Position optimization for semi-active control dampers of bridge based on energy consumed[*]

QI Xing-jun[1], LI Xiao-jun[2]
([1] Associate Professor, School of Civil Engineering, Shandong Jianzhu University, Jinan, China)
([2] Professor, Institute of Engineering Mechanics, China Earthquake Administration, Harbin, China)
E-mail: qxj123@163.com

ABSTRACT: The approach of choosing semi-active control damper positions for bridge according to active control consumed energy values is presented. With the calculation and analysis of lognitudinal seismic semi-active control for a long-span rigid-continuous bridge, the validity of this approach is proved. On base of analyzing and summarizing the calculation result, some significative suggestions are presented about damper positions for bridge seismic vibration control.

KEYWORDS: active control consumed energy, semi-active control, rigid-continuous bridge, damper position

1 APPROACH OF SETTING DAMPERS

The optimization of setting dampers for bridge vibration control is complicated. It relates not only the parameters of controlled objects including vibration mode but also the characteristic of external inspiring, characteristic of actors, control approach and expected control effectiveness. Optimization of the actors includes two problems. One is the optimization of number of actors, another is optimization of placement of position of actors. The study for number of actors is not sufficient with the reason of different control devices and control requirements, and study for position of actors is more. There are many optimizing rules in the optimization of actors including least energy rule, rule of least expecting value of performance index, rule of most control force, rule of reliability and rule of some goals optimization, etc [6].

The optimization of dampers is rationally selecting positions of dampers to get the best vibration mitigation effectiveness. For a lot of dampers the energy consumed must to be most to make the effectiveness of dampers best [4].

The kinetic equation of single freedom structural vibration control is

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)+bu(t)=-m\ddot{x}_g(t) \tag{1}$$

In the formula, m is structural mass. C is structural damping coefficient. K is structural stiffness. B is position coefficient of control device. $u(t)$ is control force. $\ddot{x}_g(t)$ is ground motion acceleration and x(t) is structural displacement.

The energy equilibrium equation of single freedom structure is

$$E_K+E_D+E_H+E_C=E_I \tag{2}$$

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In the formula, E_K is relative kinetic energy with $E_K = \int_0^T m\ddot{x}\dot{x}dt$. E_D is structural damping energy consumed with $E_D = \int_0^T c\dot{x}\dot{x}dt$. E_H is structural deformation energy including elastic energy which can be resumptive and plastic energy with $E_H = \int_0^T kx\dot{x}dt$. E_C is energy consumed of control devices (dampers) with $E_C = \int_0^T bu\dot{x}dt$. E_I is ground motion input energy with $E_I = \int_0^T -m\ddot{x}_g\dot{x}dt$. The summation of structural relative kinetic energy E_K and deformation energy E_H is seismic energy E_S absorbed by structure with $E_S = E_K + E_H$.

With definite seismic input energy of E_I, the more energy of E_C consumed by dampers the less seismic energy E_S absorbed by structure. To reduce seismic energy E_S absorbed by structure can reduce structural deformation [5]. Then the most consumed energy of active control can be used to confirm the more excellent positions of semi-active control dampers in bridge structures. Its elementary idea is:

Semi-active control can reduce structural response by changing structural stiffness of damping with a little energy. It use the structural relative displacement of relative velocity to make the semi-active control force possibly realize optimum control force of active control [1]. So we can use the active control theory to guide the setting of semi-active control dampers. First n possible positions of actors are confirmed in bridge structure. Then active control calculation is performed to get the consumed energy of n active control actors in the ground motion durative time. The actors with more consumed energy can offer more to the total control effectiveness. Consumed energy of n actors is arrayed according to their value. The semi-active dampers are set with the positions arrayed by consumed energy value.

This approach of confirming positions of semi-active dampers according to consumed energy of active control is simple and actual, and has great applied significance for the bridge structure with connecting components of bearing and expansion joint. In this paper, the semi-active control seismic response calculation is performed for a long span rigid continuous bridge to confirm the effectiveness and applicability of this approach.

2 CALCULATION MODEL OF BRIDGE

One long span rigid continuous bridge with span combination of 65+160+210+160+65 meters, and the total length is 660 meters. The middle piers are continuous rigid piers and other piers are continuous piers. Double directional sliding bearings are set on the continuous piers. Rigid piers are 40 meters high and continuous piers are 20 meters high. The three dimensional finite element model of the bridge is established with spatial beam elements with main beam and piers simulated in beam element and pier bottom fixed. The total bridge has

52 elements, 55 nodes and 326 freedom degrees. It finite element calculation model is shown in figure 1.

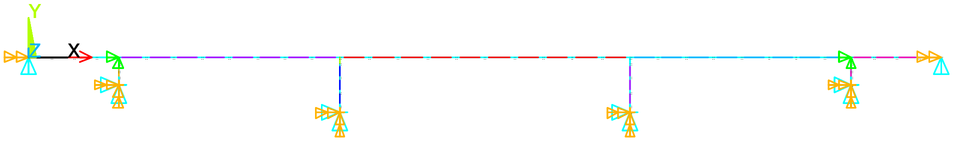

Fig. 1 finite element calculating model of bridge

3 GROUND MOTION INPUT

In the calculation, 5 actual ground motion acceleration records are chosen.

(1) Loma Prieta ground motion (1989/10/18 00:05), recording station: 47379 Gilroy Array #1.

(2) Northridge ground motion (1994/01/17 12:31), recording station: 90049 Pacific Palisades-Sunset Blvd

(3) Imperial Valley ground motion (1940/05/19 04:37), recording station: 117 El Centro Array #9

(4) Kobe ground motion (1995/01/16 20:46), recording station: 0 Nishi-Akashi

(5) Duzce ground motion (Turkey, 1999/11/12), recording station: Ambarli

All above ground motion records are coming from pacific earthquake engineering research center database in university of California. The 5 ground motion acceleration records (titled as A, B, C, D and E, respectively) are adjusted with peak acceleration of 400gal. The ground motion acceleration response spectrum is shown in figure 2 after the peak adjusted.

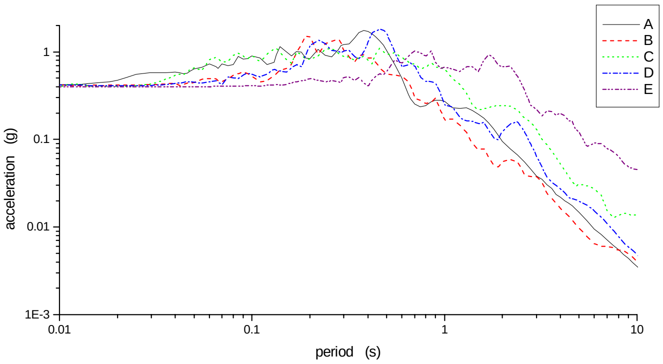

Fig. 2 five ground motion acceleration response spectrum

It is shown from the figure 2 that frequency spectrums of the five ground motions are different. The array with long period increasing is B, A, D, C and E. Ground motion E has the most long period components. The five ground motions are representative.

4 SEMI-ACTIVE CONTROL APPROACH

The semi-active control device is MR damper, and its variable damping force is

$f_{id}(t)=c_{id}\dot{y}_{is}(t)+f_{idy}\operatorname{sgn}\left[\dot{y}_{is}(t)\right]$. In the formula, c_{id} and f_{idy} are viscous damping coefficient and adjustable coulomb damping force of MR damper. $\dot{y}_{is}(t)$ is the relative velocity of semi-active control system at the position of damper. In this paper, the semi-active control algorithm is chosen as following:

Semi-active control algorithm (semi):

$$f_{id}=\begin{cases} f_{id\max} & (|u_i|>f_{id\max}) \\ u_i & (f_{id\min}\le|u_i|\le f_{id\max}) \\ f_{id\min} & (|u_i|<f_{id\min}) \end{cases} \tag{3}$$

The direction of ground motion and damper are all longitudinal. There are 10 positions chosen to set dampers. All ten dampers are divided as five groups to set because of symmetry of the bridge. They are as following: 1+2: position of bearings in bent, 3+4: position of bearings in top of two continuous piers, 5+6: position of bottom of two continuous piers, 7+8: position of top of two rigid piers, 9+10: position of bottom of two rigid piers.

The setting of dampers in bearing positions of 1+2 and 3+4 is shown in figure 3. The setting of dampers in rigid connection positions of 5+6, 7+8 and 9+10 is shown in figure 4.

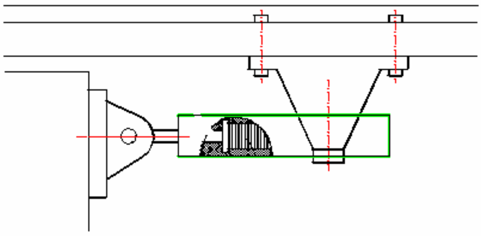

Fig. 3 damper at position of bearing

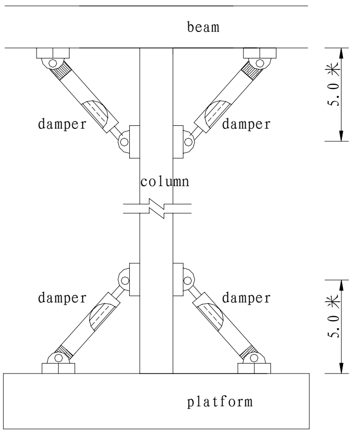

fig 4 damper at position of rigid connection

5 RESULTS OF SEMI-ACTIVE CONTROL CALCULATION

Dampers are all longitudinal. The LQR classical optimum control algorithm is chosen to confirm active control force. The right matrix Q and R are $Q=\alpha\begin{bmatrix} K & 0 \\ 0 & M \end{bmatrix}$ and $R=\beta I$, respectively with $\alpha=100\times10^{2}$ and $\beta=3\times10^{-5}$. The 4 ground motion of A, B, C and D are input, and structural consumed energy of active control is got after calculating. MR dampers with some parameters are chosen and set at the 5 positions, and active control calculation and semi-active control calculation are performed. The parameters of MR dampers are as following: viscous damping coefficient is $10\times10^{6}N.s/m$. maximal coulomb damping force is $10\times10^{6}N$, and minimal coulomb damping force is 0.

In order to scale the decreasing amplitude effect of semi-active control system, the concept of decreasing amplitude ratio is induced. Its value is defined according to seismic responses of bridge structure as following:

$$JZ_i=\frac{\left|d_i^u(t)\right|_{\max}-\left|d_i^c(t)\right|_{\max}}{\left|d_i^u(t)\right|_{\max}}\times 100\% \tag{4}$$

In the formula 4, $d_i^u(t)$ and $d_i^c(t)$ are seismic responses of i free degree of bridge without dampers and with dampers respectively. JZ_i is decreasing amplitude ratio of i free degree.

The active consumed energy is shown in table 1 for 5 groups of dampers

In order to compare the better positions of dampers, some seismic responses are chosen to be compare. They are as following: longitudinal displacement of node 6 dx6, vertical displacement of node 16 dy16, longitudinal acceleration of node 6 ax6, vertical acceleration of node 16 ay16, moment of element 13 at node 6 m6, moment of supported node 45 m45. Decreasing amplitude ratio of all the seismic responses of bridge is shown in figure 5 for the 5 positions of dampers when semi-active control is performed.

Tab. 1 The active consumed energy for 5 groups of dampers

Damper NO.		1+2	3+4	5+6	7+8	9+10
Consumed energy of dampers (MN.m)	Ground motion A	3.13	0.16	0.023	0.089	0.002
	Ground motion B	2.66	0.28	0.022	0.077	0.0017
	Ground motion C	7.77	0.69	0.036	0.23	0.0045
	Ground motion D	7.77	0.22	0.046	0.23	0.0047
	Ground motion E	19.35	3.42	0.056	0.58	0.01

Some conclusions can be shown from table 1 and figure 5 as following:

(1) The optimization array of longitudinal dampers is 1+2, 3+4, 7+8, 5+6 and 9+10, and it has no much relationship to ground motions.

(2) When one damper is set at the 5 possible positions, vibration mitigation effectiveness of the seismic response with positive vibration mitigation effectiveness is basically coincident with the optimized positions of dampers. The position of 1+2 is the best and the better is 3+4. the position of 9+10 is worst with almost no vibration mitigation effectiveness.

(3) Vibration mitigation effectiveness of seismic response is different with different positions. Vibration mitigation effectiveness with the positions of 1+2 and 3+4 is much better than that with other positions. In actual application the damper can be set at the positions of

1+2 and 3+4.

(4) As a whole, the positions confirmed according to consumed energy of active control shows the optimization of positions of dampers. The better positions can be chosen such as the position of 1+2 and 3+4 of the bridge.

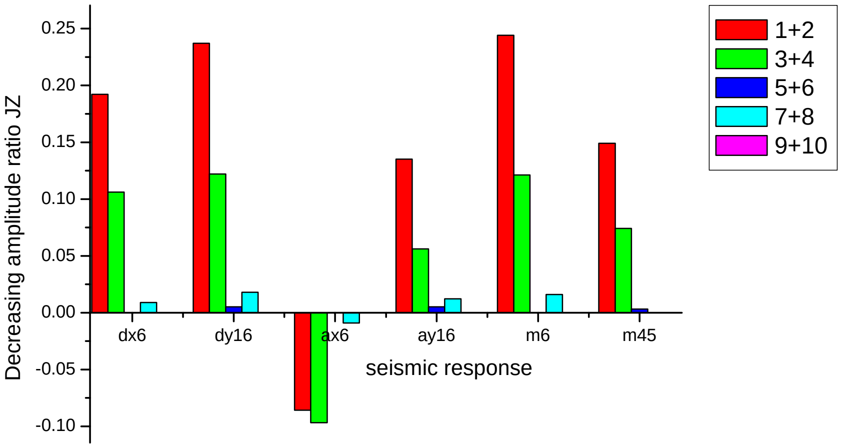

Fig. 5 vibration mitigation effectiveness of 5 positions of dampers

6 CONCLUSIONS AND ADVICE

In this paper, an approach of confirming damper positions of semi-active control for bridge is presented according to consumed energy of active control. Through semi-active control calculating and analyzing for a long span bridge, the approach is tested. Some conclusions and advice can be got as following:

(1) The approach of confirming damper positions of semi-active control for bridge according to consumed energy of active control is simple and applicable, and has no obvious relationship to ground motions. This approach can offer the basic optimizing array of damper position. For the consumed energy of active control, it optimizing array can be responding to the vibration mitigation in total.

(2) Optimization of damper position is relative to many factors including control goal, damper type and bridge parameters, etc, and vibration mitigation effectiveness is complicated. When the dampers are set at different positions, influences of the positions on different seismic responses are different. Especially for the nodes nearby positions of dampers, setting dampers has great influence on these nodes.

(3) Bridge structures have many connection components such as bearings and expanding joints. The relative deformation at these connecting components is always great, and setting dampers at these positions can get better vibration mitigation effectiveness.

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