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STUDY ON APPLICABILITY OF SEMI-ACTIVE VARIABLE DAMPING CONTROL ON BRIDGE STRUCTURES UNDER THE LARGE EARTHQUAKE MOTION

Yasunori MIYAMORI[1] and Takashi OBATA[2]

SUMMARY

Vibration control is effective method to improve safety and serviceability on bridge structures. Recently, advanced control methods such as hybrid system and semi-active system are investigated by many studies. Semi-active control system restrains vibration of structures by additional damping or stiffness, and this system can be driven by small power. In this study, semi-active vibration control analyses are performed on a cable structure model and a steel tower model by using variable damping system. Since it is difficult to design semi-active control rules by human experience, control systems are optimized by using Genetic Algorithm (GA) from response energy of structural model. From analytical results, semi-active control system has good control effects for seismic excitation. In consideration of practical use, semi-active control system has suitable applicability for vibration control on bridge structures.

INTRODUCTION

Vibration control is known for effective method to improve dynamic stability and vibration serviceability of structures (Housner et al. [1]). Applicability of seismic vibration control has been investigated mainly on tower buildings under small or medium earthquakes. There is difficulty to use seismic vibration control for bridge structures because of problem on power resources and long-term maintenance.

Several methods of vibration control have been developed such as passive control, active control and semi-active control. An active control system has superior vibration control capacity in comparatively wide frequency range. However, active control system often demands large energy and advanced control rules. In the case of AMD system applied to active control on bridges, large space and power resource are required for control devices. In recent years, semi-active control systems are researched as more practicable method on bridge structures (Soon [2], Iemura et al. [3], Miyamori et al.[4]).The semi-active control system changes structural properties according to dynamic response of structures by using variable stiffness or variable damping system. In the semi-active system, control force acts indirectly to control object, and control devices are driven by small power resources. Therefore, the semi-active control has stability of control system and high energy efficiency. Because of this stability, a simple method like an ON/OFF device control is applicable to the semi-active control system without causing spillover. From above reasons, semi-active control system has possibility of seismic vibration control on bridges by simple control system.

[1] Research Associate, Kyushu University, Fukuoka, Japan. Email: miyamo@doc.kyushu-u.ac.jp
[2] Research Associate, Hokkaido University, Sapporo, Japan. Email: obata@eng.hokudai.ac.jp

In this study, the semi-active seismic vibration control is simulated on a tower model and a cable model by using variable damping system with simple ON/OFF control method (Miyamori et al. [4]). The ON/OFF switching of damping is judged by monitoring 1st or 2nd vibration mode of structural models. The predominance of observed vibration mode is expressed by amplitude of filtered acceleration. Vibration control effect of such system is depended on the thresholds of acceleration and the values of additional damping. The acceleration thresholds and additional damping coefficients are optimized by using GA. When using this semi-active control method, time history response analyses are carried out on forced vibration. As for the excitation wave, strong ground motion of the Kushiro-oki Earthquake and the Hyogo-ken Nanbu Earthquake are used. Active control simulations are also performed to compare the control effect and applicability of control system. Therefore, the purpose of this study is to show the vibration control effects of the semi-active variable damping system on bridge structures as a way of improving seismic performance.

ANALYTICAL PROCEDURES

Modeling of structure

The tower model

Fig.1 is the general view of a three-story steel tower model used in this study. Table 1 is its structural properties. This tower model is assumed to pylon of cable stayed bridges or suspension bridges. The lumped mass system of three-degree of freedom is used for modeling as shown in Fig. 2. The vibration characteristics from natural vibration analysis are summarized in Table 2.

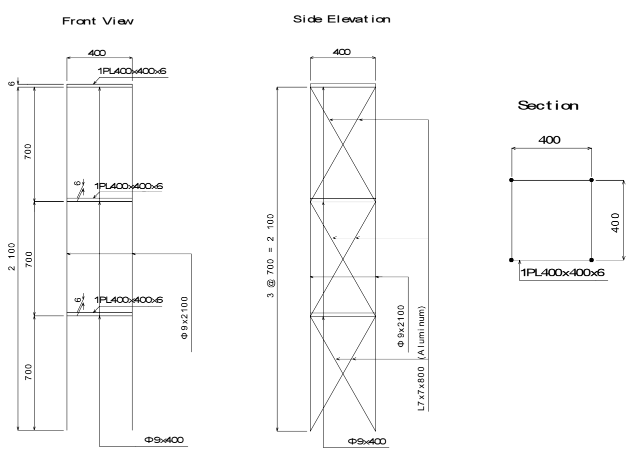


Fig. 1. General view of the tower model

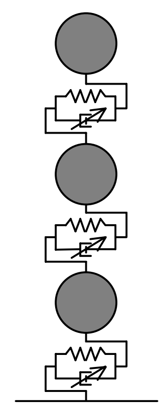


Fig. 2. Analytical model of the tower

Table 1. Structural properties of the tower model

	Mass (kg)	Stiffness (N/m)
Upper story	24.5	94367.3
Middle story	21.5	94367.3
Lower story	19.2	94367.3

Table 2. Natural vibration characteristics of the tower model

	1st mode	2nd mode	3rd mode
Natural frequency (Hz)	1.42	4.14	6.05
Natural period (sec)	0.70	0.24	0.17

Table 3. Structural properties of the cable model

Span length	1955mm	Initial tension	137.2N
Sag	60mm	Unit mass	1.79kg/m

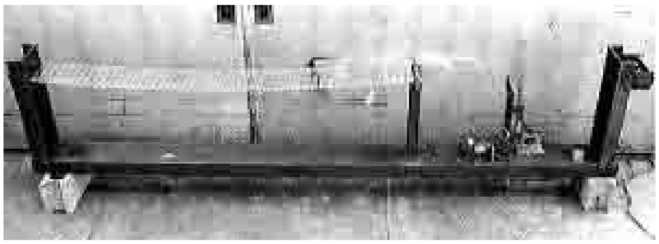


Photo 1. The cable model

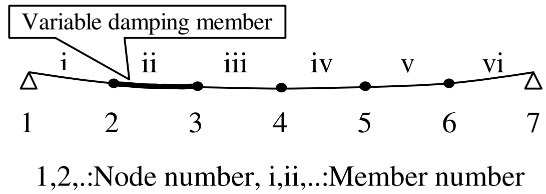


Fig. 3. Analytical model of the cable model

Table 4. Natural vibration characteristics of the cable model

	1st	2nd	3rd	4th	5th
Natural frequency (Hz)	4.38	5.18	6.83	8.83	11.1
Natural period (sec)	0.23	0.19	0.15	0.11	0.09
Effective mass ratio (%)	1.13	73.0	25.3	0.11	0.45

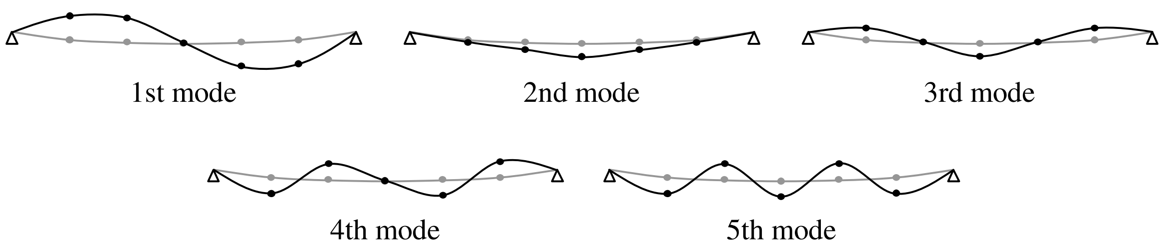


Fig. 4. Vibration mode shapes of the cable model

The cable model

The general view of the experimental cable model is shown in Photo 1, and the structural properties are shown in Table 3. This experimental model is assumed to stress ribbon bridges or catwalks. Slabs of the model are positioned separately to increase ratio of cable stiffness in whole structural stiffness and sag ratio is comparatively small. The consistent mass system of multi-degree of freedom is used for modeling of structure. Fig. 3 is the analytical model. The vibration characteristics are summarized in Table 4, and modal shapes are shown in Fig. 4 from natural frequency analysis. Natural vibration modes are in a narrow frequency range, and symmetric modes are 2nd, 3rd and 5th mode.

The semi-active variable damping control

The equation of motion of multi-degree of variable damping system is given by Equation 1 (Kawashima and Unjo [5]).

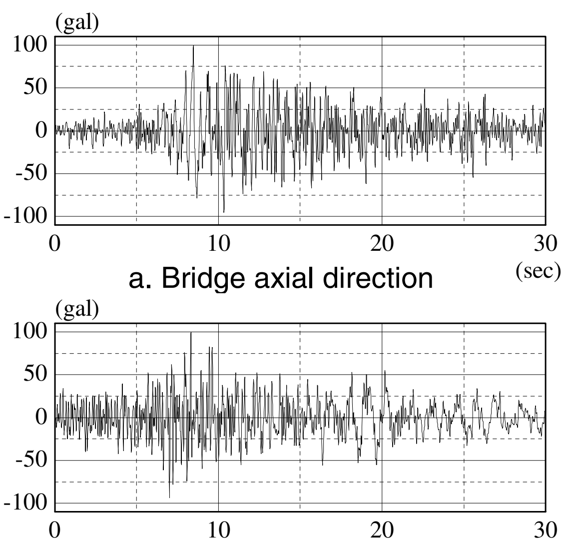
$$\mathbf{M}\ddot{\mathbf{x}}(t) + (\mathbf{C} + \mathbf{C}_v)\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{f}(t) \quad (1)$$

In which **M** is a mass matrix, **C** is damping matrix which is applied a mass proportional damping matrix, $\mathbf{C}_v$ is a variable damping matrix, **K** is a stiffness matrix and $\mathbf{f}(t)$ is a force vector. Numerical analyses are performed by using the Newmark-β method. The parameter β is set to 1/4, and time step Δt is 0.01sec.

In variable damping system, variable damping matrix $\mathbf{C}_v$ in Equation 1 changes depending on dynamic response value of structure. The variable damping matrices are composed from damping coefficients of structural control members. This variable damping can be realized using variable dampers in real structures. However variable damping coefficients of analytical models are decided without considering with real dampers for fundamental numerical simulation in this study. The variable damping is set to each stories of the tower structure. In the cable structure, variable damping is set on the element shown in Fig.3 considering with mode shapes. The decision method of variable damping affects the control result. The actual value of variable damping is determined by GA with the evaluation function considering the structural energy.

The way of damping control is an important problem to establish the semi-active control system. The ON/OFF device control method is adopted in this study for simplicity of control system (Miyamori et al. [6]). In ON/OFF control, 2 states of variable damping of the control system are considered. First state is called ‘Normal State’ which is without variable damping. Second is called ‘High-damping State’ which is a state with variable damping. The ON/OFF switching procedures are devised based on natural frequency mode and dynamic response characteristics in frequency domain. Preliminary dynamic response analyses are performed to these structures to confirm difference of dynamic response characteristics with variable damping and without variable damping. Input acceleration is the 1993 Kushiro-oki earthquake wave observed at the Chiyoda Bridge (see Fig. 5). The bridge axial direction wave is input to horizontal direction of the tower model and the vertical direction wave is input to vertical direction of the cable model. The maximum acceleration of each input wave is converted to 100gal. Fig. 6 is Fourier spectra of response acceleration of the tower model. Fig. 6a is the result of 'Normal State' in whole analytical time and Fig. 6b is the result of 'High-damping State' in whole time. Spectral peaks are occurred in 1st and 2nd mode frequencies in Fig. 6a. The 2nd mode peak disappears in Fig. 6b. The ON/OFF switching is performed based on this difference. The 2nd mode vibration is filtered by a high pass filter from acceleration data at the top of the tower in 'Normal State'. The 1st mode vibration is a filtered by low pass filter in 'High-damping State'. The variable damping is switched by comparison between these filtered accelerations and preset thresholds.

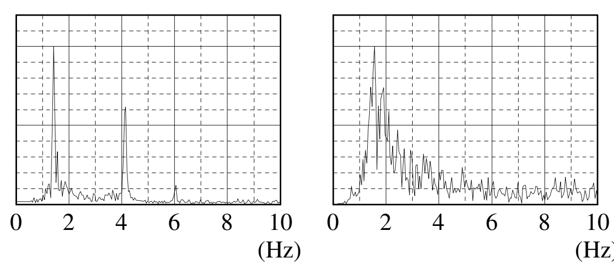
In the cable model, Fig. 7 is results of the preliminary analysis. The 2nd mode peak predominates in both Figs. 7a and 7b. Therefore only the 2nd mode peak of 'Normal State' is filtered from response acceleration of the center of the span.



a. Bridge axial direction

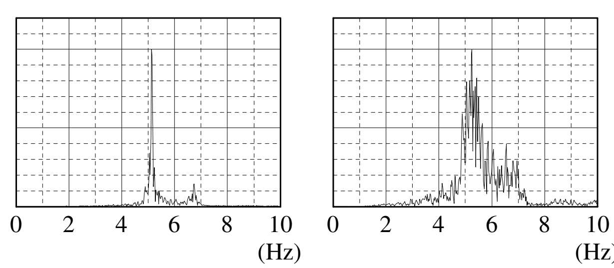
b. UD direction

Fig. 5. Input earthquake waves
(Kushiro-oki Earthquake)



a. Normal State b. High-damping State

Fig. 6. Fourier spectrum of the tower model



a. Normal State b. High-damping State

Fig. 7. Fourier spectrum of the cable model

Table 5. Optimized parameters by GA

Structural model	Variable damping coeffcients	Threshold (acceleration)	
	c_v (Nsec/m)	a_1 (m/sec^2)	a_2 (m/sec^2)
Tower model	1094.8	0.32	2.03
Cable model	33.5	0.16	—

These ON/OFF switching are executed by comparing filtered acceleration and preset thresholds based on the following rules. In 'Normal State', when the filtered acceleration is greater than the acceleration threshold of 'Normal State' that is named 'a_1', the variable damping system changes to 'High-damping State'. In 'High-damping state', when the filtered acceleration is greater than the threshold of 'High-damping State' that is named 'a_2', control system returns to 'Normal State'. In cable model, the threshold of 'High-damping State' is not defined but only the threshold of 'Normal State' is used.
The vibration control effect is directly affected by setting of these acceleration thresholds 'a_1' and 'a_2'. To design the control system in a reasonable manner, GA optimizes these parameters in this study.

Genetic Algorithm
GA is an optimization method that is taken into the concept from the principle of creature evolution (propagation, selection, crossover and mutation) (Davis [7]). The effectiveness of GA is well known as an optimization method without exact solution for solving the problem.
In this study, GA optimizes the variable damping coefficients and acceleration thresholds of the ON/OFF control. The evaluation function is defined as Equation 2 for minimizing the dynamic response of structures.

$$J_{GA} = \sum_{i=1}^{3000} (\dot{\mathbf{x}}^T \mathbf{M} \ddot{\mathbf{x}} + \dot{\mathbf{x}}^T \mathbf{C} \dot{\mathbf{x}} + \dot{\mathbf{x}}^T \mathbf{K} \mathbf{x}) \tag{2}$$

The fitness value of the evaluation function is calculated for summation of kinetic, damping and strain energy. In the optimizing procedure, time history analyses are performed on each individual in a population. The Kushiro-oki Earthquake acceleration wave is used for input wave in GA analyses. As for the process of GA analyses, the selection is used roulette wheel parent selection and the crossover is used 2-point crossover. The population size is 100, the percentage of crossover is 50% and the percentage of mutation is 5.0%. If all genes consisted of same chromosome, GA operation is judged to analytical convergence. From these GA analyses, the acceleration thresholds and the variable damping coefficients of ON/OFF control are determined for two structural models as shown in Table 5.

Active vibration control
Active vibration control analyses are performed to compare the control effect of semi-active control. The control force system like an AMD system with optimal control is applied to the tower model. The optimal control is one of well-known method for vibration control. The control force vector is calculated from multiplication of the feedback gain and the state-space vector. The control force acts the top of the tower model and the elements of the state-space vector are response displacements and response velocities in this study. The feedback gain, which affects the control result, is decided to be same as the response energy in Equation 2 comparing to the case of semi-active control.
In the cable model, the active stiffness control system in which adjustable cable tension changes the structural stiffness is adopted (Miyamori et al. [8]). The maximum control tension is 30.4N to the initial tension. The Fuzzy control theory is used for control algorithm to the cable model. In the Fuzzy control

theory, two antecedent parts and one consequent part of the Fuzzy IF/THEN rules are used. The response velocities and the response accelerations are used in the antecedent part and the control tension is used in the consequent part. The reasoning rule set is composed 25 rules. The triangle type membership functions are used and GA optimizes the maximum or minimum values of the membership functions.

ANALYTICAL RESULTS AND DISCUSSIONS

Analytical cases

Table 6 is analytical cases in this study. Two earthquake waves are input to analytical models. The Kushiro-oki Earthquake waves are used for control system design. The Hyogo-ken Nanbu Earthquake waves observed in JR Takatori Station are also used to compare the control effect under different seismic waves. Figs. 8a and 8b are acceleration waves of the Hyogo-ken Nanbu Earthquake. To compare vibration control effects on both excitation cases, the maximum acceleration values of these waves are converted to 100gal. As for the control system, semi-active control and active control simulations are performed. The variable damping system used for semi-active control in both models. As for active control, the control force system is applied to the tower model, and the active stiffness system used for the cable model.

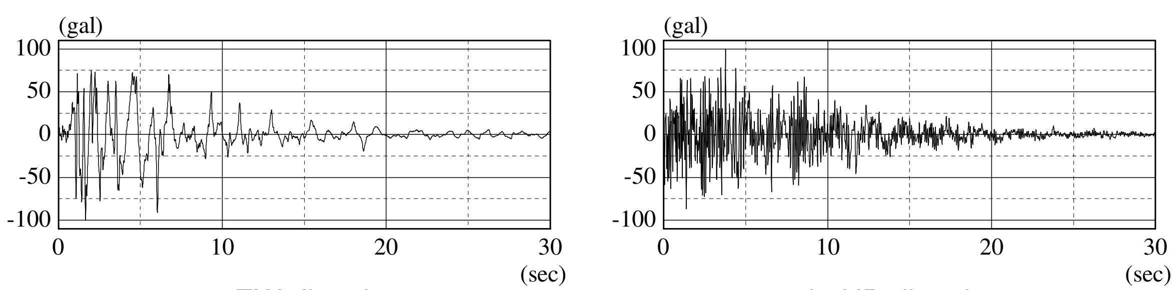
The tower model

Numerical vibration control simulations are performed on forced vibration using two excitation waves. Fig. 9 is analytical results for the Kushiro-oki Earthquake wave. Fig. 10 is results for the Hyogo-ken Nanbu Earthquake wave. In these figures, a and b are response acceleration and its Fourier spectra at the top of the model. To compare the control effects, the Fourier spectrum is non-dimensionalized by peak value of the case of without control. Figs. 9c and 10c are the time history of variable damping in the semi-active control. Figs. 9d and 10d are the time history of control force in the active control. Table 7 is the response energy calculated in Equation 2.

In Fig. 9, the dynamic response of the tower is restrained by both semi-active and active control. The active control force in Fig. 9d acts immediately after start of the simulation and the response acceleration

Table 6. Analytical cases

		Structural model	
		Tower model	Cable model
Input earthquake wave		Kushiro-oki (Bridge axial direction)	Kushiro-oki (UD direction)
		Hyogo-ken Nanbu (EW direction)	Hyogo-ken Nanbu (UD direction)
Control system	Semi-active	Variable damping system (ON/OFF control)	
	Active	Control force system (Optimal control)	Active stiffness system (Fuzzy control)



a. EW direction
b. UD direction

Fig. 8. Input earthquake waves (Hyogo-ken Nanbu Earthquake)

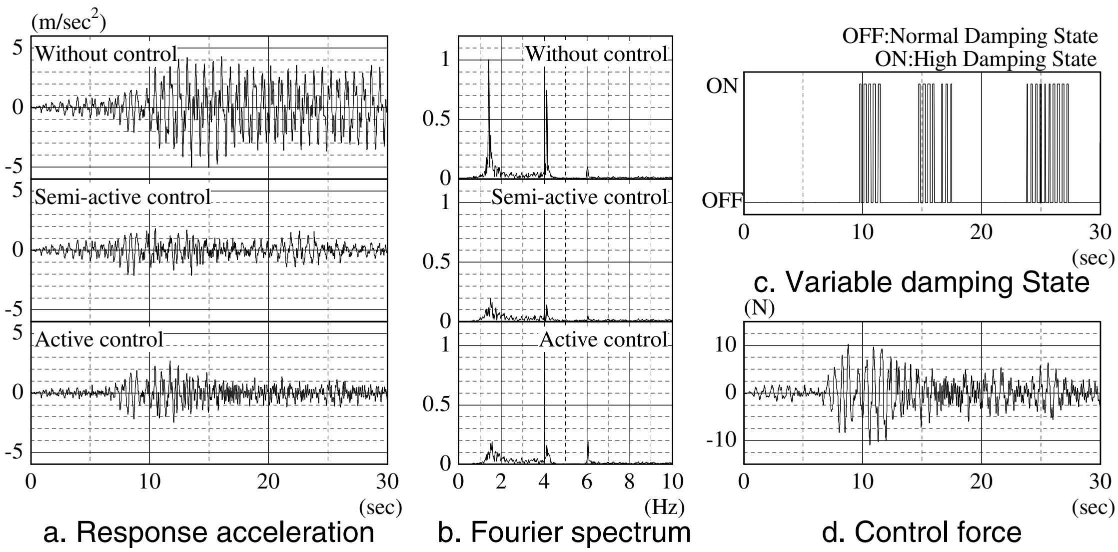


Fig. 9. Analytical results
(Tower model, Kushiro-oki Earthquake)

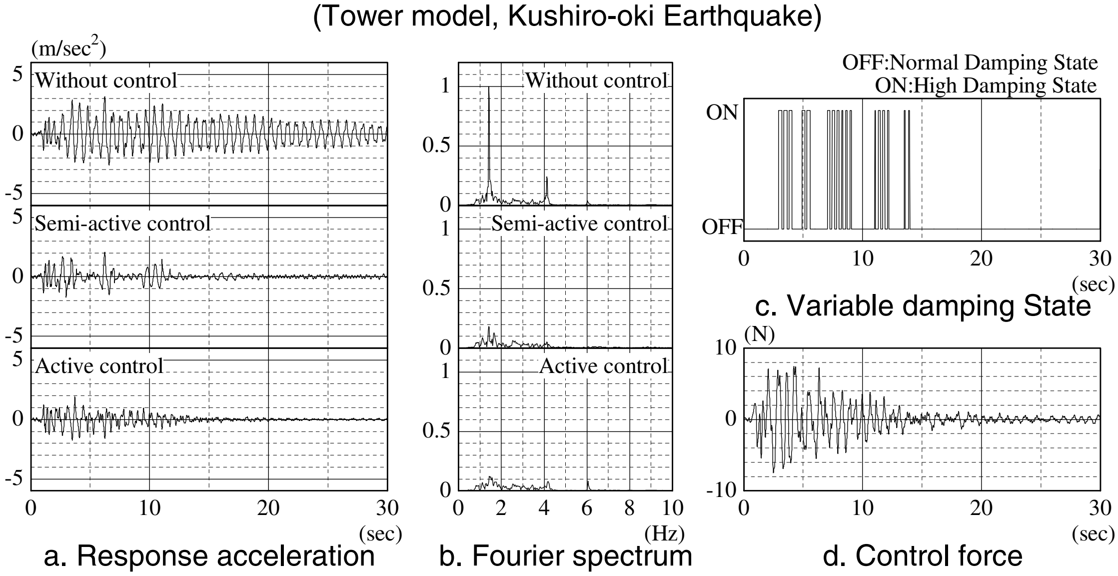


Fig. 10. Analytical results
(Tower model, Hyogoken-nanbu Earthquake)

Table 7. Response energy (Tower model) (Nm)

Control methods	Kushiro-oki Earthquake wave	Hyogo-ken Nanbu Earthquake wave
Without control	284.47	107.50
Semi-active control	21.68	13.35
Active control	30.05	10.73

is reduced in whole time. The variable damping in Fig. 9c is switched to ‘High-damping State’ approximately 10 sec and large amplitude is restrained after 10sec. The 1st mode spectral peaks of semi-active and active control also are decreased to 20% of without control. However the peak of 3rd mode at 6Hz is raised by active control although the peak disappears by additional damping in semi-active control. Moreover, the response energy of semi-active control is reduced to 1/13 in Table 7. Therefore the variable damping system with simple ON/OFF control has good control performance for earthquake excitation. In Fig. 10, vibration control effects can be confirmed almost like a Fig. 9. Inputting large acceleration at 7sec and 9sec, the response acceleration of the tower increases momentary in semi-active control. The vibration control effect of the active control becomes better than the semi-active control in Table 7. Therefore, the semi-active control is more suitable for continuous seismic wave such as the Kushiro-oki Earthquake wave.

The cable model

The vibration control simulations on the cable model are performed using two excitation waves of vertical direction. Fig. 11 is analytical results for the Kushiro-oki Earthquake wave. Fig. 12 is results for the Hyogo-ken Nanbu Earthquake wave. In these figures, a, b and c express the same results as the tower model. Figs. d are the time history of control tension of the active stiffness system. The response accelerations and its Fourier spectra are observed at the center of the span of the cable model. Table 8 is

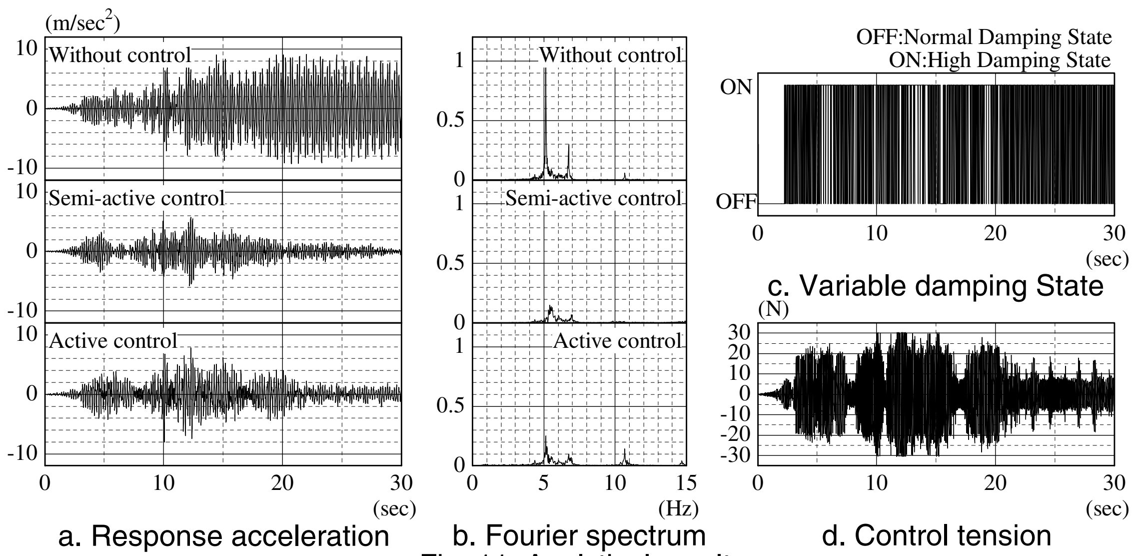


Fig. 11. Analytical results
(Cable model, Kushiro-oki Earthquake)

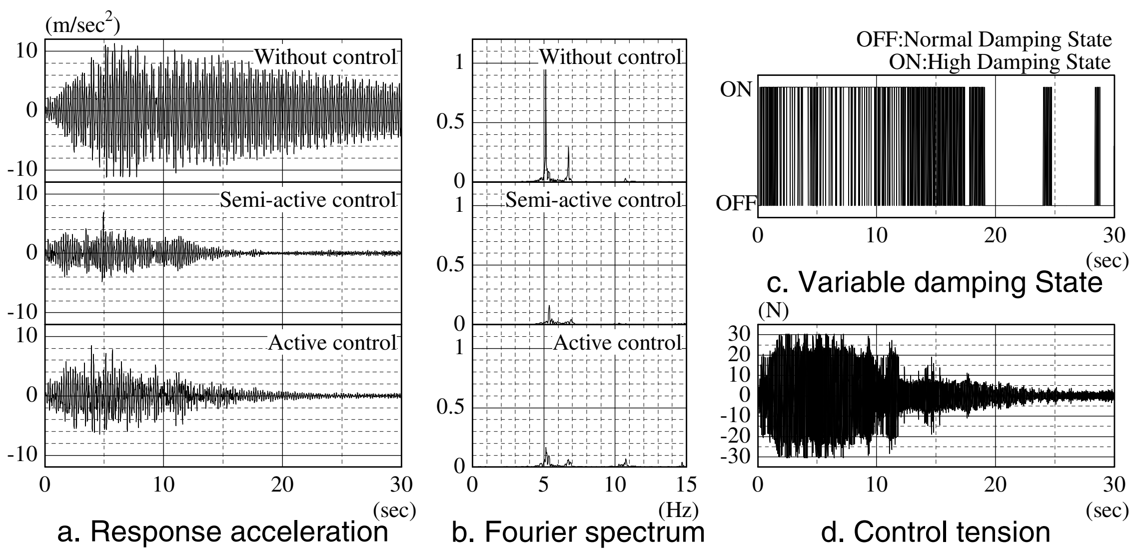


Fig. 12. Analytical results
(Cable model, Hyogo-ken Nanbu Earthquake)

Table 8. Response energy (Cable model) (Nm)

Control methods	Kushiro-oki Earthquake wave	Hyogo-ken Nanbu Earthquake wave
Without control	7.05	7.09
Semi-active control	0.53	0.42
Active control	1.00	0.83

the response energy calculated in Equation 2.

Amplitude of the response acceleration and the spectral peaks are restrained by the same way of the tower model in both active control and semi-active control. The response energy decreases to less than 7% of the energy without control in Table 8. The semi-active vibration control effect is superior to the active control for both input waves.

The semi-active control system for the cable model is designed considering only the 2nd vibration mode. From Fourier spectrum of Figs. 11b and 12b, not only 2nd mode but also 3rd and 5th modes vibration are controlled by semi-active damping control. The 5th mode peak enlarges in the active tension control by changing cable tension. The variable damping control is able to restrain all vibration modes by additional damping of a specific member of the structural model.

From these results, semi-active control system with variable damping has appropriate performance of seismic vibration control in both structural models. As for design procedures, the ON/OFF control by using GA achieves fine control effect by simple and concise methods.

CONCLUSIONS

In this study, semi-active vibration control with variable damping is simulated on the tower model and the cable model. To increase applicability of control system to bridge structures, simple ON/OFF device control optimized by GA is used. Forced vibration analyses are carried out for two cases using different large earthquake waves.

The major conclusion in this study is summarized as follows:

Both Horizontal vibration of the tower model and vertical vibration of the cable model are restrained by the semi-active control and the active control under two large earthquake waves.

The semi-active control with simple ON/OFF control is more efficient than the active control. The additional damping efficiently improves structural damping and the dynamic responses are considerable decreased. Moreover, the control effects are confirmed in not only observed vibration modes but also higher predominant modes.

GA optimizes thresholds of ON/OFF control and damping coefficients of the variable damping system. The evaluation function is defined response energy of structure. This response energy corresponds to amplitude of response acceleration waves and spectrum. Therefore, the response energy is considered to an appropriate index to estimate vibration control effect.

From results of the tower model, the variable damping system has more control effect for continuous earthquake wave with widely frequency components. The control performance declines for impulsive input wave such as horizontal components of Hyogo-ken Nanbu Earthquake wave.

From results and discussions of this study, fundamental possibility of semi-active variable damping system for seismic response control is confirmed. The applicability for real structures will be investigated as an efficient seismic control method.

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