APPLICATIONS OF QUASI-OPTIMIZING CONTROL METHOD FOR ASEISMIC STRUCTURAL RESPONSE CONTROL SYSTEM

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SUMMARY

As an aseismic active response control algorithm, a quasi-optimizing control method has been proposed by authors. The controller installed the quasi-optimizing control method may optimize predicted structural responses for a few kind of trial control forces. Those trial control forces are selected as macroscopical effective values from off-line estimations. As a practical notice, it seems to be reasonable to change ranges and resolutions of the trial control forces according to structural vibration conditions, in order to operate more effective response control. In this paper, the quasi-optimizing control method is modified by introducing a 'switching control force procedure'. In this procedure, the components of the trial control forces are updated according to instantaneous states of excitations or responses by on-line. Numerical simulations for investigating this modified control algorithm are executed on a three-stories structural model which is installed active braces on each story. As a result, by introducing switching control force procedures, it is assured that more effective response reductions and higher control performances may be gained on the quasi-optimizing control system.

INTRODUCTION

To protect structural safety against building vibrations caused by earthquakes, various kinds of vibration control systems have been proposed and investigated. The most important notice for aseismic response control is how to save structural deformations or accelerations as the maximum responses induced by earthquake disturbances during very short event time. There are a few practical buildings which are introduced active vibration control systems for earthquakes, however, the control devices installed in those buildings are almost designed as to stop their operation under strong ground motions. Most of optimal design of active structural response control systems are synthesized as a stabilized feedback controller based on non-excitation conditions after event time durations. So that, those

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systems may not have functioning property for large excitations because that unusual responses or manipulations are assumed for warranting stability of those systems. In order to establish aseismic response control system against strong ground motions, it seems very important to be considered device capacities and control performance in transitional conditions, so that, it may be effective to install feedforward controller to support those requirements. From an emphasis that the aseismic active control algorithm should be more efficient to apply for practical use, an active control algorithm named as a quasi-optimizing control method is proposed by authors [Tachibana et al.,1994 and Inoue et al.,1996,1998]. In this paper, to operate more effective aseismic response control, this control method is modified and advanced by introducing switching control force procedures. Through numerical simulations, effectiveness of this presented active control algorithm are investigated.

Table 1 Natural Periods

Order	Natural periods (s)
1st	0.8
2nd	0.28
3rd	0.19

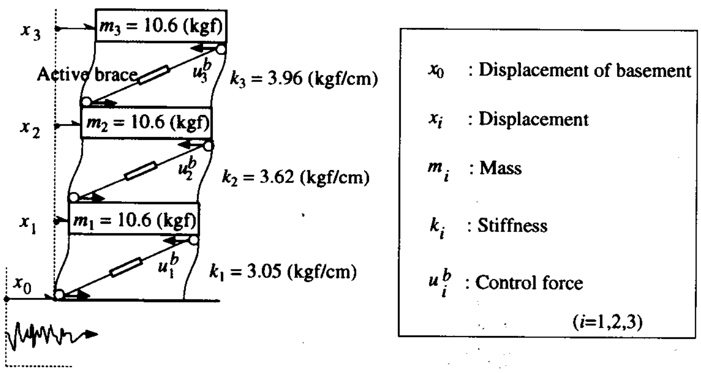


Fig.1 Structural model installed active braces

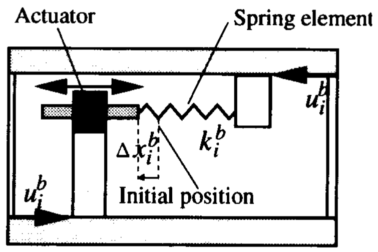


Fig.2 Control device of active brace

2. QUASI-OPTIMIZING CONTROL METHOD

The 'instantaneous optimal control' method [Yang et al.,1987] is very attractive as a control algorithm on the cases that earthquake motions are supposed as external excitations, because it can be considered step-by-step optimal control performances by introducing a time-dependent index function. However, in this method, it is very difficult to deal with the problems for capacities of control devices. In order to overcome such a practical problem, the quasi-optimizing control method has been proposed. In this method, predicted structural responses are optimized by introducing a set of limited kinds of 'trial control forces'. By installing the quasi-optimizing control method, very explicit feedback controller which is assisted in a simple feedforward controllers may be organized. In this paper, to investigate effectiveness of this control algorithm, a three degrees-of-freedom system which is installed three active brace devices in every stories is adopted and examined (as shown in Fig.1). Structural properties of this target model are also described in Fig.1 (those constants are approximately adjusted to the survey values of the experimental model in our laboratory). The active brace of each story has stiffness k_i^b , and the control force u_i^b of each story is generated by the offset Δx_i^b with each actuator (as shown in Fig.2), namely,

$$u_i^b = k_i^b \cdot \Delta x_i^b \, . \tag{1}$$

The equation of motion of this structural model can be described as a following expression.

$$\boldsymbol{M}\{\ddot{x}\} + \boldsymbol{C}\{\dot{x}\} + \boldsymbol{K}\{x\} = \boldsymbol{U}\{u^b\} - \ddot{x}_0\boldsymbol{M}\{1\} \ , \tag{2}$$

in which, $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are matrices of mass, damping and stiffness of the system, and $\boldsymbol{U}$ means a distribution matrix of control forces determined corresponding to system coordinate. $\{\ddot{x}\}$, $\{\dot{x}\}$ and $\{x\}$ are vectors of acceleration, velocity, and displacement of the system. The damping matrix is assumed as proportional to the stiffness matrix (0.5% of damping ratio is assumed for the first fundamental circular frequency in this study). $\ddot{x}_0$ means ground acceleration ($\{1\}$ is a vector which has unit quantities in all components). The natural periods of this structural model are shown in Table 1.

As the first step for installation of the quasi-optimizing control method, sets of trial control forces, which are composed as limited numbers for every control devices, are prepared. Namely, let control forces of each control device assume to limit into a few kinds of trial control forces such as $< \bar{u}_i >$ for the i -th device, where the notation $< \cdot >$ represents a 'set'. In this study, those control forces are limited into 5 kinds, those sets of control forces are selected as the same-step distribution type.

$$< \bar{u}_i > = \{ \bar{u}_{i,j} \mid j = 1, \cdots, 5 \} = \{ -u_{max}, -u_{max}/2, 0, u_{max}/2, u_{max} \}, \quad (i = 1, 2, 3) , \tag{3}$$

in which, u_{max} means the maximum control force which may be corresponding to device capacities. Control force vectors are optionally selected and assembled out of $< \bar{u}_i >$ in each control device as a follow,

$$\{ \bar{u} \} = \{ \bar{u}_1 , \bar{u}_2 , \bar{u}_3 \} , \tag{4}$$

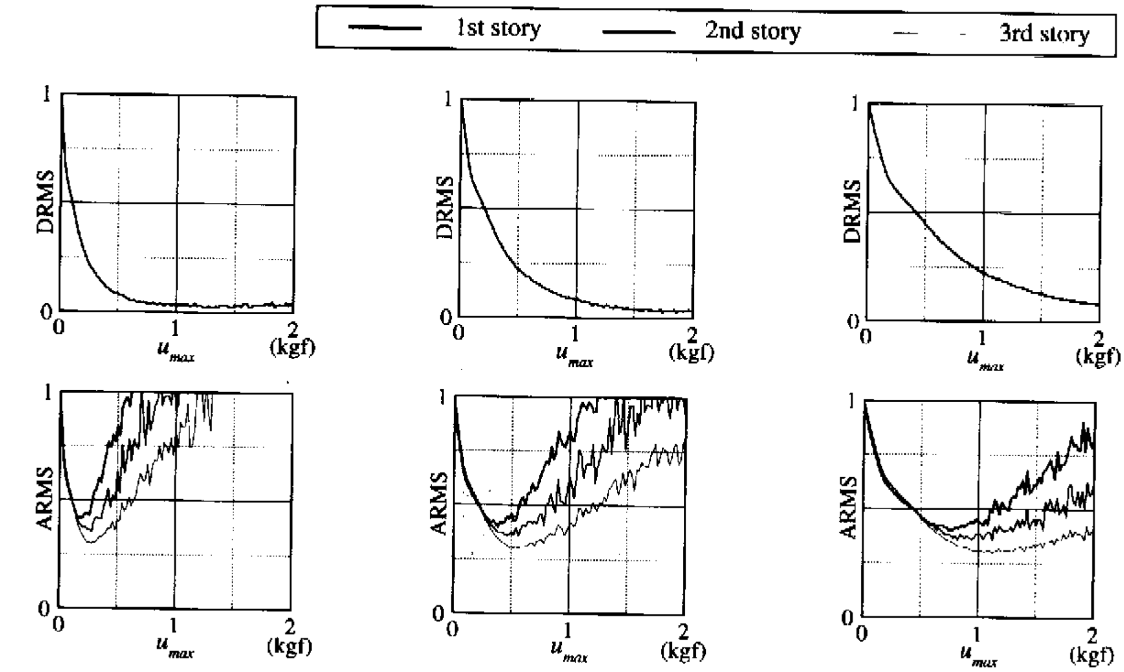
in which, each component of $\{ \bar{u} \}$ is selected as any one value from each set of trial control forces. In this case, the set of control force vectors $< \{\bar{u}\} >$ may be generated from 125 kinds of components which are defined as trial control force vectors. Structural responses for all kinds of trial control force vector are calculated by numerical integrations at each control time step. A 'digital-index function' $\bar{J}(t_{s+1})$ is defined as,

$$\bar{J}(t_{s+1}) = \{ \bar{q}(t_{s+1})^T \, \bar{\dot{q}}(t_{s+1})^T \} \begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix} \begin{Bmatrix} \bar{q}(t_{s+1})^T \\ \bar{\dot{q}}(t_{s+1})^T \end{Bmatrix} , \tag{5}$$

where, $t_{s+1} = (s+1)\Delta t_c$ is the $(s+1)$ -th control time step, and Δt_c means a control interval. $\{ \bar{q}(t_{s+1}) \}$ and $\{ \bar{\dot{q}}(t_{s+1}) \}$ represent the generalized displacement and velocity vector which are predicted at the time instant t_{s+1} . In this study, those quantities are adopted into an inter-story displacement and a velocity, respectively. Q_1 and Q_2 mean weight matrices ($Q_1 = 100$ and $Q_2 = 1$) related those indexes. In each control time step, a set of digital-indexes, $<\bar{J}(t_{s+1})>$ is calculated and a quasi-optimal control force vector $\{ u \}^*$, which makes the digital-index function $\bar{J}(t_{s+1})$ to be minimum, is determined. By comparing this algorithm with the instantaneous optimal control method, it seems that an approximate optimal control force may be gained by this method because a real control force is selected from discrete sets of trial control forces. On the other hands, if the least of extreme values are warranted, it is supposed that almost close to optimal control force may be selected.

3. THE SWITCHING CONTROL FORCE PROCEDURE

To improve feedforward controller of the quasi-optimizing control method, a switching control force procedure is introduced. The set of control forces in Exp.(3) is fluctuated by every 10 steps of control intervals by following this procedures. In this procedures, u_{max} is denoted as $u_{max}(t_s)$, the ranges of control forces become changeable by on-line (the number of trial control forces is fixed). This additional procedure is proposed to solve the following problems: "When using the quasi-optimizing control algorithm, the quasi-optimal control force vector which makes the digital-indexes minimum among the all components of trial control force vectors is selected. However, the range of trial control forces may not be adequate for all kinds of ground motions. So that, the cases which the range of control force is too wide (u_{max} is large) or too narrow (u_{max} is small) may be occurred. In those cases, the selected quasi-optimal control force vector may be far from optimal control force vector which may be given as strict solution". So, it seems to be reasonable that the maximum control force u_{max} should be updated into the suitable value according to structural vibration conditions. As the first step for introduce this 'switching control force procedure', control performances for various values of u_{max} are examined to relate the suitable ranges of control forces with the input motion levels.



(a) 50 cm/s² of the maximum **(b) 100 cm/s² of the maximum** **(c) 200 cm/s² of the maximum**

Fig.3 Relation between control performance and the maximum control force u_{max} (El Centro)

3.1 SWITCHING PROCEDURE BY INPUT LEVEL

To find out the suitable values of u_{max} related to control performances, response characteristics for various ground motion levels are investigated by numerical simulations. El Centro (1940) NS is adopted as an input ground motion, and this wave data is used by scaling down to 50, 100 and 200 cm/s² of the maximum acceleration levels. In numerical analyses, *Newmark's-β* method (β=1/4) is used, integral time step is to be 0.001 s and control time step Δt_c is to be 0.01 s. The control performances related to different values of u_{max} in each cases of different input levels are shown in Figs.3. In those figures, (a), (b) and (c) show the cases that the maximum input ground accelerations are 50, 100 and 200 cm/s², respectively.

As the estimation indexes for response reduction, DRMS(i) and ARMS(i) are used in those figures, those indexes are defined as follows,

$$DRMS\ (i) = x_{rms}\ (i)\ /\ x'_{rms}\ (i)\ ,$$
$$ARMS\ (i) = \ddot{x}_{rms}\ (i)\ /\ \ddot{x}'_{rms}\ (i)\ ,\quad (i = 1, 2, 3)\ , \qquad (6)$$

in which, x_{rms} (i) and $\ddot{x}_{rms}$ (i) mean the RMS (root-mean-square) values of the i-th story's controlled displacements and accelerations for earthquake input time duration (30 s), respectively. x'_{rms} (i) and $\ddot{x}'_{rms}$ (i) mean the non-controlled responses. As seen in Figs.3, it is assured that effective reductions of displacements are observed by increasing u_{max}, however, accelerations are increased after some reduction by increasing u_{max}. By reviewing those results, it may be adequate that suitable values of u_{max} according to each input motion level may be determined from acceleration response curves. So that, in order to save amplifying accelerations, it may be reasonable to regard the u_{max} which can makes accelerations minimize as to be the suitable values of the maximum control forces. In this study, the suitable values of u_{max} are regarded as the considerations for possibility of the control forces which can make the RMS acceleration of the top floor ARMS(3) to be minimum. Corresponding input ground motion levels are evaluated as GRMS which is defined as the RMS values of ground accelerations during 30 s of event time.

Relations between the suitable values of u_{max} and GRMS are shown in Fig.4, in which, triangular plots (▲) means simulated values. As seen in Fig.4, since it seems that suitable values of u_{max} are in proportional to GRMS in elastic conditions, the relation of suitable control forces with GRMS may be represented as a linear expression included an offset. Control forces structural vibrations on non-excitation conditions are considered as this offset value. The maximum control forces $u_{max}(t_s)$ to switch the ranges of control forces according to fluctuation of excitation levels are defined as follows,

$$u_{max}(t_s) = u^*_{max}(t_r \mid r = \mathrm{INT}(s/10)),$$
$$u^*_{max}(t_r) = u^1_{max}(t_r) + u^0_{max}(t_r),$$
$$u^1_{max}(t_r) = 0.028 \cdot \mathrm{GRMS}(0, r-1). \quad (7)$$

In this procedure, 10 steps of control time intervals are used for monitoring ground motion levels, Δt_r ($\Delta t_r = 10 \cdot \Delta t_c$) means monitoring interval time. In the above expressions, the notation INT(·) means generating integer for values in parentheses, u^0_{max} means offset value (which is adjusted to constant of 0.00056 kgf in this case), u^1_{max} means the incremental control force according to monitoring ground motion levels and GRMS(0 , $r-1$) means the RMS value of ground acceleration (GRMS(0 , 0) = 0) which is calculated during (r - 1)-th monitoring time. So that, by every 10 steps of control intervals, the maximum control force $u_{max}(t_s)$ are updated from the Exp.(7) (This values are held until r is increased).

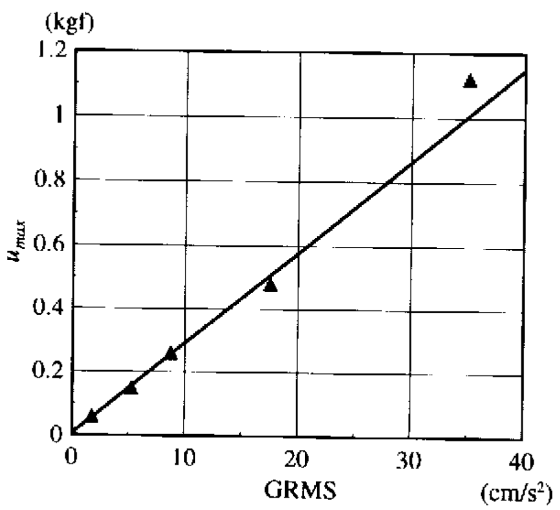


Fig.4 Suitable control force u_{max} related to GRMS (under excitations)

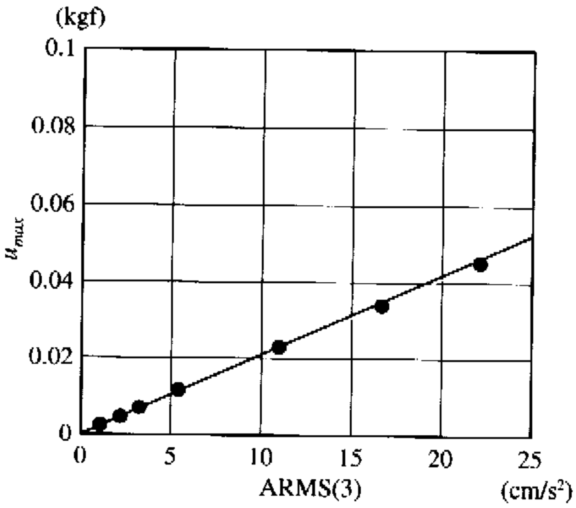


Fig.6 Suiable control force u_{max} related to ARMS(3) (under non-excitation)

3.2 SWITCHING PROCEDURE BY OUTPUT LEVEL

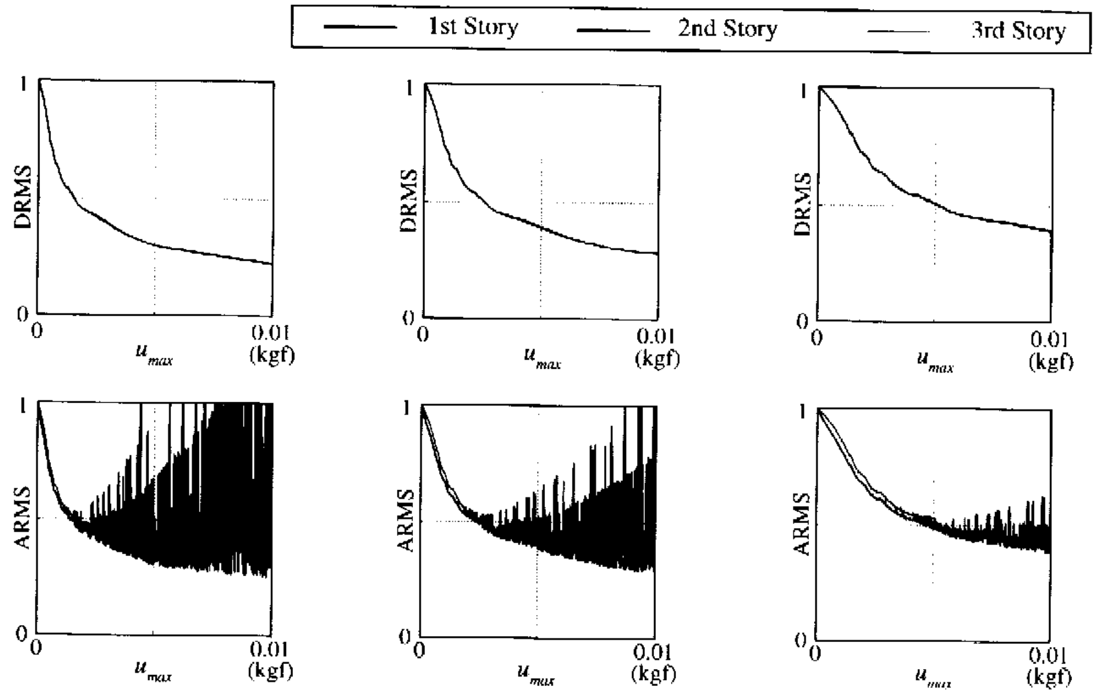
As the another considerations, suitability of the offset values u^0_{max} in Exp.(7) are evaluated through numerical study. The installation of switching control force procedure based on the relation between input ground accelerations and the maximum control forces may be functioned for using as applications of the quasi-optimizing control method in order to gain more effective reductions of structural responses against various kinds excitation levels. Since the maximum control force u_{max} is variable by this procedures based on input accelerations for ground monitoring time Δt_r, the controller may be adoptive for various kinds of ground motion levels. As a practical notice, there are further attentions, so that, it should be evaluated to the suitable control forces related to structural responses.

To find out the relations between structural responses and suitable control forces, control performances for free vibrations are evaluated (as shown in Figs.5). Impulsive accelerations are used as input ground motions, and those impulses are fit to 50, 100 and 200 cm/s^2 of the maximum accelerations. In those figures, (a), (b) and (c) show the cases that the maximum accelerations are to be 50, 100 and 200 cm/s^2, respectively. As seen in Figs.5, displacements are decreasing according to the increment of the maximum control forces. However, accelerations may be unstable by increment of the maximum control forces. Those tendencies may be remarkable for controlling for smaller levels of vibrations.

The suitable control forces may be regarded as the maximum values which make accelerations to decrease without unstable conditions. In this study, those values are selected from response characteristics of the top floor's RMS of accelerations ARMS(3). ARMS(3) are used as the estimation indexes of structural responses (ARMS(3) are calculated for 30 s after input impulse). In Fig.6, the maximum control forces related to ARMS(3) are plotted by circular plots (●). As seen in Fig.6, since it seems that the maximum control forces are in proportional to ARMS(3) in elastic condition, the relation between the maximum control force u^0_{max} (with non-excitation conditions) and ARMS(3) may be expressed as a following expression.

$$u^0_{max}(t_r) = 0.0021 \cdot \mathrm{ARMS}(3, r-1) \quad . \tag{8}$$

It is reasonable to stop control operation when structural responses become very small, so, this expression has no offset value.



(a) **50 cm/s^2 of the maximum** (b) **100 cm/s^2 of the maximum** (c) **200 cm/s^2 of the maximum**

Fig.5 Relation between control performance and the maximum control force u_{max} (impulse)

4. NUMERICAL INVESTIGATIONS OF SWITCHING CONTROL FORCE PROCEDURE

To investigate proposed new procedure for modifying the quasi-optimizing control method, three cases are adopted for comparative studies. Those cases are simulated different kinds of switching control force procedures in each other.

CASE-1 (Fixed Control Force Procedure) :

The maximum control force is fixed to constant value (u_{max}=2.2 kgf). This control procedure is the same with the previous proposed quasi-optimizing control method.

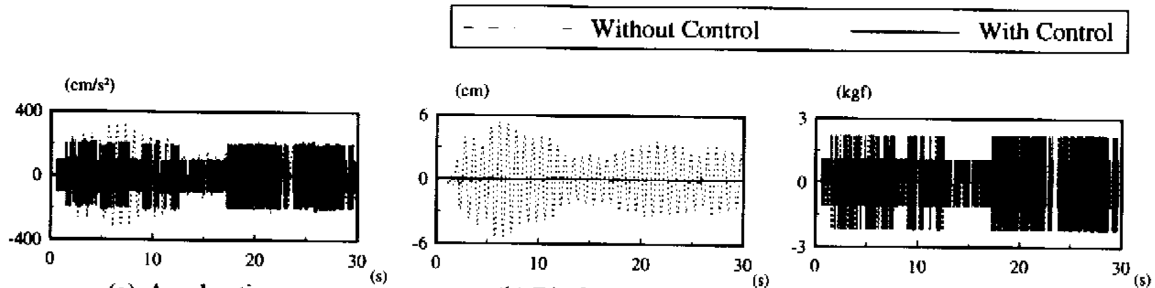
CASE-2 (Variable Control Force referring GRMS) :

The maximum control forces $u_{max}(t_s)$ are switched by every monitoring time interval, by referring input ground motions. The maximum control forces $u_{max}(t_s)$ are determined by introducing Exp.(7) (u^0_{max} is used as constant value, $u^0_{max} = 0.00056$ kgf).

CASE-3 (Variable Control Force referring GRMS and ARMS(3)) :

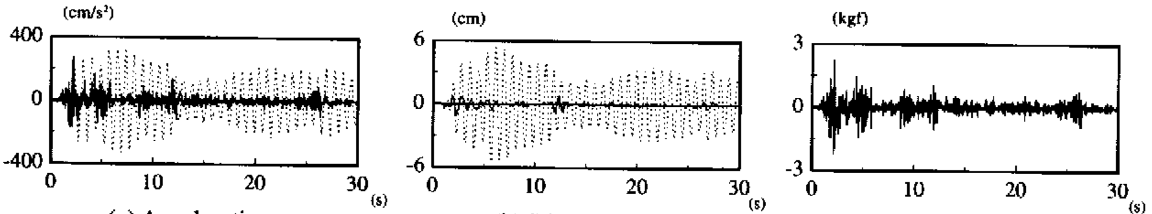
The maximum control forces $u_{max}(t_s)$ are switched by introducing Exp.(7) and Exp.(8) (u^0_{max} is used as variable value by Exp.(8)). So that, the monitorings are operated for both input ground motions and structural acceleration responses.

El Centro (1940) NS, which is scaled down to 100cm/s² of the maximum acceleration, is used as input ground motion. Numerical simulations of response control corresponding to those 3 cases are executed. Time histories of the top story's accelerations, displacements and control forces in the *CASE-1*, *CASE-2* and *CASE-3* are shown in Figs.7, Figs.8 and Figs.9, respectively.



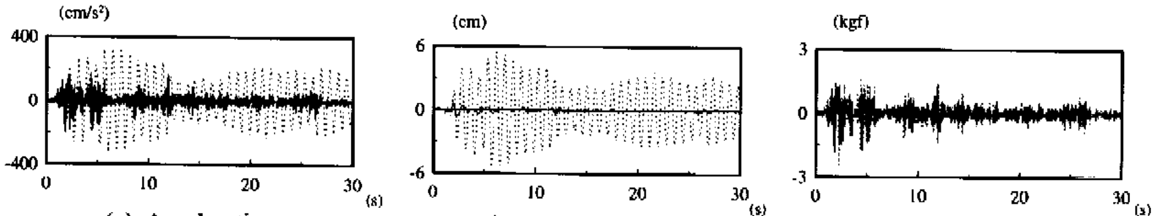
(a) Accelerations (b) Displacements (c) Control force

Fig.7 CASE-1 (Fixed Control Force Procedure)



(a) Accelerations (b) Displacements (c) Control force

Fig.8 CASE-2 (Variable Control Force referring GRMS)



(a) Accelerations (b) Displacements (c) Control force

Fig.9 CASE-3 (Variable Control Force referring GRMS and ARMS(3))

By comparing those figures, it is assured that remarkable reductions of displacements are observed in the *CASE-1*. However, in this case, effect for reduction of accelerations may be very few. In the *CASE-2*, effective reduction of acceleration response can be gained, also good reduction of displacement may be gained and total control forces may become very small. However, reductions of displacements are decreased a little by comparing with the effects in the *CASE-1*. By introducing the switching control force procedures according to both input motion and responses (which is simulated in the *CASE-3*), both accelerations and displacements can be effectively reduced. In this case, control forces may become to the same level with the *CASE-2*, and those levels may become much smaller than the *CASE-1*. The maximum values and the RMS values corresponding to those results are shown in Table 2 and 3, respectively. Those results and considerations mentioned above are more clearly assured by referring those tables. As a results, it is assured that the quasi-optimizing control method which is introduced the switching control force procedures is very effective as the aseismic response control algorithm.

Table 2 Maximum values of the top story

	Acceleration (cm/s²)	Displacement (cm)	Control force (kgf)
Without Control	332.2	5.5	———
CASE-1	242.6	0.7	2.2
CASE-2	280.4	1.2	2.2
CASE-3	199	0.8	2.4

Table 3 RMS values of the top story

	Acceleration (cm/s²)	Displacement (cm)	Control force (kgf)
Without Control	138.3	2.3	———
CASE-1	131.2	0.09	1.44
CASE-2	32.1	0.22	0.32
CASE-3	35.4	0.14	0.37

5. CONCLUDING REMARKS

In this paper, aseismic active vibration control algorithm as advanced applications of the quasi-optimizing control method is proposed by introducing switching control force procedures. Numerical considerations are executed for 3 kinds of case studies. As a result for those comparative studies, it is assured that to change the maximum control force according to both input ground motions and structural responses is very effective for operating high-performed aseismic response control.

6. REFERENCES

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