Application of the Pseudo Negative Stiffness Damper to the Benchmark Cable-stayed Bridge

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Application of variable dampers controlled with the pseudo negative stiffness algorithm to the benchmark cable-stayed bridge was carried out in order to study the efficacy of such control algorithm for cable-stayed bridges.

1. Introduction

Benchmark control problems allow researchers to apply various control strategies, such as passive, active, semi-active, or combination thereof, to cable-stayed bridges, and to compare results directly in terms of a specified set of performance objectives **[1]**. The benchmark cable-stayed bridge considers the issues of different types of earthquakes, three dimensionality, multi-support excitations, incidence angle, and control robustness.

2. Background of Research

Many active control systems for civil engineering applications operate primarily to modify structural damping. Moreover, semi-active control in seismically excited structures is mainly to dissipate energy from the structure. Therefore, it is thought to be significantly beneficial if the damper itself is controlled to produce artificial hysteretic loop. This will simplify the control algorithm and reduce the amount of sensors.

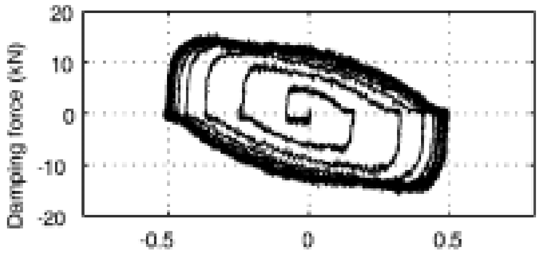

Figure 1. PNS controlled variable damper subjected to sinusoidal input **[2]**

3. Variable Damper Controlled with the Pseudo Negative Stiffness (PNS) Control

Experimental test has been performed by Iemura and coworkers **[2]** on the variable orifice oil damper. The relationship among damping force f_D, orifice opening ratio h, and piston velocity $\dot{u}$ is shown in **Equation (1)**. The damper force f_D must be as near as possible to the demand force F_d. It is calculated in **Equation (2)** using measured relative displacement u and relative velocity $\dot{u}$, where K_d is an arbitrary negative value (representing negative stiffness) and C_d is an arbitrary positive value (representing damping coefficient). The discussion about the values can be found in reference **[1]**. Opening ratio h can then be controlled based on **Equation (3)**. However, opening ratio h can only be applied in the range of $h_{\min}$ (0.05) and $h_{\max}$ (0.80) because of the limitation of the damper. The experimental result is shown in **Figure 1**.

$$f_D = \mathrm{sgn}(\dot{u})\left[\left(\frac{159.23}{h^2}+307.2\right)\dot{u}^2+0.6\right](\mathrm{kN}) \quad (1)$$

$$F_d = K_d u + C_d \dot{u} \quad (2)$$

$$h = \sqrt{\frac{159.232}{\dfrac{\left(\dfrac{F_d}{\mathrm{sgn}(\dot{u})}-0.6\right)}{\dot{u}^2}-307.2}} \quad (3)$$

4. Seismic Response of the Benchmark Cable-stayed Bridge

Phase I and phase II benchmark cable-stayed problems have been utilized for applications of the pseudo negative stiffness (PNS) dampers. The benchmark cables-stayed bridge is shown in **Figure 2**. The PNS dampers and elastic bearings are applied in parallel, between the deck and the towers. The damper hysteretic loops are shown in **Figures 3a** and **3b** for the linear viscous and PNS dampers, respectively. And, the damper plus bearing hysteretic loop is shown in **Figures 3c** and **3d** for the linear viscous and PNS dampers, respectively.

Keywords　benchmark bridge, viscous damper, pseudo negative stiffness damper, hysteretic loop
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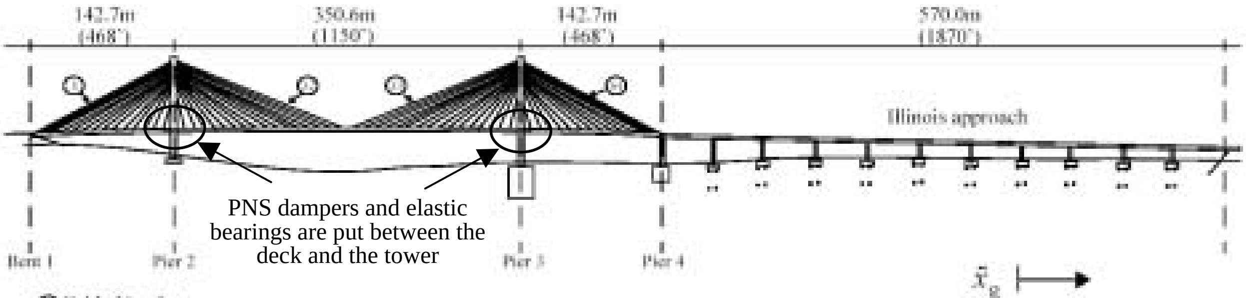

Figure 2. Bill Emerson Memorial Bridge, USA

It is clear from the figures that PNS damper results in lower total force (damping plus bearing forces) and lower displacement of the device. This matter will result in lower seismic response of the whole structure. **Table 1** shows the evaluation criteria for the bridge for linear viscous damper, PNS damper, and active control (active control from **[3]**). The earthquake input energy is also lower for the PNS damper (**Figure 4**).

5. Conclusions

PNS damper is effective in reducing seismic response of cable-stayed bridges. PNS damper results in significantly better seismic reduction than those of linear viscous damper and comparable to those of active control.

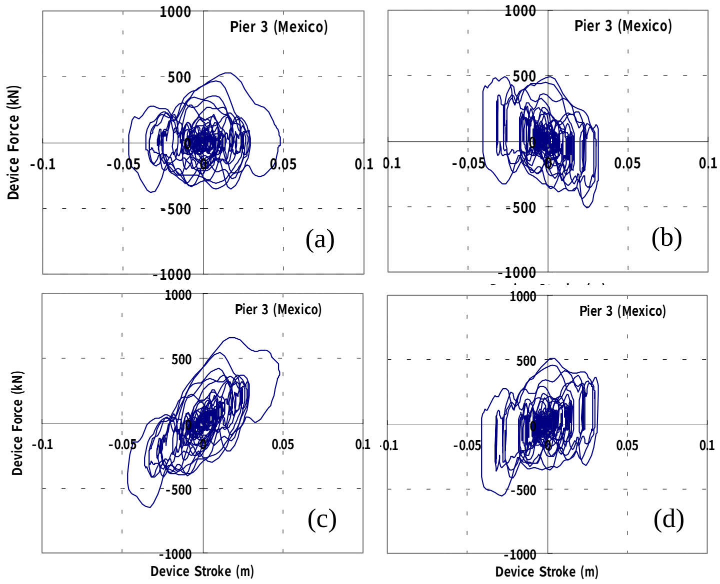

Figure 3. Hysteretic loop for (a) Viscous damper, (b) PNS damper, (c) Viscous damper plus bearing, and (d) PNS damper plus bearing (Mexico earthquake)

6. References

[1] Iemura, H. and Pradono, M. H. (2003) Application of Pseudo Negative Stiffness Control to the Benchmark Cable-stayed Bridge, *Journal of Structural Control*, (To be published).

[2] Iemura, H., Igarashi, A., and Nakata, N. (2001) Semi-active Control of Full-scale Structures using Variable Joint Damper System. *The 14th KKNN Symposium on Civil Engineering*, Kyoto, Japan, November 5-7.

[3] Jung, H-J, Spencer, B.F., Lee, I-W. (2001) Benchmark Control Problem for Seismically Excited Cable-stayed Bridges using Smart Damping Strategies. *Proc. IABSE Conference*, Seoul, June.

Table 1. Seismic response of the benchmark cable-stayed bridge (The largest among three input earthquakes)

Evaluation Criteria	Passive*	PNS**	Active***
J_1 (shear force at tower base)	0.482	0.467	0.498
J_2 (shear force at deck level)	1.234	1.193	1.197
J_3 (moment at tower base)	0.607	0.504	0.441
J_4 (moment at deck level)	1.094	0.890	0.865
J_5 (deviation of cable tension)	0.167	0.117	0.156
J_6 (deck displacement)	2.798	2.476	1.978
J_7 (normed shear force at tower base)	0.412	0.375	0.351
J_8 (normed shear force at deck level)	1.220	1.127	1.006
J_9 (normed moment at tower base)	0.567	0.478	0.327
J_{10} (normed moment at deck level)	1.195	1.066	0.844
J_{11} (normed deviation of cable tension)	0.024	0.023	0.015
J_{12} (force by control devices)	3.922e-3****	3.710e-3****	1.961e-3
J_{13} (stroke of control devices)	1.449	1.320	1.085
J_{16} (number of control devices)	20	20	24
J_{17} (number of sensors)	0	4	9

Note : * Linear viscous dampers and elastic bearings between the deck and towers
** PNS dampers and elastic bearings between the deck and towers
*** Actuators between the deck and all four piers
**** Total force of dampers plus elastic bearings

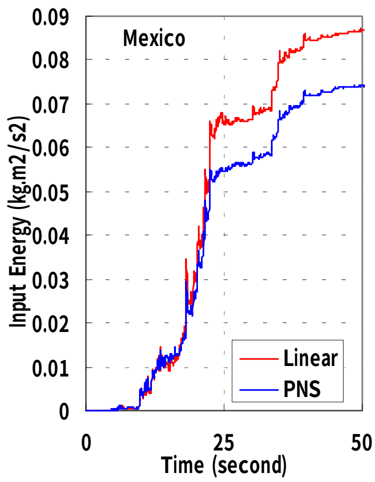

Figure 4. Earthquake input energy to the bridge