure 9 and table 5 shows the results in case of setting the weight values, $w_1=0.9$ and $w_2=0.1$. The result shows that the response acceleration is equal to the target value in spite of reducing the number of damper.

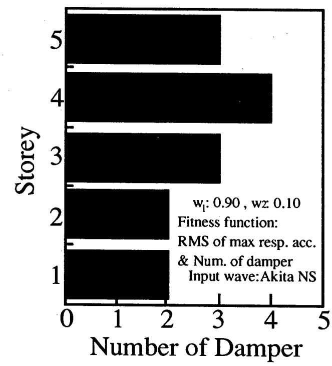


Fig. 9 Damper arrangement shape

Table 6 Simulation results

	Max. response acc. RMS (m/s^2)		Number of Damper	
input wave	GA solution	Target value	GA solution	Target value
Akita NS	0.5429	0.5443	14	15

Therefore, in this study, it was shown that this system could comply with the user's various requirements by setting the weight values in the fitness function suitably.

4. CONCLUSION

This paper showed the results of the damper arrangements and the response results to satisfy the multiple design condition regarding vibration control requirements of structures and buildings. Moreover, this paper also showed that this system could comply with the user's requirement flexibly by setting the weight value suitably. Although a user has to decide these parameters through trial and error because there is no efficient methodology currently, this algorithm seems to be very useful to design a proper installation of the dampers to mitigate the seismic response of complex structure easily found in the nuclear or non-nuclear field.

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