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CONTROLLABLE FLUID DAMPERS FOR SEISMIC PROTECTION OF STRUCTURES

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Abstract: In this paper the advantages of semiactive dampers for vibration control are discussed and it is shown that they can be a practical solution to the problem of protecting structures from earthquakes. In particular, there is a class of ground motions that induces large rapid displacements containing long periods which can devastate flexible structures. Herein, it is shown that the ability of controllable-fluid dampers to develop a controllable friction force and a plastic-type energy dissipation can be a practical solution to this problem. A case study is presented to demonstrate the need and potential of controllable-fluid dampers in seismic protection applications. Some control strategies are discussed.

1. Introduction

The nature of control theory and practice is determined by the applications under consideration. For instance, structural control has distinctive features that govern the direction of research. For seismic protection applications structural control is applied to massive structures, involves excitations whose precise properties are not known before hand, involves adjustment of relative large forces; but is concerned with relative low accuracy.

In the last decade considerable advances have been accomplished in the area of vibration isolation and passive energy dissipation and new promising systems have been developed which can be used for seismic retrofitting of existing structures (ATC-17-1, 1993). These systems, also known as earthquake protective systems, consist of passive, semi-active or active devices, and can considerably minimize seismic demand of buildings and bridges.

2. Passive Control Systems

A passive control system may be used to increase the energy dissipation capacity of a structure through discrete energy dissipation devices placed either within a seismic isolation system or over the height of the structure. Such systems may be referred to as supplemental energy dissipation systems and have been reviewed by Soong and Constantinou (1994), ATC (1993), EERI (1993), and Constantinou and Symans (1993). The objective of these systems is to absorb a significant amount of the seismic-input energy. Depending on their construction, these devices may also increase the stiffness and strength of the structure to which they are attached (ATC 1994). Supplemental dissipation devices may take many forms; and dissipate energy through a variety of mechanisms including the yielding of mild steel, viscoelastic action in elastomeric or acrylic materials, shearing action of viscous fluids and sliding friction.

The basic philosophy in seismic isolation is to lengthen the fundamental period of structures in order to reduce the induced seismic forces. However, the reduction in forces is accompanied by an increase in displacement demand. For this reason, additional damping is often introduced. As an example, a major application in the U.S. of additional fluid dampers combined with elastomeric bearings is in the under-construction San Bernandino County Medical Center (ENR, 1995). The hospital is seismically isolated and the 186 fluid dampers are placed at the isolation level in parallel with high-damping elastomeric bearings. The dampers are installed horizontally with one end attached to the super-structure and the other attached to the foundation. Vane-type fluid dampers have been incorporated to the Higashin-Kobe Bridge, a 900m long cable-stayed bridge that survived the January 17, 1995 Kobe Earthquake (Ito et al. 1991); however, the damper-connections have been damaged during this earthquake because the bridge experienced significant motion along the transverse direction.

3. Diversity of Ground Motions

Although, seismic isolation is in general an effective technique to protect structures from earthquakes with high frequencies and sharp accelerations (accelerations with relative large amplitude and short duration), there is a class of ground motions that is particularly challenging to accommodate, especially for flexible structures. These motions contain large rapid displacement pulses, say one or two pulses from 0.5 to more than 1.0 meter at velocities of 1.0 m/sec or higher; and they are usually attributed to what seismologists call near-

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source effects. The large displacement pulses observed in records from the Northridge-USA, Kobe-Japan and Aigion-Greece earthquakes, resemble an abrupt pulse which is a severe load for flexible structures and an important challenge for structural control studies (Hall 1995). Figure 1 shows the acceleration, velocity and displacement histories of the January 17, 1994 Northridge earthquake recorded at the LADWP Rinaldi receiving station. This motion resulted in a forward only (nonreversing) ground displacement, that resembles a smooth step-function, and a velocity pulse that resembles a finite delta-function. For instance, in this situation seismic isolation with elastomeric bearings or other low-stiffness isolators is inappropriate since it further increases the fundamental period of the superstructure and a long-period ground motion induced from a near source earthquake will be devastating. Some simple calculations reported by Hall et al. (1995) confirm that strong near-source ground motions impose severe loading conditions on a seismic-isolated building and many of the analyses show that if the same building is fixed to the ground it will yield less. These observations suggest that in the case of rapid, long-period ground motions the structure should be "locked" to the ground rather than being supported on flexible bearings. Consequently, an active mechanism which can provide rigidity is needed in some cases. In addition to the diversity in the characteristics of seismic motions, the concurrent presence of other dynamic loads of different nature such as traffic and wind, require that protective devices in structural systems have to perform satisfactorily within a wide range of loading conditions.

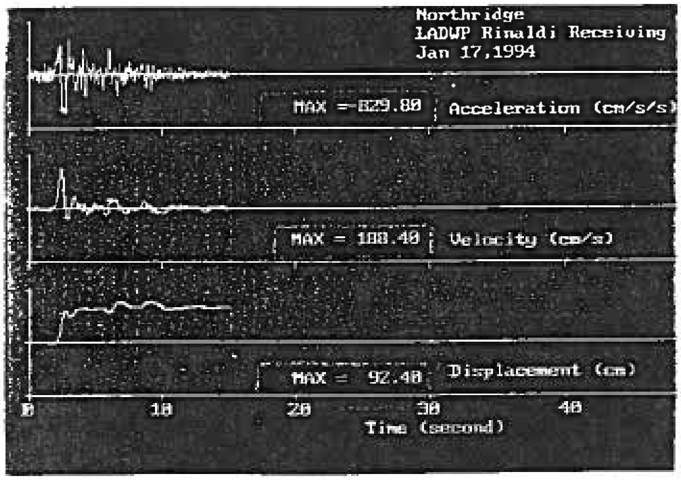

Figure 1: Rinaldi-Station record

4. Seismic Protection with Controllable-Fluid Dampers

The above challenges motivated the development of semi-active dampers. Semi-active dampers combine the advantages of passive energy dissipation (Constantinou and Symans 1994) with the benefits of active control (Housner et al. 1994) to produce optimal, yet stable and reliable damping systems. A semiactive control systems generally originates from passive control system which has been subsequently modified to allow for the adjustment of mechanical properties.

Different types of semiactive dampers have been proposed for civil engineering applications, ranging from hydraulic dampers with mechanically controlled orificing (Kawashima and Unjoh 1993, Patten et al. 1996, Symans and Constantinou 1995) to electrorheological fluid dampers (Gavin and Hanson 1994, Makris et al. 1996, Burton et al. 1996).

During the last two years an electrorheological fluid damper has been designed, constructed and tested at the University of Notre Dame. The damper is a compact device which can generate large forces and is suitable for civil engineering applications. This is achieved by generating in the damper the so called Hagen-Poisseille flow. A photograph of the constructed damper is shown on Figure 2.

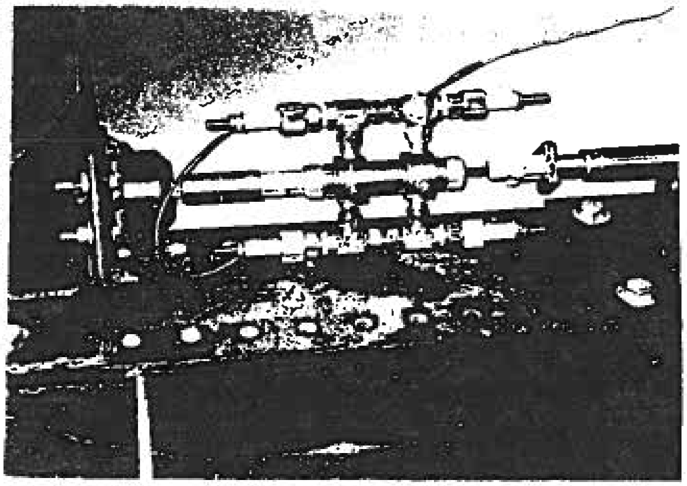

Figure 2: Electrorheological fluid damper.

The damper consists of an outer cylinder and a double ended piston rod that pushes the ER-fluid through a stationary annular duct. The electric field is created perpendicular to the fluid flow across the bypass. The main advantages of this semi-active damper are that:

a) There are no moving parts within the damper besides the piston. b) It is a compact device that can produce relatively large forces. c) Because of the yield forces that ER-dampers can develop, they can provide significant rigidity and when the yield forces are exceeded they can dissipate substantial energy. d) Once the power fails the damper operates as a passive device that provides a reasonable amount of damping. e) The damper can operate in a passive state during many seismic events

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where viscous damping alone is sufficient to mitigate the response. f) The proposed damper can be positioned in any direction as opposed to other dampers which have to be positioned horizontally due to the presence of a free surface.

Figure 3 shows recorded force-displacement loops without electric field ($E = 0$) and with $E = 4.5$ kV/mm. At no electric field, the resulting force is due to viscous stresses only, whereas when field is applied, the material exhibits a yield stress which has to be exceeded in order for the ER-material to flow. The resulting plastic stresses due to the presence of electric field are rate independent. As the piston velocity increases, viscous effects dominate over plastic effects, and the fraction of the total force that is controlled through the ER-duct reduces. The damper response is nearly frequency independent but velocity dependent.

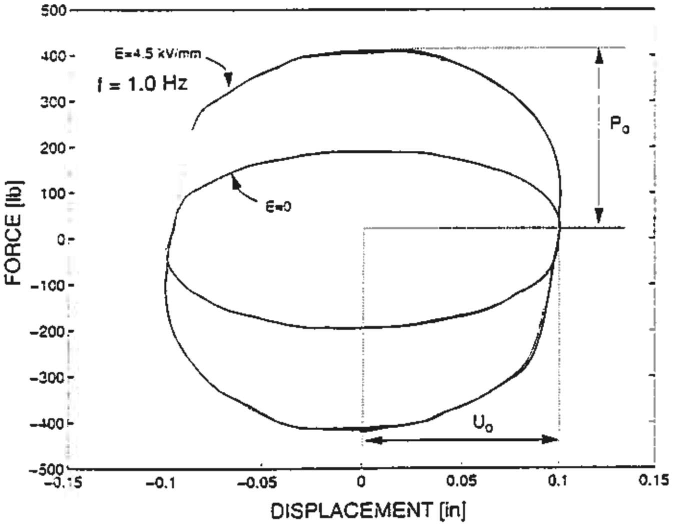

Figure 3: Recorded force displacement loops with and without electric field.

A simple phenomenological model that can approximate the nonlinear behavior of the damper under the presence of electric field is the Bingham model of viscoplasticity, where $P_y(E)$, is the field-dependent friction-type force that results from the yielding of the ER-material, and $C(E)$ is the field-dependent viscous-damping coefficient of the damper that results from the viscosity of the fluid. Accordingly,

$$P(t) = P_y(E)\ sgn\,[\dot{u}(t)] + C(E)\dot{u}(t). \qquad (1)$$

This macroscopic model was motivated from the mechanical behavior of the electrorheological fluid used within the damper in conjunction with the pattern of flow of the ER-fluid through the bypass shown in Figures 3 (Makris et al. 1996, Burton et al. 1996a). Dividing by the mass of the superstructure, equation (1) takes the form

$$\frac{P(t)}{m} = \epsilon(E)\omega_p V_p\ sgn\,[\dot{u}(t)] + 2\xi(E)\omega_0\dot{u}(t) \qquad (2)$$

where ω_p = predominant frequency of the pulse, ω_0 = first modal frequency of the structure, V_p = velocity amplitude of the pulse, $\xi(E)$ = field-dependent viscous-damping ratio of the system and $\epsilon(E)$ is the field-dependent plastic-damping ratio. When viscous forces and friction-type forces dissipate the same amount of energy per cycle, then

$$\epsilon = \frac{\pi}{2}\frac{\xi}{\beta}, \qquad (3)$$

in which, $\beta = \omega_p/\omega_0$, is the frequency ratio. Dissipation forces given by equation (2) are of interest in earthquake engineering because combine controllable friction-type forces with viscous forces. The significance of having a damper that can provide adjustable friction-type forces is illustrated with the following case study.

5. Case-Study: The Purdue Avenue Building

In the city of Los Angeles, CA, there is a 3-story braced steel-frame residential building located on Purdue Avenue, Los Angeles, which is supported on helical steel springs and viscoelastic fluid dampers and has a first isolation period of 0.625 sec. The response of this structure excited by the Northridge earthquake has been investigated in detail by Makris and Deoskar (1996). In that study the ground motion that was recorded below the isolators of the building was used, and it was found that bearing displacements probably reached the displacement capacity of the isolation system which is 5.5 cm. Luckily this isolated building is located 24 km south-southeast of the Northridge epicenter and survived the Northridge earthquake.

To the south of the epicenter the shaking from the Northridge earthquake was strong but mostly in the form of high frequencies and sharp accelerations. For this type of ground motions, seismic isolation is beneficial. Indeed, Makris and Deoskar (1996) showed that the isolation system of the Purdue-Avenue building reduced the maximum structural acceleration by approximately 45%.

Near the epicenter and to the north motions with longer periods, exhibiting large velocities and displacements, have been recorded. For instance, the Rinaldi-station motion shown on Figure 1 was recorded in the vicinity of the epicenter. In these areas the isolation system of the Purdue-Avenue building would have been detrimental.

Figure 4 plots an analytically constructed pulse, named pulse type-A, which represents realistically forward pulses like the one shown on Figure 1. A pulse type-A excitation is a simple sinusoidal pulse

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with acceleration, velocity and displacement histories given by

$$a_{gA}(t) = \omega_p \frac{V_p}{2} \sin(\omega_p t), \quad 0 \geq t \geq T_p \qquad (4)$$

$$v_{gA}(t) = \frac{V_p}{2} - \frac{V_p}{2} \cos(\omega_p t), \quad 0 \geq t \geq T_p \qquad (5)$$

$$d_{gA}(t) = \frac{V_p}{2} t - \frac{V_p}{2\omega_p} \sin(\omega_p t), \quad 0 \leq t \leq T_p \qquad (6)$$

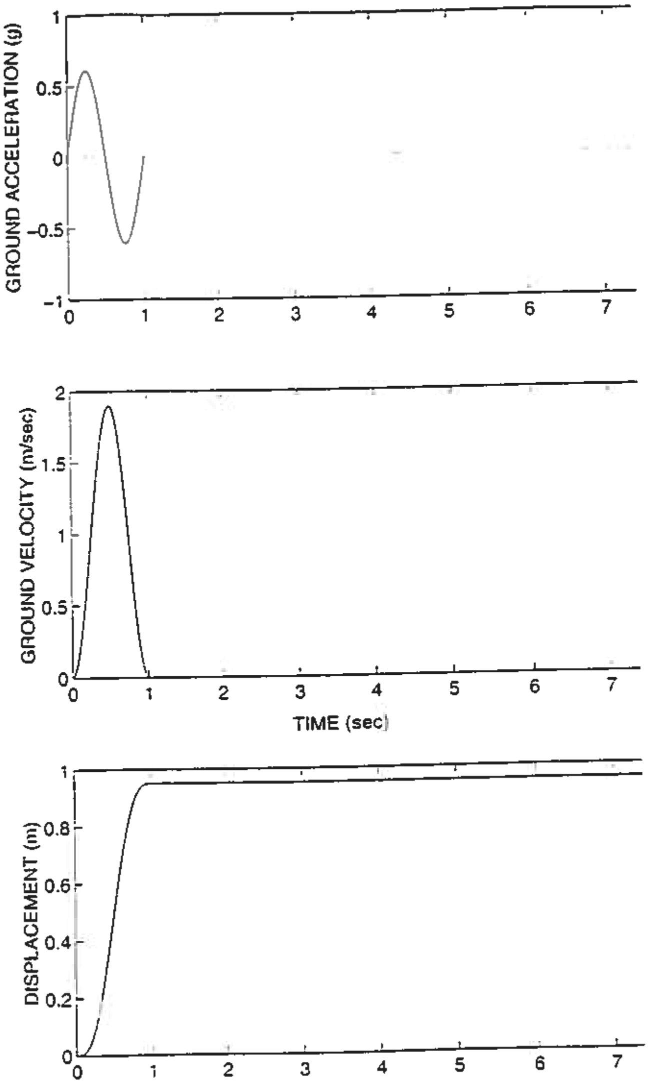

Figure 4: Pulse type-A ground motion.

where V_p is the amplitude of the velocity pulse, and $T_p = 2\pi/\omega_p$ is the predominant period and duration of the pulse. The value of T_p can be easily extracted from equations (5) and (6) by dividing the maximum pulse-displacement with the maximum pulse-velocity

$$\frac{|d_{gA}|_{\max}}{|\nu_{gA}|_{\max}} = \frac{T_p}{2} \Rightarrow T_p = 2\frac{|d_{gA}|_{\max}}{|\nu_{gA}|_{\max}} \qquad (7)$$

Going back to Figure 1 the validity of formula (7) is verified. With $|d_{gA}|_{\max} = 92.4$ cm and $|\nu_{gA}|_{\max} = 188.4$ cm/sec, $T_p \approx 1.0$ sec. Indeed, the width of the velocity pulse on the center plot is about 1.1 sec which is in agreement with the computed value from (7).

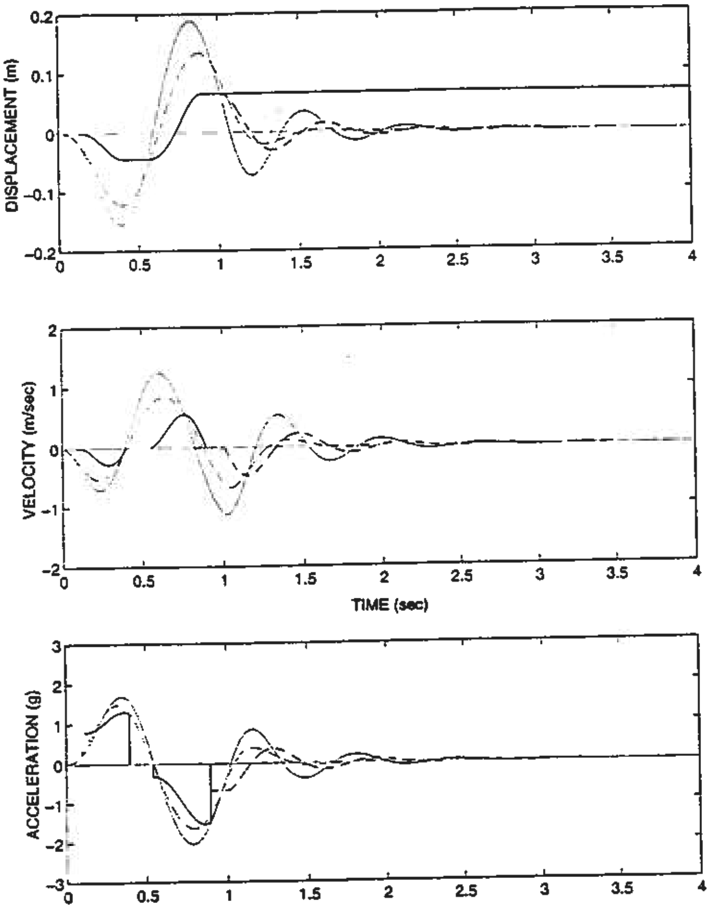

Figure 5: Response of the Purdue Avenue building to pulse type-A excitation.

Figure 5 plots the relative to the ground displacement and velocity, and absolute acceleration response histories of a SDOF system with isolation period equal to the first isolation period of the Purdue-Avenue building, $T_0 = 0.625$ sec, when subjected to the pulse excitation of type-A shown on Figure 4. The light continuous line on Figure 5 is the response of the SDOF with viscous damping, $\xi = 0.234$, which is equal to the first modal damping ratio of the isolated building. In this case the displacement of the bearings exceed 18 cm (three times the displacement capacity of the isolation system of the Purdue-Avenue building) and the acceleration is of the order of 1.8 g. Consider now the case where in addition to the viscous dampers a device that can deliver friction-type (rigid-plastic) forces is incorporated. The heavy solid line on Figure 5 is the response of the SDOF system with $\xi = 0.234$ and $\epsilon = 0.65$. The zero-velocity segments along the response of the isolated structure with friction-type dampers are due to finite sticks of the superstructure. The analytical solution of the equation of motion when friction-type dampers

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are used and the detection of the sticking mode is discussed in the paper by Makris and Constantinou (1991). The additional friction-type forces to the existing viscous forces reduced the clearing displacement from 18 cm to 5.5 cm which is the displacement capacity of the isolation system of the Purdue-Avenue building. It is interesting to note that while friction-type forces reduce drastically the maximum displacement they are responsible for the permanent displacement of the superstructure. The use of semiactive dampers can eliminate this problem. The heavy dashed line shows the response of the building when the friction-type forces are removed at the end of the pulse-excitation. Although this is an elementary way of controlling the structural response, Figure 5 demonstrates that an adjustable combination of friction and viscous forces can provide optimum structural response. Control strategies for ER-dampers are discussed in the next section.

The additional plastic damping ratio of $\epsilon = 0.65$ corresponds to an additional viscous-damping-ratio value of 0.27, which together with the initial viscous-damping-ratio value 0.234, adds up to $\xi = 0.50$. The light dashed line on Figure 5 is the response of the SDOF with viscous damping ratio $\xi = 0.50$ and $\epsilon = 0$. Despite the large amount of viscous damping, the bearing displacements exceed 12 cm (more than two times the displacement capacity of the isolation system of the Purdue-Avenue building) and the resulting velocities and accelerations are larger than the velocities and accelerations computed when the initial viscous damping was enhanced with friction-type damping (heavy lines).

From the above comparisons one can clearly recognize that for these rapid, long period motions, viscous damping alone has marginal effect in reducing the response; whereas, friction-type damping can substantially reduce all displacements, velocities and accelerations. On the other hand, viscous damping alone is beneficial when high-frequency motions with sharp accelerations excite the structure. This strong need for adjusting the type of dissipation mechanism in order to protect a structure from two totally different motions that were generated from the same earthquake only some 20 km apart, shows that semiactive dampers can be a promising alternative to protect effectively structures from major earthquakes.

6. Anticipation and Control Strategies

In order to take advantage of the unique rigid-viscoplastic behavior of ER-dampers, a simple mechanism that will announce the arrival of the seismic pulse is needed. A sensor placed in the vicinity of the structure to be protected may provide the necessary information and a warning about an approaching seismic wave will be transmitted. The electric field of an ER-damper may be activated in milliseconds and therefore a sensor placed even close to the perimeter of the property where the building is located, may be adequate to provide warning for the damper to be activated. At this stage it is not clear how much information is needed on the incoming seismic wave in order to decide whether to activate the controllable ER-damper or not.

Modeling the response of a semi-active damper is a central task not only for the design and characterization of the device, but also for the development of robust control algorithms. When deriving mathematical models of a dynamical system that are to be used to derive control strategies for that systems, it is useful to keep the following in mind: The model must satisfy two competing requirements. First it must be general enough so it adequately describes the dynamical behavior of interest, but it also must be simple enough so to be amenable to available analysis and design control techniques. Note that if feedback is to be used, which is typically the case, then significant uncertainties in the model parameters may be tolerated, depending of course on how demanding the control requirements are, as the feedback mechanism introduces significant robustness to uncertainty. So typically models for control purposes may be chosen to be simpler, and less accurate, than the models used say in simulations, and this is desirable in order to be able to use existing control design methodologies. Caution should be exercised in feedback control as inadequately designed control laws may destabilize an otherwise stable system leading to extremely undesirable behavior.

Significant progress has already been made by our research group in modeling the ER-damper using standard macroscopic models, but also neural networks; the neural net-work modeling and control is discussed below. To model the ER-damper, we first used simple macroscopic models from the theories of viscoplasticity and viscoelasticity. At zero electric field and small frequencies the damper response is nearly viscous since a small friction force (25 lbs) originating from the piston seals is also present. As frequency increases the damper exhibits some elasticity and the behavior is nearly viscoelastic. It was found that for the case of zero field the relaxation effects at higher frequencies are more important than the minor nonlinear effects. As the applied electric field increases the damper behavior tends to become viscoplastic. For instance at $E = 3$ kV/mm the nonlinear effects are more important than the relaxation effects, and the Bingham model given by (1) yields the most favorable prediction for the damper force when subjected to

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the 1940 El Centro earthquake. The performance of macroscopic models can be improved by adding terms on either sides of the force-displacement constitutive equation. For instance, the Bingham and Maxwell model can be combined in one equation: $P(t) + \lambda \dot{P}(t) = P_y \, sgn\,(\dot{u}) + C\dot{u}(t)$, to capture both nonlinear and relaxation effects.

The neural network that we developed to approximate the response of our ER-damper was constructed and trained with the Dependance Identification Algorithm (Moody and Antsaklis, 1996). This algorithm is designed to work with continuous training and uses the concept of linear dependence, instead of the desired boolean output value, to group patterns together. It is an extremely fast algorithm for function approximation with the advantage that it generates the appropriate network, thus eliminating the need for experimentation to determine the number of hidden neurons. An early study demonstrated that the developed neural network is very promising in approximating the ER-damper response at no field ($E = 0$) and at 3kV/mm (Burton et al. 1996a, b). At present we are investigating the problem of extending the developed neural network to capture the damper at intermediate stages between zero and 4.5 kV/mm.

Based on these methods appropriate control strategies will be developed using both constitutive models and neural networks. This envisioned that initially switching control strategies will be implemented by switching the electric field in the ER-damper. If necessary continues variation of the controlled field will be applied. This research in progress.

5. Conclusions

Semiactive dampers can be a practical alternative for seismic protection of structures. In particular it was shown through a case study that an adjustable plastic dissipation supplied from and electrorheological damper might be an attractive solution for protecting structures from long-period rapid ground motion. Some control strategies associated with the implementation of semiactive dampers in civil structures have been discussed.

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