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# CASE STUDY OF VARIABLE ORIFICE DAMPER FOR SEISMIC PROTECTION OF STRUCTURES

BY

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**Abstract**. The seismic protection is, without any doubt, a worldwide priority, and that is why one of the main preoccupations of the researchers in the field is finding some innovative concepts concerning the seismic protection of the structures. The aim of the paper consists in the analytical and numerical study of the variable orifice damper implemented in a single degree of freedom (SDOF) structure in order to increase people's safety and reduce the seismic risk. The variable orifice damper is the common semi-active hydraulic device which may be utilized as part of seismic isolation system or within the lateral bracing of a structure. The semi-active control strategy is realized using *on–off clipping* control algorithm.

It is concluded that the variable orifice damper afforded a substantial reduction of the displacement response of a SDOF system in comparison to the response with passive control fluid device.

**Key Words**: Control System; Earthquake Engineering; Dynamic Model; Control Device; Damping.

## 1. Introduction

In recent years, passive, active, hybrid and semi-active control systems represent the four new concepts in the use of supplemental damping strategies for response reduction in civil engineering structures subjected to strong earthquakes and severe winds [1], . . . , [3]. From historical point of view, passive control techniques such that base isolation and passive control devices are the first of them implemented. A lot of researches have studied structures equipped with these passive systems and a lot of practical realizations were already implemented in many countries. The passive control systems, attached or embedded to a structure, reduce or/and dissipate the energy inputted to the structure. These devices do not need an external power source and they are more economic and easy in applications.

An active control system is defined as one in which a large external power source or many, from tens kilowatts to several megawatts, control actuators that apply forces to the structure in a prescribed manner [1]. These forces can be used to both add and dissipate energy in the structure.

A hybrid control system consists from employment of an active control device to improve and supplement the performance of passive control system. Alternatively, the passive devices embedded in a structure can decrease the amount of required energy power if an active control system is installed in that structure [1]. On the other hand, semi-active control systems combine promising alternative between the passive and active techniques, offering the reliability of passive devices, while they can potentially achieve similar performances of fully active systems [4], [5]. According to presently accepted definitions, a semi-active control device is one that has properties that can be adjusted in real time but cannot input energy into the system being controlled. Such devices typically have very low power requirements, which are particularly critical during seismic events when the main power source to the structure may fail.

## 2. Semi-Active Control Systems

A semi-active control system is defined as one that needs energy only to change the mechanical properties of the devices and to develop the control forces opposite to the motion of structure [1].

Semi-active control systems are a class of active control systems for which the external energy requirements are smaller amounts than those of typical active control. Also a semi-active control system originates from a passive control system which dissipates energy on principles such as phase transformation in metals, deformation of viscoelastic solids or fluid and sliding friction are modified to behave in a semi-active manner. A battery power, for instance, is sufficient to make them operative to control in real time parameters of the structure such as spring stiffness or the viscous damping coefficient. The stability is guaranteed, in the sense that no instability can occur, because semi-active devices use the motion of the structure to develop the control forces. A semi-active device will never destabilize a structural system whereas an active device may destabilize a structural system even though it has a low energy demand. Examples of such common semi-active devices have been classified as following: semi-active hydraulic devices:

a) variable stiffness devices;
b) controllable friction dampers;
c) controllable fluid dampers;
d) semi-active tuned mass damper;
e) semi-active tuned liquid damper;
f) variable orifice tuned column liquid damper.

For the first time, Karnopp [6] performed analytical studies of semi-active hydraulic devices for automotive vibration isolation applications, investigating a semi-active fluid viscous damper. Two valves are used independently to controll the damping during compression and tension (Fig. 1). The common skyhook strategies were examined with respect to minimize the absolute velocity of a vehicle.

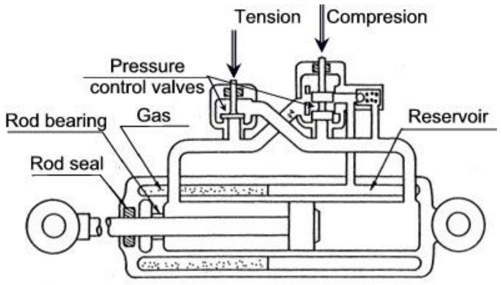


**Fig. 1.** – Semi-active fluid damper described by Karnopp.

The variable orifice damper is the common device of the semi-active hydraulic devices [7]. The device consists of a fluid viscous damper combined with a variable orifice on a by-pass pipe containing a valve in order to control the reaction force of the device (Fig. 2). The damping characteristics of a variable orifice can be controlled between two damping values (low damping when the valve is completely opened and high damping when the valve is completely closed) by varying the amount of flow passing through the by-pass pipe from one chamber of the piston in the other. In the intermediate positions of the valve opening process, the device produces a specific damping dissipation. The adjustment of the valve can be made usually electromechanically (*e.g.* servo valve or solenoid valve).

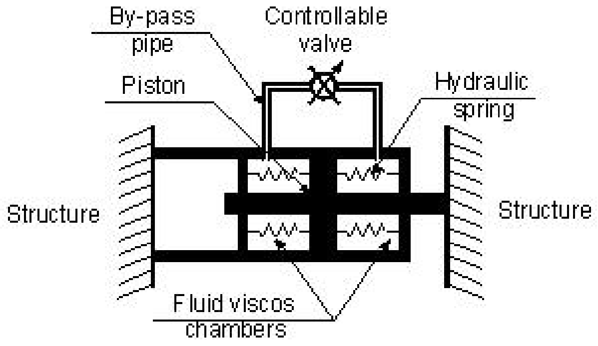
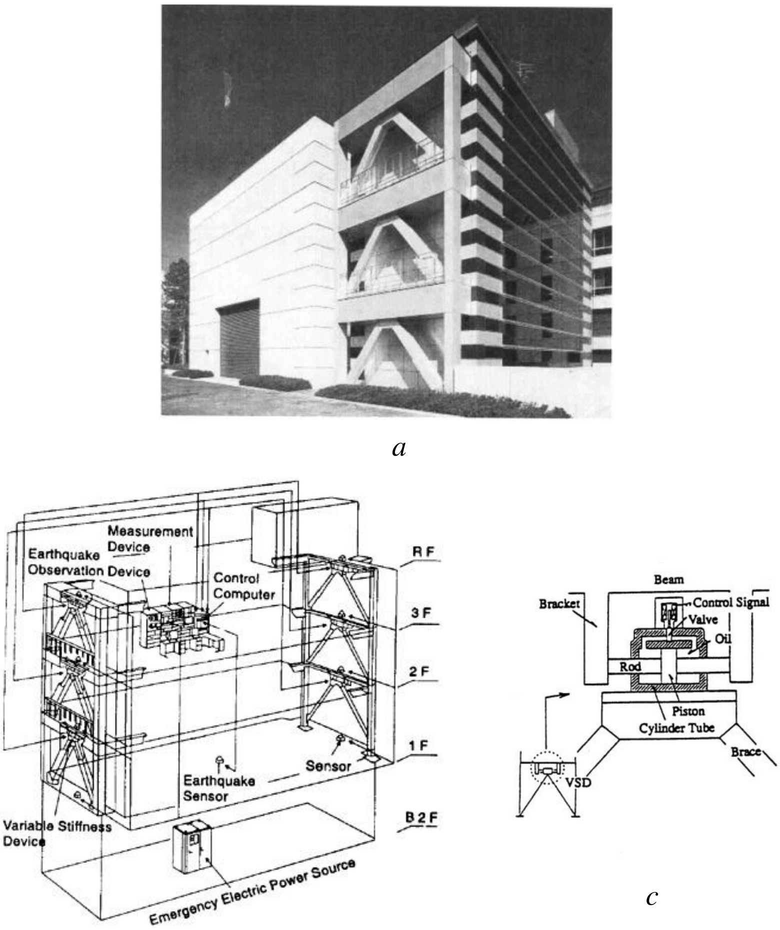


**Fig. 2.** – Scheme of variable orifice fluid damper.

A variable stiffness device is achieved to get an auxiliary structure or stiffness element be attached or detached from the main structure so that structural system can be change to realize non-resonant states to dynamic hazard mitigation [2].

The Kajima Research Laboratory was the first building equipped semi-active systems using three Active Variable Stiffness devices (Figs. 3 *a* and 3 *c*) [10].

Kajima Corporation built the structure for own research centre in Tokyo. The control system may be called *semi-active* because the lock mechanism of one bracing system within the structure has on–off behaviour. It is composed of a normally closed solenoid valve regulating oil flow from one chamber of the piston in the other. The operation of valve requires a power of 20 W. The natural frequencies of the structure may be changed due to their independent controllability of devices. The received information from the sensors that are distributed at each floor, is conducted to a digital computer where the control strategy is implemented (Fig. 3 *b*).



*a*

*b*

*c*

**Fig. 3.** – The Kajima Research Laboratory building equipped with semi-active systems: *a* – external view of building; *b* – scheme of semi-active control system; *c* – active variable stiffness device.

During his live the building was subjected to three little earthquakes in order to activate the system. The record of the response has shown a better behaviour than that with numerical simulations of the structure with the semi-active control system.

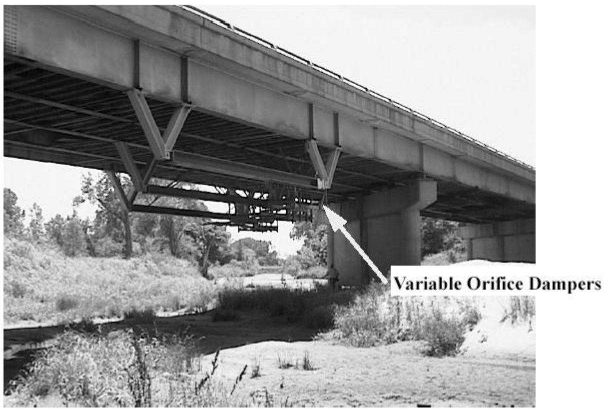
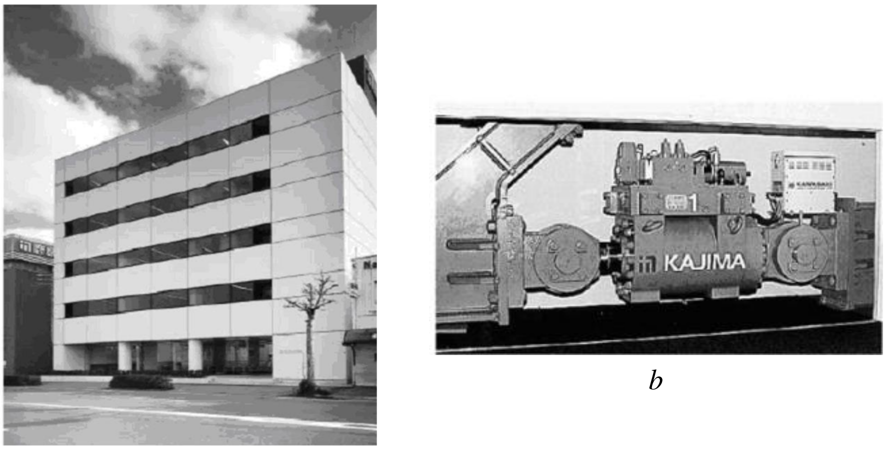


**Fig. 4.** – External view of Walnut Creek Bridge.



*b*

*a*

**Fig. 5.** – The Kajima Shizuoka building equipped with semi-active systems: *a* – external view of building; *b* – view of semi-active hydraulic damper.

The second application of semi-active control systems was achieved on a bridge on the interstate highway I-35, USA (Fig. 4). Some variable orifice dampers were installed under the deck to dissipate the energy induced by traffic. In 1994 Sack and Patten experimented the system and later, in 1997, Patten *et al.* monitored it for two years, between 1997 and 1999, demonstrating the implementation effectiveness of this technology [11], [12]. The principle of the device is based on on–off behaviour requiring only a power from a battery to switch the valve.

In 1998, Kajima Corporation implemented other semi-active system in the Kajima Shizuoka Building in Japan [11]. The building has 5 floors, and at each storey, excepting of the last storey, inside the walls on the both side of building are implemented semi-active devices; so in total there are implemented 8 semi-active dampers. Each device contains a flow control valve, a check valve and an accumulator and can generate damping coefficient in a continuous range between 200 and 1,000 Ns/mm (Fig. 5). The control algorithm is based on Linear Quadratic Regulator (LQR) theory.

## 3. Case Study of Variable Orifice Damper

Let's consider a SDOF model in order to make energy comparisons among passive and semi-active control strategies. The corresponding dynamic characteristics are as follow: $m = 10{,}000$ kg; $k = 2{,}000{,}000$ N/m; $c = 2{,}815$ Ns/m; $\omega = 14.14$ rad/s; $T = 0.44$ s; $f = 2.25$ Hz; $\xi = 0.01$. The system is subjected to El Centro seismic record.

The force in the passive fluid damper is expressed as

$$f_d = C\,|\dot{x}|^{\alpha}\,\mathrm{sgn}(\dot{x}), \tag{1}$$

where $\dot{x}$ is the velocity of the piston rod, $C = 5{,}000$, a constant and $\alpha = 0.5$ coefficient situated in the range of approximately 0.5 to 2.0.

On–off clipping control is used in order to design the semi-active strategy. There are two steps in order to design a clipping control for any type of semi-active device. First, an active control law computes a desired control force, $f_c$. In this case any type of active strategies can be chosen (optimal control, integral force feedback control, $H_2$ or $H_\infty$ control) because the second step is independent from it. Next, secondary clipping controller tries to make the semi-active device to replicate the force that the active device would apply on the structure. For on–off clipping control, the following rule is usually used: if the magnitude of the force, $f_d$, produced by the device is smaller than the magnitude of the desired optimal force and the two forces have the same sign, the voltage applied to the current driver is increased to the maximum level so as to increase the force produced by the damper to match the desired control force. Otherwise, the commanded voltage is set to zero. The command signal is described by the following formula:

$$U = U_{\max} H\left[(f_c - f_d)\, f_d\right], \tag{2}$$

where $U$ is the command signal, $H[\ldots]$ – the Heaviside step function, $U_{\max}$ – the maximum voltage applicable on the semi-active device to obtain the maximum damping and $f_d$ and $f_c$ – the measured and required control forces. The control is accomplished by measuring the actual relative velocity of the floor structure. The required force is given by the relationship

$$f_c = g\dot{x}, \tag{3}$$

where $g = 30,000$ Ns/m is control gain. There is considered an actuator, which acts on the structure.

The variable orifice damper is controlled by two functions capable to describe the passive damping force *versus* velocity paths. In passive control off case for numerical simulations, when the commanded voltage is set to zero the force is expressed by (1) but the constant $C$ has the value of $1,000$. Also, in passive control on, when the commanded voltage is set to maximum the constant $C$ has the value of $5,000$.

The control performance of the semi-active damper in term of displacement is compared with uncontrolled case, passive off case and passive on case under El Centro's earthquake. The obtained results demonstrate that there is a general reduction of the displacement in semi-active control case.

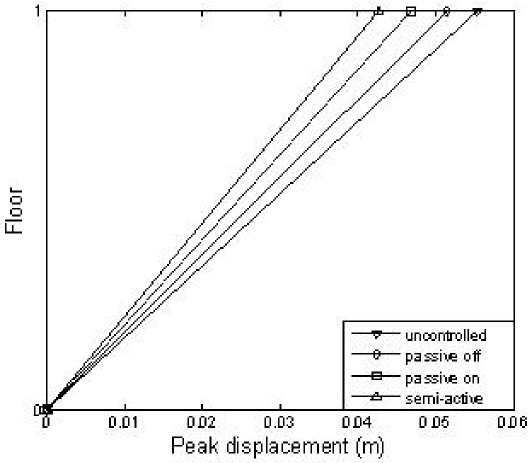


**Fig. 6.** – Comparison of peak displacement responses of the SDOF system between uncontrolled case, passive off case, passive on case, semi-active case and active case under El Centro's earthquake

## 4. Conclusions

The variable orifice devices are shown to be an effective method of natural hazard mitigation for buildings. Two different kinds of passive controls and one semi-active control are analysed. Semi-active control is the best choice because the results of computer simulations indicate significant improvements in building displacement.

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# APLICAŢII PRACTICE ALE SISTEMELOR DE CONTROL SEMI-ACTIV LA STRUCTURILE CONSTRUCŢIILOR

(Rezumat)

Protecţia seismică este, fără indoială, o prioritate în lumea întreagă şi de aceea una din preocupările principale ale cercetătorilor din domeniu a devenit găsirea unor concepte inovatoare în ceea ce priveşte protecţia seismică a structurilor de rezistenţă. Scopul acestei lucrări constă în studiul analitic şi numeric al disipatorului cu orificiu variabil implementat într-o structură cu un grad de libertate dinamică (1GLD) pentru creşterea siguranţei oamenilor şi reducerea riscului seismic. Disipatorul cu orificiu variabil este cel mai cunoscut dispozitiv semi-activ hidraulic, care poate fi utilizat ca parte componentă dintr-un sistem de izolare seismică sau în cadrul contravânturilor laterale ale unei structuri. Strategia de control semi-activă este realizată prin algoritmul de control *clipping on–off*.

Se trage concluzia că disipatorul cu orificiu variabil produce o reducere substanţială a răspunsului în deplasări ale unui sistem cu 1GLD în comparaţie cu răspunsul în cazul dispozitivului pasiv cu fluid.