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CONTROL OF STRUCTURAL RESPONSE WITH A NEW SEMI-ACTIVE VISCOUS DAMPING DEVICE

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Abstract. *Semi-active control devices can perform significantly better than passive devices, but also have the potential to achieve the performance approaching that of a fully active system. Semi-active devices offer significant promise for their ability to add supplemental damping and reduce seismic structural response in an easily controllable manner, and can be used in some modes to modify or reshape hysteretic structural response. However, many current semi-active devices are highly complex, limiting robustness, while those that can generate larger forces suffer from increased response lag time to do so. Thus, an ideal semi-active device would offer high forces, low complexity, and fast response. The semi-active viscous dampers could offer all these properties and could reduce not only the displacement response of a structure, but also the base shear. There are three semi-active viscous dampers, a 1-4, 1-3 and 2-4 device. In this study, a spectral analysis over periods of T= 0.2-5.0 sec under 20 design level earthquakes from the medium suite of the SAC project is used to compare three device control laws individually or in combination to sculpt structural hysteretic behaviour. Performance is assessed by evaluating reduction factors (RFs) compared to an uncontrolled structure for maximum displacement (S_d) and total base-shear (F_b), indicative of structural and foundation damage, respectively. Results show that combining the control laws to reshape the hysteresis loop can reduce the median value of both S_d and F_b by approximately 30% for periods less than 3.0 sec and 20% for periods more than 3.0. Thus, the results show that the proposed device and control laws have significant effect to reduction both structural response and base-shear. Overall, these results indicate the robustness of potentially very simple and robust semi-active viscous dampers to mitigate the risk of seismic damage to both the structure and foundation in a way that is economically suitable for either new designs or retrofit.*

INTRODUCTION

With the development of construction techniques, it is possible to build large-span bridges, pipelines, dams, and high-rise buildings. However, this achievement also generates problems, specifically how these structures can be protected from external excitation, such as strong winds and severe earthquake ground motions. Some solutions to reduce loss of life and damage due to natural hazards include systems such as base isolation, rocking, and bracing systems. To improve the performance of these systems, supplemental control devices that are intended to absorb a portion of the seismic response energy and protect structures from damage, can be incorporated in to these passive systems.

Supplemental damping systems can be divided into three broad categories: active, semi-active and passive. Active systems are complex and expensive because they require high speed, high force actuators and significant energy input. Passive solutions avoid these issues, but cannot provide any adaptive capability to different responses and tuned, passive solutions may not be robust to changes in structural response. An interesting and appealing compromise is given by semi-active control systems that require only a relatively small external power source for operation but offer the ability to adapt to structural response.

Semi-active devices have two main advantages over passive or active control devices. First, they do not require a large external power source for operation, as active devices do. This characteristic is because of changes in the physical space or material properties that create their dissipative forces. Therefore, with careful implementation, semi-active devices cannot in principle destabilize the structure because they do not add energy to the system, but simply absorb or store vibratory energy [1].

Second, the smart control of these devices makes them more able to provide a reliable, low-damage system than passive devices, regardless of the uncertainties of input ground motions. This aspect is enhanced by the ability to sculpt device hysteretic behaviour in some, but not all, semi-active devices.

The potential of many classes of semi-active devices and control methods, including variable stiffness and variable damping, to mitigate damage during seismic events is well documented [1-6].

Many prior semi-active devices have been air or fluid based systems based on the principles of variable stiffness [1, 5, 7, 8] , but were complex and could not produce the very large control forces often required for controlling structures. A further, potentially more robust, means of achieving such a semi-active device is to use a controllable, electromechanical, variable-orifice valve to alter the resistance to flow of a conventional hydraulic fluid damper. Feng and Shinozuka [9] were the first to consider this concept. However, the extra plumbing and the low resolution orifices made this device essentially very similar to the resettable device of Jabbari and Bobrow [10], and produced primarily on/off or high/low control without the ability to realize much of the potential benefit. Moreover, the ability to sculpt the hysteretic response of a device, and thus of the whole structure, is only obtained by direct control of its the device motion in each direction (with sign) [1, 7, 11, 12].

Semi-active devices can also be highly complex and possibly have limited force. To address these shortcomings, Hazaveh et al [11, 12] evaluated the concept of semi-active viscous dampers and examined three types of device control laws (a 1-4, 1-3 and 2-4) to sculpt hysteretic behaviour. The 1-4 device provides damping in all four quadrants and is thus equivalent to typical passive viscous dampers (Figure 1.a). Figure 1.b shows the 1-3 device that provides resisting forces only in the first and third quadrants of the force-displacement graph, resisting motion away from equilibrium (zero-displacement). Finally, the 2-4 device provides damping in the second and forth quadrants, resisting motion only toward equilibrium (Figure 1.c). The semi-active viscous damper appeared to be an appealing solution for reducing seismic response, with minimal to no risk of structural or foundation damage. In particular, the basis of industrial viscous dampers in high-force applications and adverse operating conditions demonstrates the potential to robustly deliver the high force necessary.

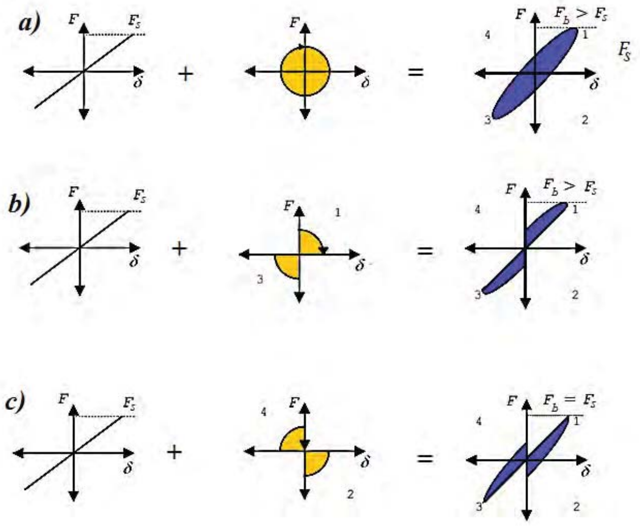

Figure 1. Schematic hysteresis for a) 1-4 device, b) 1-3 device, and c) 2-4 device [11] .

In this study, the effect of three control laws of a semi-active viscous damper and combination of them was investigated. The effect of different control laws on the displacement and base shear of the structure is evaluated using a single degree of freedom spectral analysis subjected to 20 earthquake ground motions from the SAC LA medium suite [13]. The goal is to identify the range of potential reductions in displacement (damage) and base shear (foundation damage and cost) that can be achieve with these devices and assess the impact of the different control laws.

1 ANALYSIS

This paper investigates the relative effectiveness of the four semi-active devices on the seismic response of a simple SDOF structural system fitted with a semi-active variable orifice viscous damper. The model structure includes inherent structural equivalent structural viscous damping of 5%. The semi-active viscous damping devices can add 5% to 45% additional damping to the structure when activated, and ~0% when not active.

The research utilizes one earthquake suite from the SAC project [13]. The suite represents ground motions having probabilities of exceedance of 10% in 50 years in the Los Angeles region, and is referred to as the medium suite. Response statistics can thus be generated from the results of this probabilistically scaled suite with an expected return period of 524 years.

Response spectra are produced for the medium suite of earthquake ground motions, and spectral response plots were plotted for the structural displacement (Sd) and the total base shear (Fb) in a T = 0.2 – 5.0 sec range in increment of ΔT= 0.1 second. Period is changed by modifying the stiffness. The total base shear that is an indication of the required foundation strength defined as the sum of the base shear for a linear structure and the resisting forces from the semi-active viscous damping device.

The reductions achieved by the addition of semi-active viscous damping devices are represented by reduction factors (RFs), normalized to the uncontrolled, no device, case results. These factors enable easy comparison of the different control laws and are a multiplicative factor. RFs less than 1.0 indicate reductions in the response metric, and greater than 1.0 an increase.

The optimal control law depends upon structure-specific parameters such as natural periods. Figure 2 shows the scheme of combination of the 1-4 and 2-4 device together to achieve result. Response spectra were created for the three device control laws and combination of them (Figure 2) from 0.2 to 5.0 seconds in 0.1 second increments, as compared to the single degree of freedom structure.

A median (the log-normal mean) and 5%, 25%, 50%, 75%, and 95% percentile represent the variation observed within this ground motion suite. These percentiles define relative risks of exceedance. The median (50th percentile) is the middle or expected result. The 95th percentile shows the largest RF likely to occur for ground motions of this likelihood of occurrence. These statistics provide the framework for a probabilistic based or risk based performance based design approach. They thus indicate the likely range of benefits.

The expected value of the response and the relative spread (or dispersion) over the suite of ground motions are thus captured. To eliminate the likelihood of erroneous conclusions being drawn about the viability of a control law due to atypical performance for a single earthquake instead of using individual earthquakes, this earthquake suite yielding 20 results is used. Hence, the approach should be robust to variabilities. Finally, the structural response of the three control law and combination of the 1-4 and 2-4 control law are compared with each other.

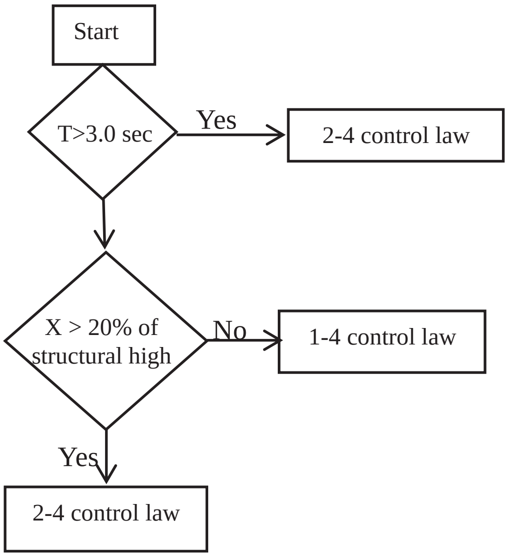

Figure 2: The scheme of combination of the 1-4 and 2-4 device with each other

2 RESULTS AND DISCUSSION

Figure 3 compares the different percentile RFs for S_d for all four control laws and the 15% additional damping provided by the device. All of these four control law have RF<1.0. However, as expected, the largest reductions were recorded for the 1-4 device as it has the biggest area enclosed by hysteretic loop and consequently the higher energy absorption and dissipation.

Figure 4 compares the different percentile RFs for S_d for all four control laws. The results indicate that the range of the total base-shear force RF of the 1-4 control law is 0.55-0.90, 0.57-1.00 and 0.57-1.35 for periods 0.5, 2.5 and 4.5 seconds, respectively, which represent stiff, seismic and wind governed periods. Moreover, the 95th and 75th RF for F_b for the 1-4 control law exceeds 1.0 after T=2.5 and 3.8 seconds, respectively.

Like the 1-4 control law, the 1-3 control law has RF <1.0 for S_d for most periods and the total base shear greater than 1.0 for high period structures, as shown in Figure 3-4. However, in the 1-3 control law, the 95th and 75th percentile RF exceeds 1.0 from lower periods of T=1.6 and 3.4 seconds, respectively. The 50th percentile F_b exceeds 1.0 for periods over 4.5 seconds.

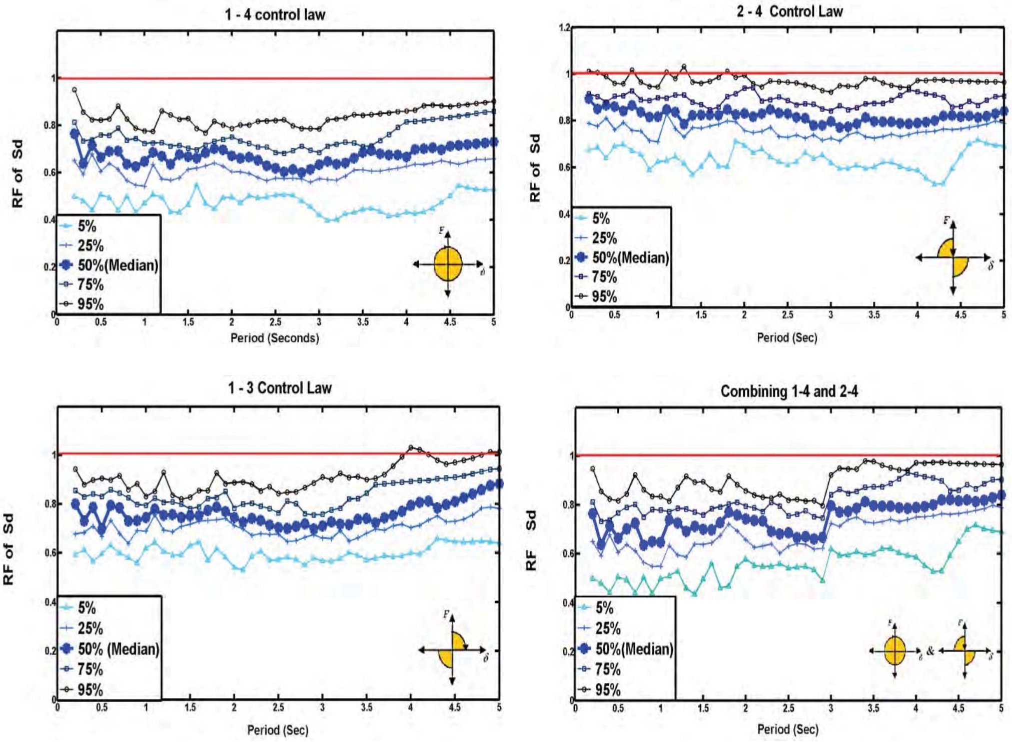

Figure 3. The different percentile RFs for Sd for the 1-4, 2-4, 1-3 and combination of 1-4 and 2-4.

For the 2-4 and combination of the 1-4 and 2-4 control law, similar to the 1-3 and 1-4 control laws, a S_d RF < 1.0 is valid for all periods from 0.2 to 5.0 seconds. However, the RF for F_b is less than 1.0 for the 2-4 and combination control law for all periods. Thus, it reduces both S_d and F_b, as hypothesized.

However, the combination control law could mitigate S_d and F_b more than the 2-4 control law. Figure 3 shows that for structures with period less than 3.0 seconds the combination control law could reduce the displacement more than the 2-4 control law. Moreover, the total base shear of that is slightly better than the 2-4 control law. Therefore, the combination control law could have a positive aspect of the 2-4 control law to have RF of F_b less than 1.0 for all of the periods and have reasonable S_d RF of the 1-4 control law.

Hence, the choice would depend on the designer and any relevant codes/guidelines specifying a maximum acceptable risk of exceedance.

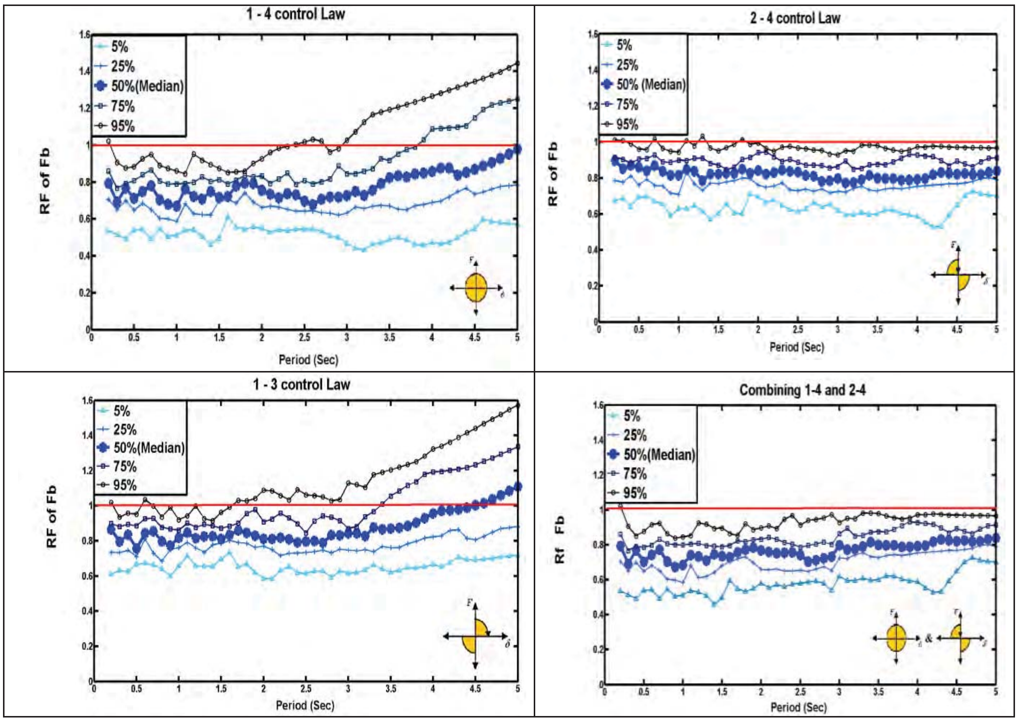

Figure 4. The different percentile RFs for Fb for the 1-4, 2-4, 1-3 and combination of 1-4 and 2-4.

3 CONCLUSION

The semi-active viscous damper that allows a broader range of control laws than classical semi-active devices that has been investigated in this research. The most appropriate hysteresis loop is provided by the ability to semi-actively re-shape hysteretic behaviour via broader control laws. Based upon the investigation described herein, the following conclusions can be drawn:

- Minimizing base shear and structural response, depending on design requirements, can be achieved by sculpting the hysteretic behaviour semi-actively.

- Spectral displacement (sd) reduction factors showed considerable reductions achieved, with similar results between the 1-3 and 2-4 control law. The largest reductions were seen for the 1-4 device. However, these latter results come at the expensive of increased risk of increased base shear. Moreover, the results of RF of S_d for combination control law are closed to S_d RF of the 1-4 control laws.

The two control laws that reduce total base shear, as well as displacement response, are the 2-4 and combination device. However, the combination of the 1-4 and 2-4 control law could use the advantage of the both methods. Therefore, the combination method could reduce the structural response as well as the 1-4 control law and have a stable RF of F_b for all of the periods as same as the 2-4 control law.

Finally, the results presented provide initial insight that could lead to quantify risk and reward in term of foundational structural design parameters in a framework suitable for typical performance based design, to ease translation into practice.

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