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Spectral analysis and Assessment of a net-zero base-shear energy dissipation approach for seismic energy mitigation

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ABSTRACT: Combining passive and semi-active damping has unique benefits that cannot be achieved through other damping techniques alone. Passive high force to volume (HF2V) lead dampers offer high energy dissipation, but have no ability to customise overall response. Semi-active resetable devices offer adaptability and custom hysteresis loops that can reduce both displacement and base shear, but are limited in overall energy dissipation capability. Together, these devices offer a new concept to maximised displacement response reduction, without increasing base shear – a net zero base-shear concept. This paper combines HF2V devices, with design force levels up to 10% of weight, and a resettable device with nominal stiffness of 100% of column stiffness. A spectral analysis is run to size the HF2V device iteratively at each period to achieve maximum reductions in displacement without increasing median base shear.

The results show up to 50% reduction in base shear for the low suite, and up to a 40% reduction for the medium and high suites. Towards longer periods, base shear reduction factors tend to 1.0, indicating net-zero base-shear. This situation is never reached below a structural period of 2.5s, where median base-shear reduction factors are less than 1.0, indicating a reduction in base-shear as well as displacement and structural force. Overall, these results are independent of HF2V device scaling, as analyses using ground motion specific mean velocities and 1m/s mean velocity for sizing the device capacity yield closely similar results. Comparisons are also drawn between the performance of the combined damping system to that of the passive and semi-active systems alone.

1 INTRODUCTION

The development of energy dissipation technologies for seismic protection of civil infrastructure has received significant research interest in recent years on both passive and semi-active systems. High force-to-volume (HF2V) lead extrusion-based devices are one emerging passive technology (Rodgers et al., 2007a, 2008a). Emerging semi-active devices that can sculpt device specific and unique hysteresis loops are a further option for some special cases (Chase et al., 2006; Rodgers et al., 2007b, 2009a). In particular, semi-active resetable devices have several key advantages over fully active systems. The absence of a large power source makes them simpler and more reliable than a fully active system. Moreover, due to the fact that they are reactive and do not add energy to a system, with careful implementation, they guarantee stability (Barroso et al., 2003; Chase et al., 2004). Semi-active systems also offer a broader range of control than tuned passive systems and are therefore more responsive to changes in structural behaviour due to non-linearity, damage or degradation. However, they have an important drawback in that they typically do not offer the same energy dissipation capacity available from similar sized passive energy dissipation devices.

More specifically, semi-active resetable devices offer the unique opportunity to sculpt or re-shape the structural hysteresis loop to meet design needs (Chase et al., 2006). For a sinusoidal response, a typical viscously damped, linear structure has the hysteresis loop definitions shown schematically in Figure 1a, where the linear force deflection response and the circular force-deflection response due to viscous damping combine to give an elliptical overall hysteresis loop. Figure 1b shows the same behaviour for a resetable device where all stored energy is released at the peak of each sine-wave cycle and all other motion is resisted (Jabbari and Bobrow, 2002). This device is referred to as a "1-4 device" as it provides damping in all four quadrants, and has the ability to dissipate significant energy. However, the resulting base-shear force is increased. If the control law is changed such that only motion towards the zero position (from the peak values) is resisted, the force-deflection curves that result are shown in Figure 1c. In this case, the semi-active resetable damper force reduces base-shear demand by providing damping forces only in quadrants 2 and 4; a "2-4 device".

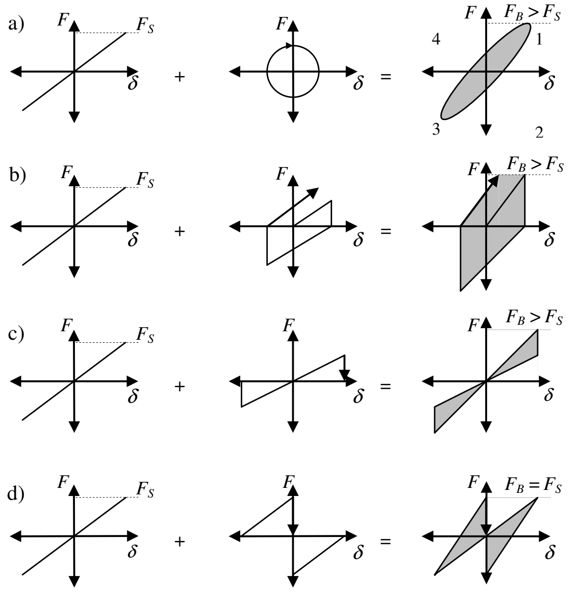

Figure 1: Schematic hysteresis for a) viscous damping, b) a 1-4 device, c) a 2-4 device. F_B = total base shear, F_S = base shear for a linear, undamped structure. $F_B > F_S$ indicates an increase due to the additional damping.

The main advantage of passive systems is robustness and minimum complexity. They do not require any sensing, computing or actuation mechanisms and can thus be relatively inexpensive to implement. They also offer greater energy dissipation for a given device size or volume, which is important for some applications. High capacity and low-cost passive systems developed and currently used for energy absorption and base-isolation applications include lead extrusion dampers (Cousins and Porritt, 1993) and lead-rubber bearings (Robinson, 1982; Robinson, 1995). Hence, they are a well developed structural technology accepted within the structural design community.

Lead extrusion dampers used in previous structural applications have been quite large due to the relatively low internal pressures (Cousins and Porritt, 1993). Their large size is often considered an impediment, preventing implementation into several possible applications. Therefore, a much smaller, compact and, high internal pressure damper has been developed that enables significant new structural applications, particularly in extending applications to implant dampers within structural connections (Rodgers et al. 2007a). Importantly, they can still provide the high force and energy dissipation capacities of the much larger devices, while being small enough to be placed directly into a structural connection. Hence, they are referred to as high force-to-volume (HF2V) devices, and have been proven in several studies (Rodgers et al., 2008a, 2008b, 2009b; Mander et al., 2009)

2 COMBINED NET-ZERO DAMPING SYSTEM CONCEPT

Both passive and semi-active systems have advantage, in terms of cost, simplicity and influence on overall structural response. Rodgers et al. (2007b) showed that semi-active devices with the 2-4 control law have the ability to reduce the structural force (column shear force), while also reducing the total base shear using a 2-4 control law in Figure 1. However, the 2-4 devices achieve this outcome at a cost of significantly reduced energy dissipation for a given device compared with using the 1-4 control law. A similar spectral investigation is performed for the passive HF2V devices in Rodgers et al. (2008a). This research showed that while the passive HF2V devices do not have the same ability to customise the overall structural hysteresis, substantial response reductions can be achieved with an unsophisticated implementation of realistically sized HF2V devices. Hence, the combination of these semi-active resetable devices utilising the 2-4 control law, and the passive HF2V devices could lead to improved response reductions without increasing total base-shear demand.

The addition of HF2V damping to the resetable devices could lead to a 'net-zero base-shear' design approach. The concept involves adding passive damping to the 2-4 devices, such that the base-shear is essentially unchanged from the uncontrolled structure, but that the displacement and force reductions are increased. More simply, passive devices could provide added response reduction in parallel with 2-4 devices and thus the damping forces transmitted to the foundation would 'replace' the base shear 'savings' from the reduction in response achieved with semi-active devices. The overall concept seeks to maximize the complementary strengths of these devices.

Figure 2 presents a schematic representation of the net-zero concept. In the left plot, the structural displacement, and hence the structural force (ie: the shear force resisted by the column) are reduced by the addition of supplemental damping. The middle plot of Figure 2 presents the contributions of the HF2V and the 2-4 resetable devices, and the combined response of the overall damping system. The right plot presents the sum of the structural and damping forces, which represents the total force transmitted to the foundation, termed the total base-shear. It can be seen in this final schematic that the total base-shear for the controlled and uncontrolled structure can be similar, despite the reduced structural column forces in the controlled structure. This research presents a spectral analysis similar to that in Rodgers et al. (2008a, 2007b), but analysing the combined system, to investigate the 'net-zero base shear' concept. If "net-zero" results are achieved, the sum of the reduced structural force, $F_{s\text{-controlled}}$, and the damping force, $F_{damping}$, will exactly equal the uncontrolled structural force, $F_{s\text{-uncontrolled}}$. To achieve the "net-zero" target, iteration is needed, as there is a complex trade-off between the amount of damping force added and the corresponding reduction in structural force.

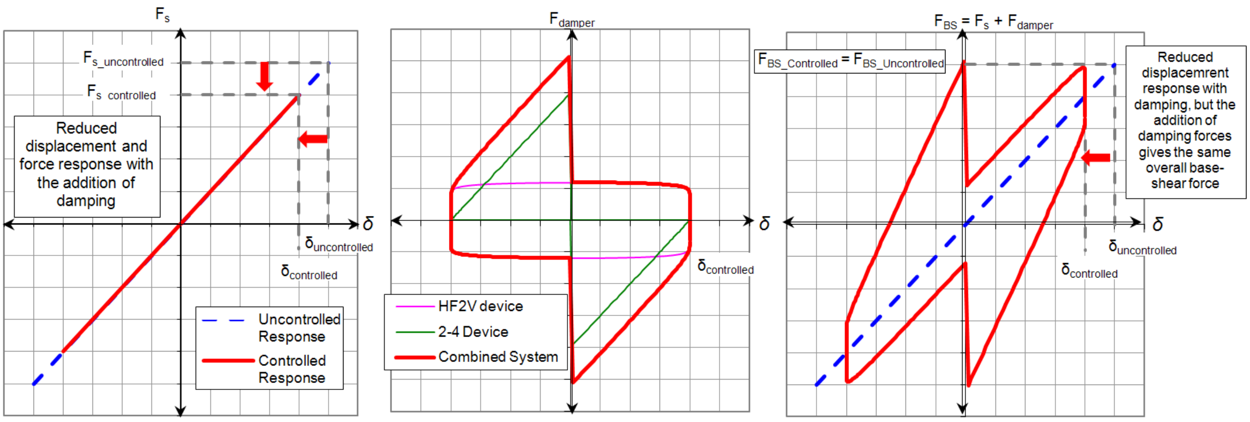

Figure 2: Schematic of the net-zero base-shear concept.

3 DEVICE DYNAMICS AND MODELLING

3.1 *Semi-Active Resetable Devices*

Semi-active devices are hydraulic spring elements with a resetable un-stretched spring length. They add a non-linear stiffness to the structure. The piston stores energy by compressing the working fluid, with peak energy storage occurring at peak piston displacement. At this point, the stored energy can be released by discharging the fluid/air to the non-working side of the device, thus resetting the un-stretched spring length, as seen in Figure 3a. This approach yields the 1-4 behaviour of Figure 1b.

Figure 3b shows a modified device design where each chamber can be controlled independently (Chase et al., 2006). It eliminates the need to rapidly dissipate energy between the two chambers. The resulting independent control of the pressure and energy dissipation on each side of the piston allows greater flexibility in designing the overall device behaviour. This design thus enables a much broader range of control laws as each valve can be operated independently, such as the 2-4 device of Figure 1c.

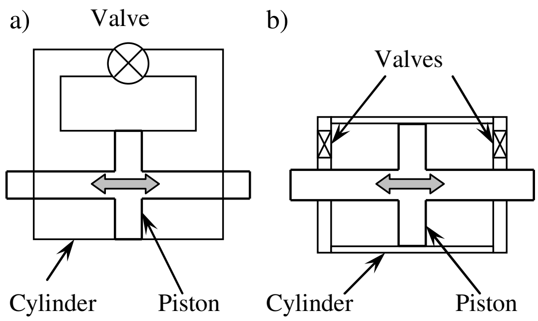

Figure 3: Semi-active device schematics a) Conventional design with single valve and external plumbing system, b) Independent chamber design where each valve vents to atmosphere for a pneumatic device.

The resetable device force is controlled by a reset displacement, x_{reset}, the location at which the valve was last reset and the pressure equalised. Device stiffness is defined as a percentage of column stiffness to ensure realistically sized devices are utilised, and can be related to geometric device parameters (Mulligan et al., 2010). For this manuscript, the device stiffness is set to 100% of the column stiffness (Rodgers et al., 2007b), and the force is defined:

$$F_{resetable} = K(x - x_{reset}) \tag{1}$$

where $F_{resetable}$ is the resetable device force, K is the device stiffness (100% of column stiffness), x is the resetable device displacement, and x_{reset} is the device displacement at the last valve reset.

3.2 *High Force-to-Volume (HF2V) Lead Damping Devices*

The HF2V prototypes (Rodgers et al., 2007a, 2008a) are a bulged shaft design for low cost and ease of manufacture, as shown in Figure 4. The plastic deformation associated with the extrusion process absorbs large amounts of energy and provides a much stiffer damper capable of absorbing far more energy than an equivalent sized fluid viscous damper due to the much larger bulk modulus of lead.

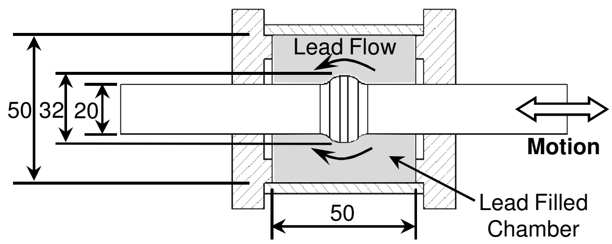

Figure 4: Cross-sectional view of a typical HF2V damper.

HF2V damping devices are modelled as weakly velocity dependent non-linear viscous dampers (Pekcan et al., 1999). As such, the device force, F_{HF2V}, is defined:

$$F_{HF2V} = C_{\alpha}\dot{x}^{\alpha} \tag{2}$$

where C_{α} is a constant dependent on device geometry, $\dot{x}$ is the shaft velocity, and α is the velocity exponent, equal to 0.12 for a bulged-shaft lead extrusion damper (Mander et al., 2009; Pekcan et al., 1999; Rodgers et al., 2008a). For the analytical investigation, the value of the device constant, C_{α}, is determined from the design force level of the HF2V device. The design force is defined as a percentage of seismic structural weight, giving a non-dimensional damper capacity, ε, defined:

$$\varepsilon = \frac{C_{\alpha}\dot{x}_{ref}^{\alpha}}{W} \tag{3}$$

where W is the total seismic weight of the structure (N) and $\dot{x}_{ref}$ = 1 m/sec (Rodgers et al., 2008a; Pekcan et al., 1999).

4 METHOD OF ANALYSIS

This paper presents a spectral investigation of the combined effects of the semi-active resetable devices using the 2-4 control law, and passive HF2V dampers. The spectral investigation is performed for a seismically excited single degree of freedom structure fitted with the combined damping system. The model structure includes internal structural damping of 5%. The research utilises three earthquake suites from the SAC project (Somerville et al., 1997), representing ground motions having probabilities of exceedance of 50%, 10% and 2% in 50 years respectively in the Los Angeles region, referred to as the low, medium and high suites, respectively. Response statistics are generated from the results of each suite. The distribution of responses can be modelled by a log-normal probability density function. Thus, the spectra can be analysed using the appropriate lognormal statistics (Kennedy et al., 1980). Variables within each suite may thus be represented by a median (the log-normal mean) and log-normal standard deviation (Limpert et al., 2001). This is the same approach utilised in Rodgers et al. (2007b, 2008a) and thus facilitates direct comparisons for the component part of the analysis.

The investigation focuses on the reductions achieved in displacement, which is directly related to structural force, and total base-shear. The analysis is performed by simulating the response of the structure with a net-zero damping system. The resetable device uses the 2-4 control law, and has stiffness set to 100% of column stiffness as in Rodgers et al. (2007b). The HF2V device is set for a peak force of 10% of structural weight. These are realistic values that can be realised for actual devices in realistic buildings.

These responses are then compared to the response of the uncontrolled structure. These reduction factors are thus directly comparable to those for the controlled structure using only the resettable (Rodgers et al., 2007b) or HF2V device (Rodgers et al., 2008a) alone. From those analyses the contribution of each element to the whole can be clearly delineated.

5 RESULTS AND DISCUSSION

Figure 5 shows the displacement reduction factors for each suite and each case. The reduction in displacement for the net-zero damping system is the greatest for the low suite, and then less for the high suite, as expected for higher intensity ground motions. It is up to 70% for the low suite, 65% for the medium suite and 55% for the high suite, respectively. Even for long structural periods, displacement reductions are above 40%. These reductions are higher or than or equal to most of those achieved with either semi-active or passive damping alone.

In most cases, where the net-zero approach has a smaller reduction in displacement, the difference is ~10% or less, and only occurs at long periods (T = 3-5 seconds), where structural designs are dominated more by wind loading than seismic response. However, in all cases, the net zero damping system reduces displacement more than a semi-active damper alone. Conversely, in all 3 suites, at longer periods, the passive damping system brings larger reductions than the net zero approach. Specifically, these changes occur above periods of T = 1.5s, T = 3s and T= 4s for the low, medium and high suites, respectively. It should be noted that beyond these values, the net-zero point was typically achieved with passive damping less than 10% of weight. Therefore, the lower response reductions achieved compared with the passive case alone is due to the smaller size of the passive dampers.

As seen in Figure 6, for longer periods, the use of passive dampers alone can greatly increase base shear. This trend can be explained at least in part by the behaviour of the passive damping devices. For long periods, the spectral displacement is larger and will likely result in more energy dissipation for the passive dampers. The cost of these large structural force reductions is increased base-shear. Therefore, when iteratively solving for the net-zero point, the size of the passive damping devices implemented (as a percentage of seismic structural weight) is typically less than the 10% used for the passive devices alone. Therefore, in this longer period range, the structural force reductions achieved through the net-zero approach are smaller than that achieved with passive damping alone. Hence, the net-zero approach appears particularly suited for structures where seismic concerns dominate design, and passive HF2V devices alone tend to provide the reductions at longer periods.

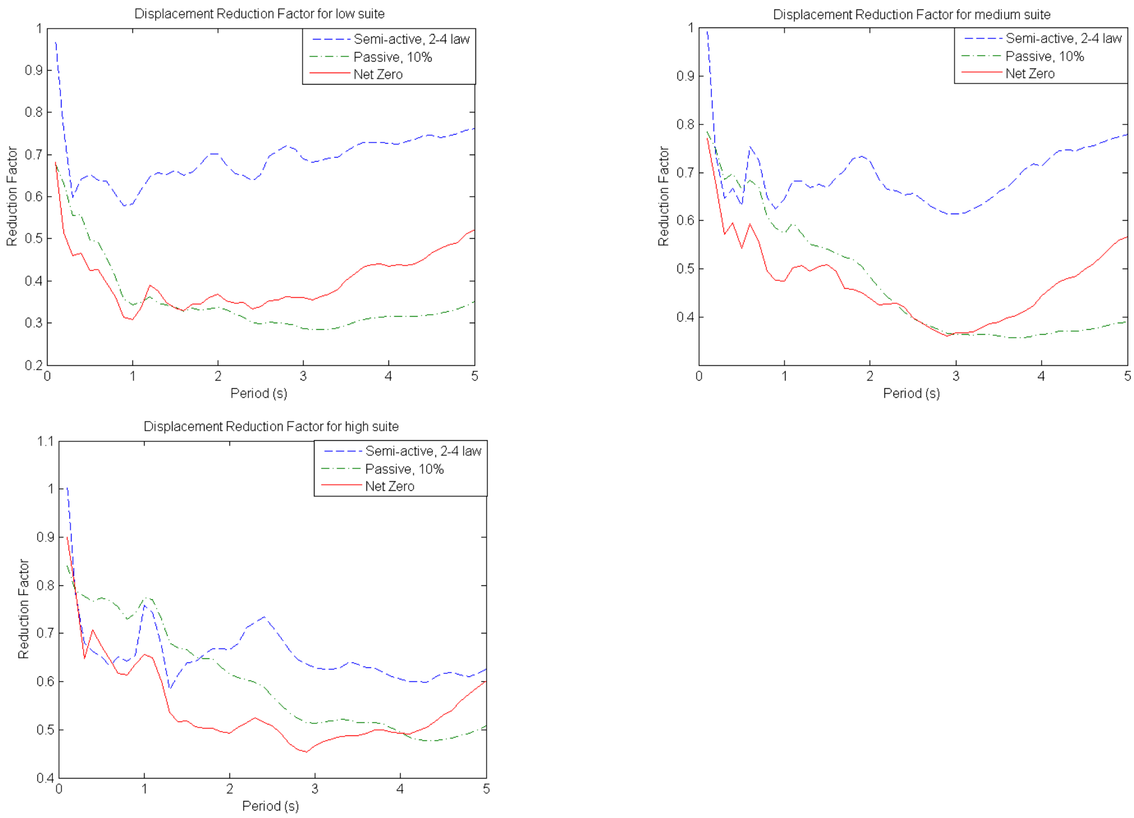

Figure 5: Displacement reduction factor for low, medium and high suites, using semi-active, passive and net zero damping systems.

Figure 6 shows the same comparison for base-shear, which is significantly reduced when using semi-active and net zero damping. In contrast, HF2V damping can significantly increase total base-shear by up to 3.5 times for the low suite. The semi-active system brings a better reduction in base-shear than the net zero approach after a certain period (T = 2s, T = 3.25s and T = 3.75s for low, medium and high suites). This result is expected, as the overall concept trades base-shear force reductions for increased displacement reduction by adding HF2V devices in combination with semi-active 2-4 devices. In all 3 cases, base-shear reduction for the net zero system only returns to net zero (RF=1.0) at long structural periods. However, it should be noted that if the 10% capacity on passive damper size is reached before "net-zero" is achieved, the result is desirable. While the aim of the "net-zero" philosophy is to get no change in base-shear, if a realistic capacity on the passive damper size is implemented (i.e. 10%) and the base-shear is still reduced, then the outcome is actually better than intended. Increase structural response reductions are achieved while also maintaining a reduction in base-shear.

As expected, a resetable device controlled by a 2-4 law significantly reduces total base shear but has a lesser impact on displacement. In contrast, passive HF2V devices greatly reduce displacements but increases base-shear significantly. In combination, the net zero system brings overall improved results in both displacement and base-shear. In fact, for periods less than T = 1.5s, T= 3s and T = 3.75s (for low, medium and high suites), the net zero approach gets unmatched results in both fields. Hence, the overall concept is most effective for periods where seismic design concerns are paramount.

Increasing passive damping capacity in the net zero system could bring even better results. However, this choice would likely imply unrealistically sized dampers (Rodgers et al., 2007a; 2008b; Mander et al., 2009). By increasing the HF2V dampers further to reach net-zero for base-shear reduction, higher displacement reductions can be achieved. Importantly, beyond a certain point, the structure becomes effectively near rigid and may no longer be a good balance of design. In particular, as displacements decline, accelerations increase, thus increasing the risk of damage to occupants and contents. Using a maximum of 10% capacity of structural weight for the passive device in the net zero system can be realistically achieved and maintains a good design balance.

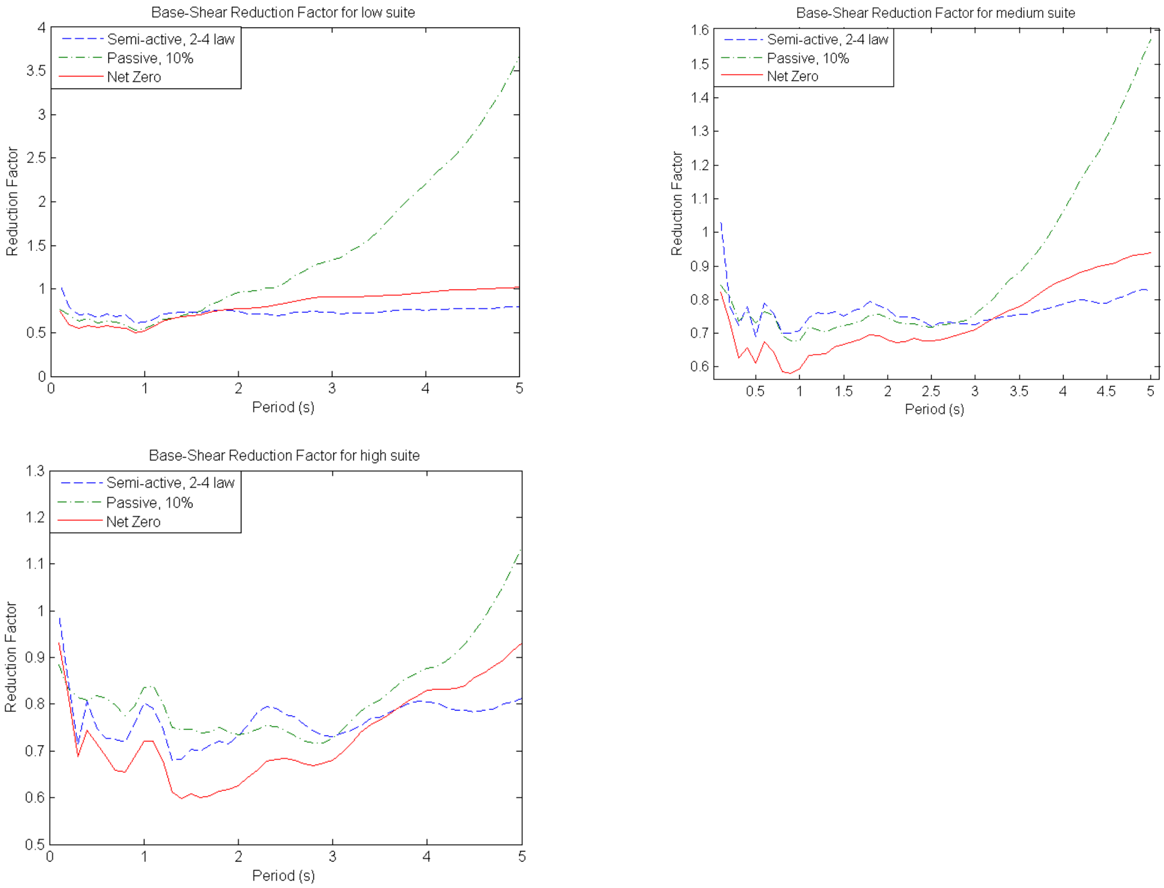

Figure 6: Base-shear reduction factor for low, medium and high suites, using semi-active, passive and net zero damping systems.

To determine if the assumed reference velocity ($\dot{x}_{ref}$ = 1.0 m/sec) affects the results, simulations are also run varying the reference velocity. In particular, the analysis was re-run where for each ground motion in each suite, $\dot{x}_{ref}$ was selected to be 50% of the pseudo-spectral velocity for the uncontrolled structure. This choice results in a wide range of pseudo-spectral velocities with $\dot{x}_{ref}$ =0.03-4.98m/s. However, due to the weak velocity sensitivity of these devices (velocity exponent α = 0.12) this wide range of velocities results in only a modest change in C_α and therefore the nominal device force. Despite the pseudo-spectral velocity ranging from 0.03 m/s to 4.98m/s, this results in maximum range of -34% to +21% change in C_α, as seen in Figure 7. It should be noted, however, that this insensitivity to the reference velocity is specific to these devices and their weak velocity sensitivity. For a standard viscous damper (α = 1.0) the force range is much larger and larger again for an air-damper with force proportional to velocity squared (α= 2), as seen in Figure 7. Therefore, if modelling these devices, consideration of the likely spectral velocity of the structure is much more important.

Therefore, on running the analysis, very similar results were found for Figures 5-6. In both displacement and base shear reduction factors, the maximum difference was approximately 5% of the absolute value shown in Figures 5-6, which is well within building construction and design variations. To illustrate this result clearly, the low-suite results with $\dot{x}_{ref}$ = 1.0 m/sec and customised $\dot{x}_{ref}$ value are shown in Figure 8. It confirms that using 1.0 m/s as reference velocity (Pekcan et al., 1993; Rodgers et al., 2007a) is suitably accurate when defining passive damping forces. Hence, this choice does not notably influence the results and trends.

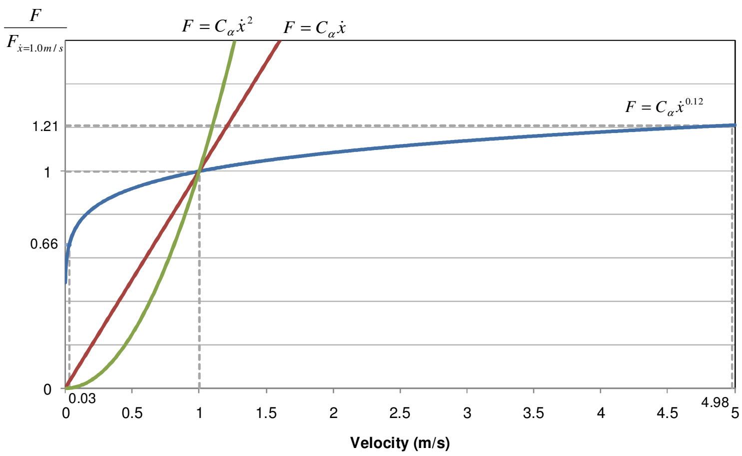

Figure 7: Force range of velocity dependant dampers with α=.012, 1.0 and 2.0. When α=0.12, the force is insensitive to changes in velocity, but this is not true for other values of α.

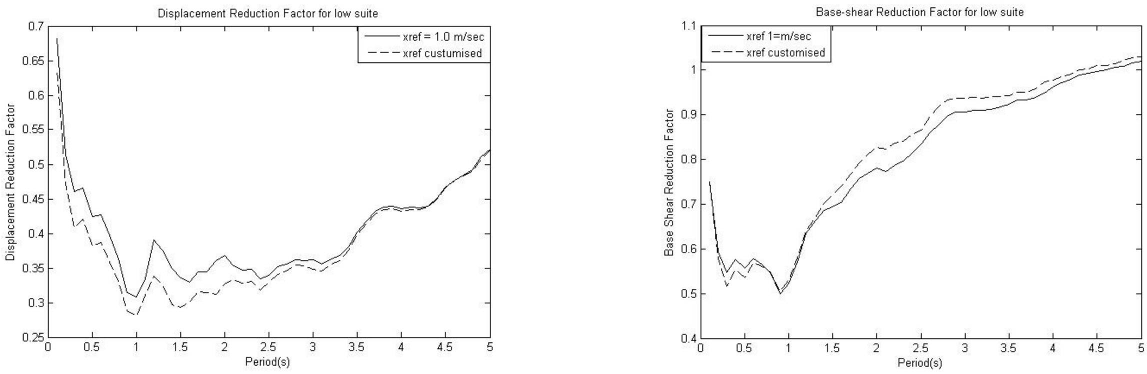

Figure 8: Displacement and base-shear reduction factors for low suite, with $\dot{x}_{ref}$ = 1m/s and $\dot{x}_{ref}$ customised.

6 CONCLUSIONS

This research presented a novel combination of semi-active and passive devices that reduces displacement response, while maintaining the same or reduced base-shear. The results show that combining a resetable device, using the 2-4 control law, with an HF2V device can achieve results greater than using either device alone. Using realistic values this concept can reduce displacements up to 70%, while still reducing base shear up to 50%. Base shear tends to go back toward a net zero condition as HF2V dissipation is added. Further reduction in displacement could be achieved, bringing base-shear closer to net zero, but would imply unrealistically sized HF2V devices, and a poor design balance, making the structure overly rigid. It was also confirmed that using a standard reference velocity of 1.0 m/s to calculate the lead damper forces has only a very slight impact on results when compared to tailoring the reference velocity to the spectral velocity of the uncontrolled structure.

Hence, three main conclusions can be drawn:

1) Emerging semi-active 2-4 resetable devices combined with passive (HF2V in this case) offer the opportunity to significantly increase response reductions and reduce damage without increasing demand on the foundations – a unique outcome.
2) The spectral analysed show that this net-zero concept can be effective, and provide a direct pathway to performance-based design methods and guidelines.
3) The fact that net-zero base-shear was rarely achieved with realistic device sizes indicates opportunity for further improvement or optimisation of these systems and results

These conclusions and results remain to be confirmed on large or full-scale tests, although initial independent device experiments were successful and matched prior spectral analysis results.

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