STRUCTURAL CONTROL BASED ON SEMI-ACTIVE VARIABLE FRICTION DAMPERS

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SUMMARY

This paper discusses a methodology of semi-active structural control using a variable friction damper. The presented algorithm is quite simple and straightforward, in which only the slip level of the friction damper is controlled in response to the interstory response velocity of the damper-installed story so as to maintain the target constant ductility factor. In conducting control there is advantageously no need of having other response information than the output measurement with respect to that story where the variable friction damper is installed. The effectiveness of the proposed semi-active control is demonstrated both by means of computer simulations and scale model experiments.

INTRODUCTION

One of the major and substantial issues among structural engineers community, in particular in those countries and regions having frequent seismic events, is how to establish the seismic hazard protection strategy for civil structures. The significance of the establishment of such a strategy has increased with the recent rapid trend of modern urbanization all over the world. One of the drastic and innovative breakthroughs in such a strategy is the development and implementation of active response control of civil structures during an earthquake. Since the first active-controlled building in the world was born in Tokyo, Japan in 1989 [Kobori, et al 1991a, b], about 30 buildings in Japan have employed active or hybrid control systems [Housner et al., 1997; Nishitani, 1998]. Active structural control will expectedly bring about a sweeping change in the seismic resistant design scheme of civil structures, thus creating a new era for earthquake engineering field.

Despite that, active control of structures has not yet achieved its ultimate purpose; that is providing a structure with safety against severe seismic excitation. In the current stage of active structural control, several issues remain unsolved to carry out the ultimate purpose. One of such typical issues is, for instance, how to provide the control system with a large enough amount of energy to conduct fully active control of a huge structure in case of severe seismic event. As a practical and promising solution to that issue, semi-active control methodologies have been lately proposed [for example, Kurata et al, 1998; Kurino and Kobori, 1998; Spencer et al, 1998; Yoshida et al, 1998; Nishitani et al, 1999]. These methodologies based on semi-active control seem to play an important role in the future stage.

This paper discusses semi-active control utilizing a variable friction damper system. A friction damper dissipates energy by entering beyond its yield or slip point into the non-linear range of performance and forming a hysteresis loop. In another word, the friction damper is ineffective as long as its slip level is not exceeded. The friction damper would not work against a small seismic excitation with the slip level too high, while quite low slip level would unfavorably produce large displacement even during a moderate seismic event. In this paper, rather simple semi-active control algorithm of the slip level of damper is proposed. The authors presented the similar variable damper system aiming at the reduction of the first modal response [Nishitani et al, 1999]. In comparison with the employed algorithm in that study, the control algorithm to be proposed in this paper is rather simple for a multi-degree-of-freedom structural system. The effectiveness of the proposed control is theoretically and experimentally demonstrated.

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BASIC PHILOSOPHY OF SEMI-ACTIVE CONTROL

To present the basic idea of the control algorithm to be discussed, a single-degree-of-freedom system (SDOF system) with a friction damper is considered (Fig.1). The friction damper provides a damping effect to the structural system by forming a hysteresis. The hysteresis of the damper is depicted in Fig.2. In the semi-active friction damper to be discussed, only the slip level, f_d , is to be controlled in such a way that the damper should form certain type of appropriate hysteresis for any seismic excitation no matter how strong or severe the seismic excitation is.

The equation of motion of the SDOF system is given by

$$m\ddot{x} + c\dot{x} + kx + f = -m\ddot{x}_g \tag{1}$$

in which x : displacement relative to the base, c : viscous damping coefficient of the building, k : stiffness of the building, $\ddot{x}_g$: earthquake ground acceleration, and f : force due to friction damper.

Until the friction damper exceeds its slip level, it gives the structure only an additional stiffness. Once the slip level has been exceeded, it has a hysteresis, yielding a damping effect. In this paper the target hysteresis of the friction damper is chosen so as to have ductility factor of two, because it is known that with ductility factor of two a perfect elasto-plastic SDOF system subjected to a steady-state sinusoidal excitation would yield the most efficient energy dissipation [Tajimi, 1965]. For a steady-state sinusoidal excitation, the constant ductility factor of two can be carried out under the condition that the damper should slip whenever the response displacement changes its sign, i.e. it passes through the zero point. Instead of the direct employment of this rule with respect to the displacement, it is rather practical to have a slip at the moment of the peak velocity occurrence. This is because the rule of arranging the slip level according to the value of the response velocity can be applied to the case of the initial occurrence of slip.

To demonstrate the validity of the basic control idea mentioned above, numerical simulation is conducted. Control is assumed to be conducted under the assumption of the measurement of the relative velocity to the ground, $\ddot{x}_g$. The data used for the simulation are: m=1 [kg], c=24.5 [N s/m], k=2450 [N/m], k_d=272 [N/m] and $\ddot{x}_g$ is the NS component of the 1940 El Centro earthquake (El Centro 1940 NS) with PGA=100 [cm/s^2]. Fig.3 plots both the simulated response displacement and damper-generated force as functions of time in the same graph. It is recognized that the damper slips satisfactorily in good accordance with the spirit of the algorithm, i.e., the slip occurs nearly at the same time the displacement changes its sign even though the excitation is not steady-state sinusoidal. The simulated hysteresis of the damper is presented in Fig.4.

The basic philosophy is extended to the case of multi-degree-of-freedom (MDOF) system. The semi-active variable friction damper system is installed in the first story of a multi-story building. The extension of the idea to a MODF structural system is straightforward in applying the proposed algorithm. Like the case of SDOF system, control of the friction damper slip level is conducted depending on the first story response velocity relative to the ground. In the next section, the validity of the propoed control is demonstrated through numerical simulations and experiments.

NUMERICAL SIMULATIONS AND EXPERIMENTAL VERIFICATION

Numerical simulations and experimental verifications are presented.

In the numerical simulations, a three-degree-of-freedom shear structural model representing a three-story building is controlled. The parameter values of the employed model are: m_1=m_2=m_3= 14 [kg] for each story mass; and k_1=k_2=k_3= 10000 [N/m] for each story stiffness and k_d= 6000 [N/m]. The damping proportional to the stiffness matrix is assumed so as to have the damping ratio of mode 1 equal to 0.03. These values are basically determined from the experimental building model to be presented. As mentioned previously, the control philosophy has nothing different from the case of SDOF system. Only the data of the first story response velocity relative to the ground is needed.

Assuming the measurement of the first story response velocity, control is conducted for the excitation of the earthquake of El Centro 1940 NS with PGA = 100 and 200 [cm/s^2]. For the purpose of presenting how the damper works during the control operations, Fig.5 represents the relationships between the damper generated forces and the first story displacements, i.e. the hysteretic loops of the damper for PGA=100 and 200 [cm/s^2]. These figures presented in Fig.5 demonstrate that the proposed algorithm produces satisfactory hysteresis having the damper ductility factor very close to two, even though the building is not subject to a steady-state sinusoidal excitation. Fig.6 shows the third story displacements with and without control, while Fig.7 depicts the controlled and uncontrolled response accelerations for the third story.

Following the computer simulations, experimental verification is conducted. The photograph of the device utilized for experiments is shown in Fig.8. In this device, friction force is controlled by holding a horizontal plate by air-regulated cramp. The cramp holds the plate firmly with increasing air pressure, thus providing a model only with an additional stiffness in response to interstory displacement. By decreasing the air pressure and thus decreasing the holding force of the cramp, the device could adjust the slip level or friction force. The photograph of Fig.9 shows the experimental three-story building model with the air-cramp friction damper. The parameters are the same as utilized in the numerical simulations.

As the test of the control device for experiments, in the first place, the effectiveness of passive control is examined by fixing the slipping level as 30 [N]. The building model is subjected to the excitation of El Centro 1940 NS with PGA=100 [cm/s^2]. The experimentally obtained hysteresis of the passive friction damper is given in Fig.10. It is recognized that the constant slip level has been brought about with a satisfactory degree.

Following the passive control operation testing, semi-active control experiments are then conducted. The model is also excited by El Centro 1940 NS with PGA = 100 [cm/s^2]. In conducting experiments, the displacement of the first story relative to the ground is actually measured by means of laser displacement meter. The data are converted to the velocity data through differential operations. Fig.11 represents the hystersis loop of the damper obtained experimentally, demonstrating the relationship between the friction damper force and first story response. Figs.12 and 13 compare the controlled and uncontrolled response displacements and accelerations for the third story, demonstrating the satisfactory control effects.

CONCLUSION

Semi-active control utilizing a variable friction damper is discussed. The employed algorithm is very simple. The scheme is based on the idea of controlling only the slip level by judging from the behavior of the response velocity so as to have the constant damper ductility factor. In conducting control, there is advantageously no need of having other response information than the output measurement with respect to that story where the friction damper is installed. The effectiveness is presented by computer simulations and experiments. Even though the algorithm is very straightforward, fairly good control operations are performed. With further improvement of the algorithm, more efficient control performance would be expected.

ACKOWLEDGMENT

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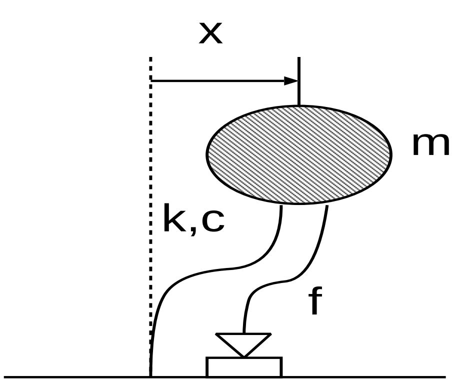


Figure 1: SDOF system with friction damper

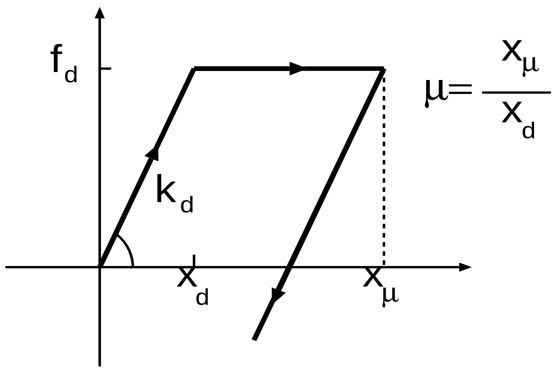


Figure 2: Hysteresis loop of friction damper

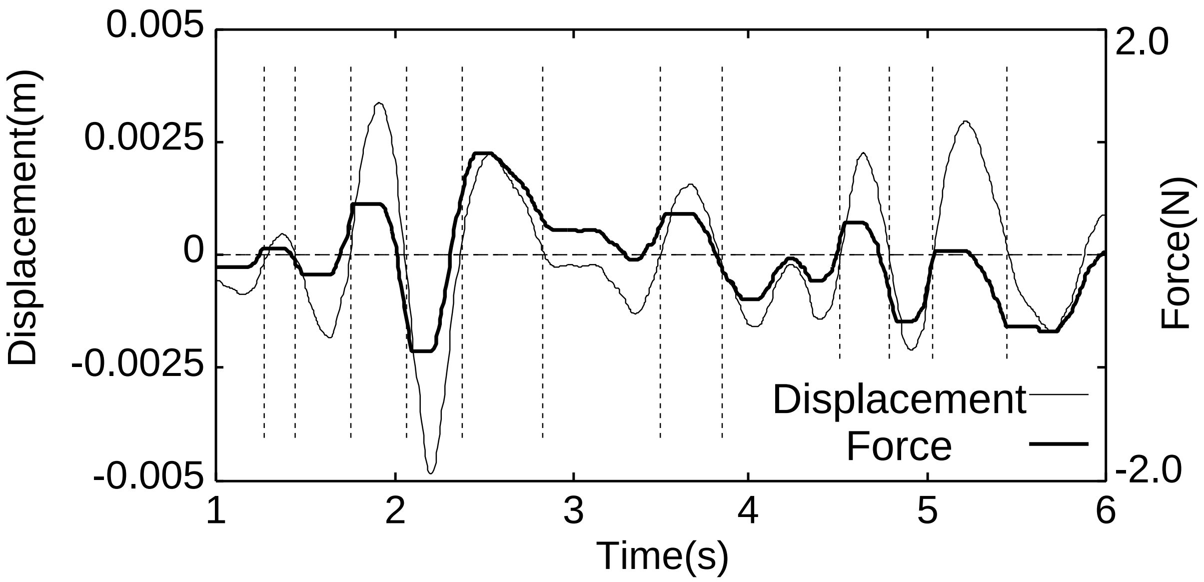


Figure 3: Relationship between displacement and damper force

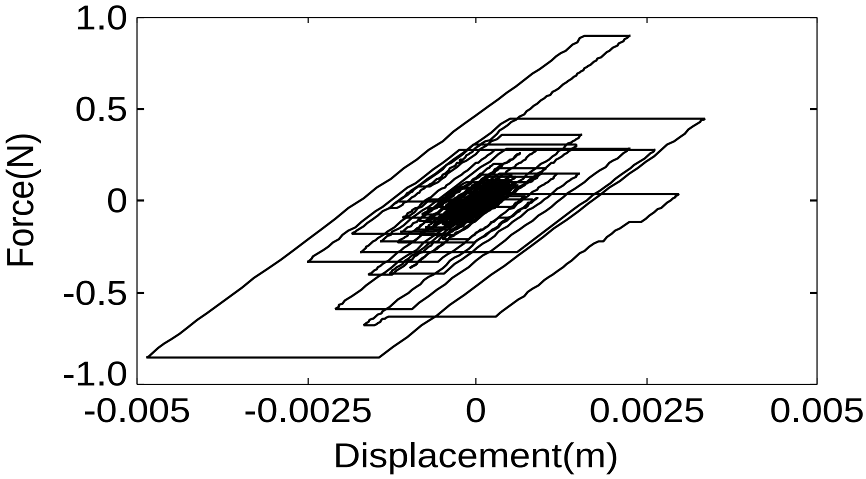
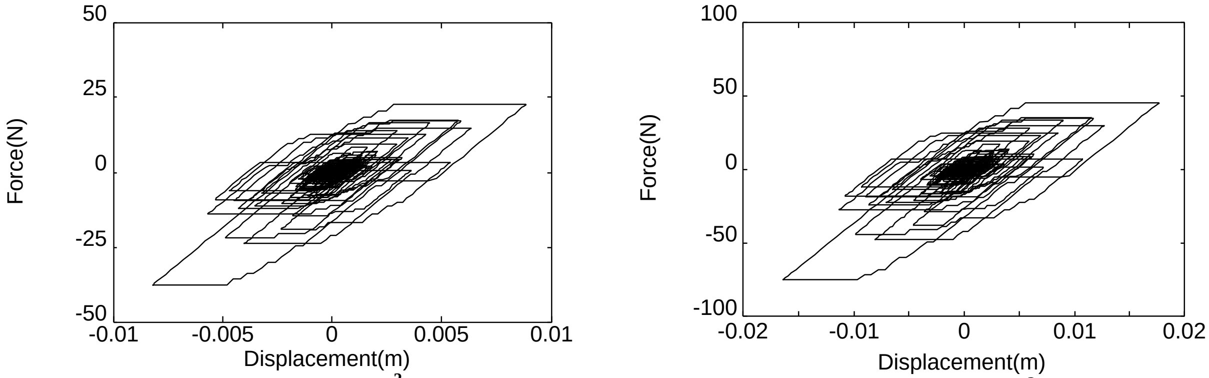
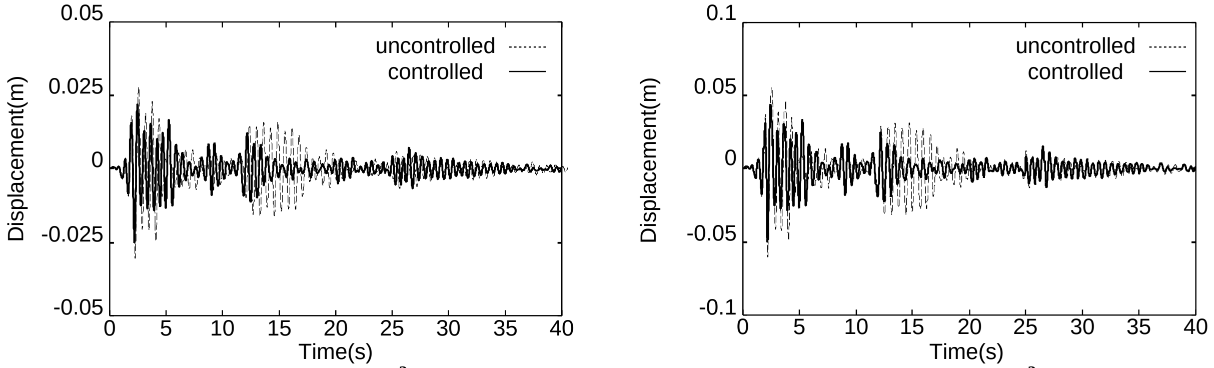


Figure 4: Simulated hysteresis loop of friction damper



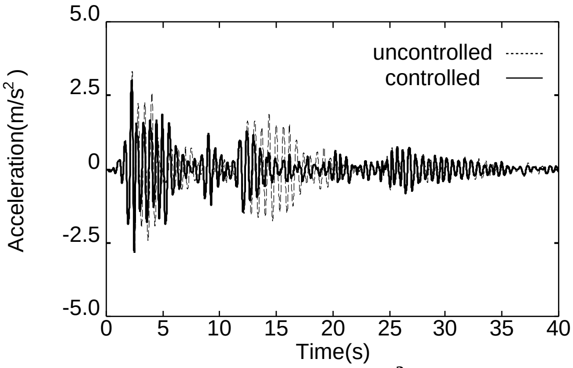
(a) PGA = 100 cm/s^2 **(b) PGA = 200 cm/s^2**

Figure 5: Hysteresis loops of friction dampers

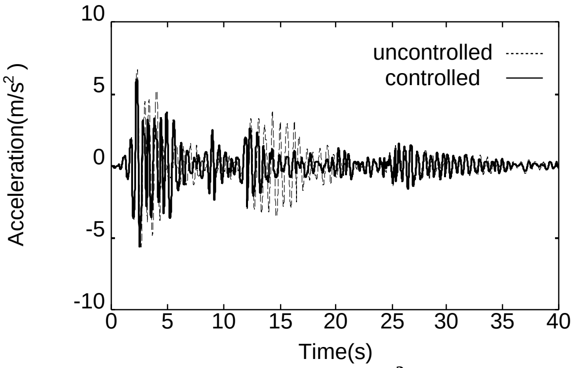


(a) PGA = 100 cm/s^2 **(b) PGA = 200 cm/s^2**

Figure 6: Response displacements of third story



(a) PGA = 100 cm/s^2



(b) PGA = 200 cm/s^2

Figure 7: Response accelerations of third story

Figure 8: Photograph of air-cramp friciton damper

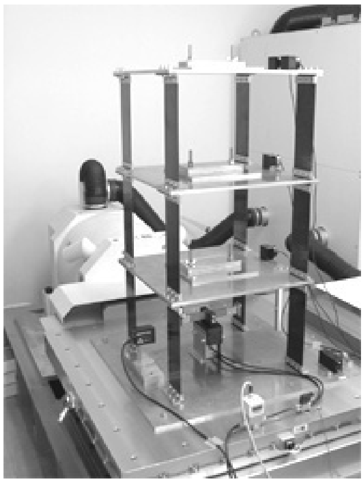


Figure 9: Photograph of experimental model

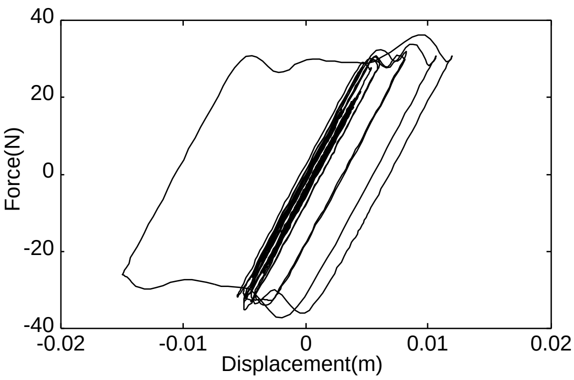


Figure 10: Experimental hysteresis of passive friction damper

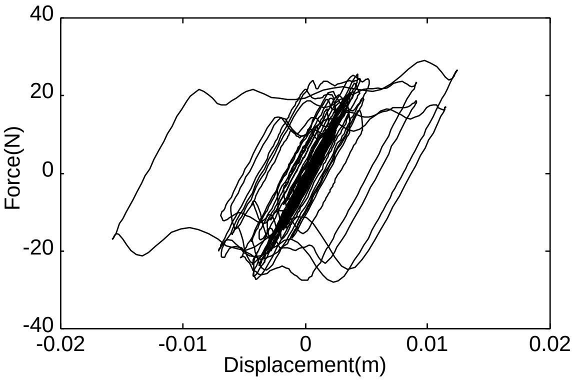


Figure 11: Experimental hysteresis of variable friction damper

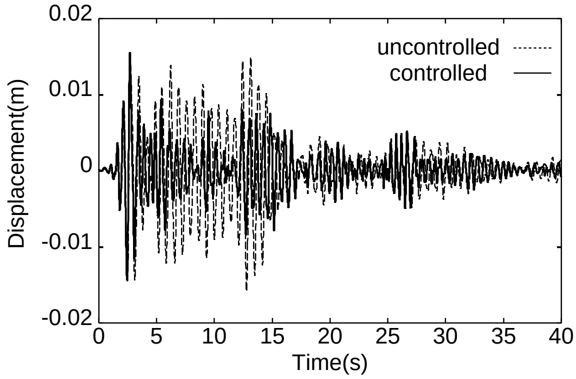


Figure 12: Experimental response displacements of third story

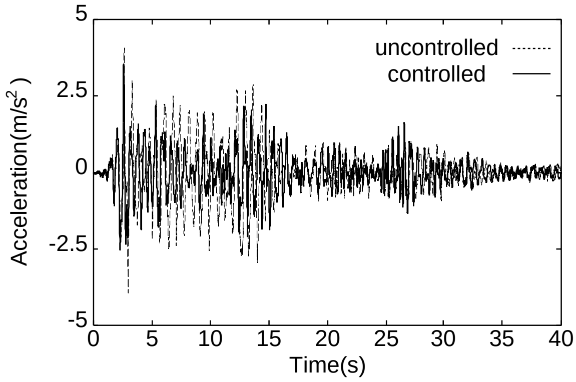


Figure 13: Experimental response accelerations of third story