CUSTOMISING SEMI-ACTIVE RESETABLE DEVICE BEHAVIOUR FOR ABATING SEISMIC STRUCTURAL RESPONSE

Geoffrey W. Rodgers[1], J. Geoffrey Chase[1], Kerry J. Mulligan[1], John B. Mander[2] and Rodney B. Elliott[1]

SUMMARY

Semi-active resetable actuators have been shown to be capable of significantly improving seismic structural response and customising structural hysteresis loops to reduce both displacement and base shear demands. Hence, device behaviour and dynamics can be tailored to the application. However, the maximum forces produced, in particular with air as the working fluid, can be a limiting factor to avoid extreme device sizes. This investigation incorporates an actively controlled (stored) high-pressure air source to enhance the capabilities of such resetable devices. The devices are designed using a validated non-linear model incorporating the dynamics and non-linearities of the working fluid, valves, sensor lags and computational limitations. Initial simulations show 100-600% increases in the peak device forces, with 100% obtained when the initial pressure is doubled. In addition, the high-pressure source allows greater manipulation of the device behaviour and response. This additional flexibility enables, for example, devices that are more resistant or resist differently in opposing directions. The impact of device enhancements over standard resetable devices is then demonstrated experimentally. This paper extends these novel resetable devices to create more flexible and actively controlled devices for semi-active structural control. Finally, a "net-zero base shear design" concept is presented, where the added damping reaction forces are exactly offset by structural response reductions to give large displacement reductions with no overall change to base shear forces – maximising control with no impact on the foundations.

INTRODUCTION

Background

Semi-active resetable devices have shown significant potential for reducing structural motion and corresponding damage during earthquake loading by combining the benefits of passive and active control systems [1-6]. Like passive devices, semi-active devices are purely dissipative and assimilating active device system control methods, semi-active devices are able to respond to structural non-linearity and changes over time.

Semi-active resetable devices are essentially springs where the unstressed length can be reset at any point in the input motion cycle. A piston displacement from the prior neutral or unstressed position results in the working fluid being compressed generating a resistive force. Resetable devices as originally proposed by Bobrow *et al*. [7] use a single valve to control the resetting to the initial pressure, as shown in Figure 1a. This method of integrated chamber design relies on pressure equalisation between the two device chambers.

Development of Large Scale Resetable Devices

A novel approached developed by the authors incorporates a valve on each chamber allowing the chamber pressures to be controlled individually, as shown in Figure 1b [8-10]. This separated or individual chamber approach removes the interdependency of the chamber pressures. Hence, a wide variety of control methods are possible, which result in system response configurations that can be optimised for each structural application. In addition, the segregated chamber devices and the sculpting ability is able to reduce the demand on the structural system by active manipulation of the device hysteretic response, thus further improving the structural response and structural control system benefits [9, 11].

The details of the basic control laws are presented in Figure 2. Given a sinusoidal response, a typical viscously damped, linear structure has the hysteresis loop definitions schematically shown in Figure 2a, where the linear force deflection response is added to the circular force-deflection response due to viscous damping to create the well-known overall hysteresis loop. Figure 2b shows the same behaviour for a simple resetable device where all stored energy is released at the peak of each sine-wave cycle and all other motion is resisted. This form is denoted a "1-4 device" as it provides damping in all four quadrants.

A stiff damper will 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 2d. In this case, the semi-active resetable damper force actually reduces the base-shear demand by providing damping forces only in quadrants 2 and 4; this is denoted a "2-4 device". Figure 2c shows a damper that resists motion only away from equilibrium, also increases base shear, and is denoted a "1-3 device". Detailed step-by-step description of the control laws is provided in the Appendix in Figures A-1 to A-3 for clarity.

[1] *Department of Mechanical Engineering, University of Canterbury, Christchurch*

[2] *Zachry Department of Civil Engineering, Texas A&M University, College Station, Texas*

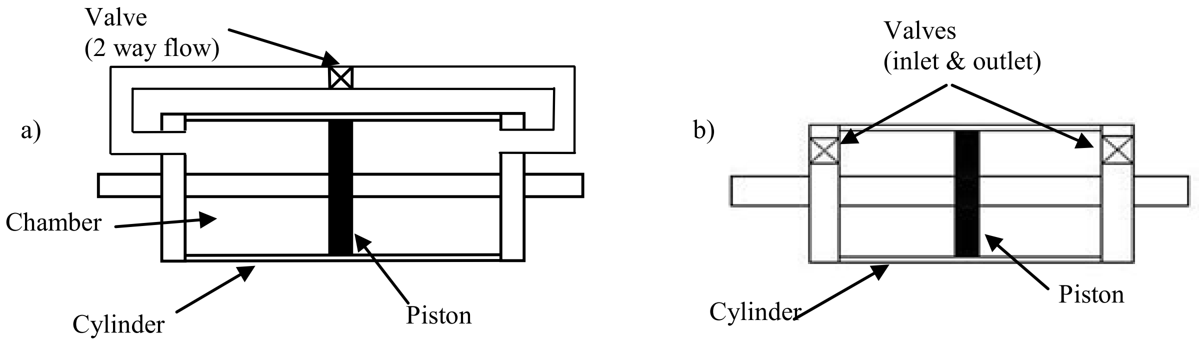

Figure 1. ***a) Original semi-active resetable device schematic as proposed by Jabbari and Bobrow [14]; b) Separated chamber design schematic with a valve controlling each chamber, thus removing interdependency of chamber.***

Development of semi-active resetable devices has shown the significant potential these simple and low cost devices have at dissipating structural energy and mitigating damage in a variety of structural applications [8, 12, 13]. However, the implementation of resetable devices in realistic structures is limited by relatively modest device forces compared to the device size or overall architectural footprint. Mulligan [9] proposes and discusses possible methods of mitigating these relatively low response force compared to the device size. These mitigating methods include combining resetable devices with other dissipating devices to create a system that dissipates a large amount of energy while having the benefits of a controlled device.

Another method is increasing the resetable device response force scale by increasing the device stiffness. This increase in stiffness is achieved by increasing the base or charging pressures. This paper introduces and discusses a method to increase the response forces and increase the feasibility of incorporating semi-active resetable devices into real structures.

The analysis of these pressure-charged devices resulted in some interesting and unusual hysteretic responses, not all of which immediately lend themselves to structural applications. However, the range of possible hysteretic responses for these pressure-charged devices illustrates the full potential capabilities of “hysteresis sculpting”. It should also raise the idea that a wide variety of responses are possible and thus encourage structural designers to extend their thoughts to what is desired, rather than what is possible and commonly accepted today.

METHODS

The hysteretic response of the resetable devices is non-linear, as shown in Figure 3. This non-linearity results in low response stiffness for relatively small piston displacement (low active chamber pressure) and high response stiffness for relatively large piston motion (high active chamber pressure). To achieve greater forces without changing the device dimensions it is proposed to shift the working range of the device into the higher stiffness region.

An increase in device stiffness may be achieved by increasing the base pressure in each chamber by pre-pressurising the active chamber using a high pressure air source. This high pressure source increases or steps up the base or initial active chamber pressure, moving the whole device response into a higher pressure zone. The result is thus a more rapid increase in stiffness for a given piston displacement. The pre-pressurising air source value becomes an additional variable in the device response with the potential to extend the hysteresis manipulation abilities.

The resetable device force response is dependent on the differential pressure between the two device chambers. Hence, the greater this differential pressure the greater the resisting force produced. The base pressure is the pressure in the active chamber before the air is pressurised due to a change in chamber volume caused by a piston displacement. Increasing the base pressure in the active chamber prior to any piston motion greatly increases the differential pressure between the chambers because the other chamber does not necessarily have the increase in base pressure. This differential increase shifts the entire hysteretic curve, as it is available through any subsequent piston motion.

The sculpting ability of the force-deformation behaviour [8-10] is also further enhanced with the addition of a high pressure air source. The active chamber can be either pre-pressurised or allowed to work from atmospheric pressure. This level of chamber control and management raises the possibility of the device having differential response depending on the type or direction of structural motion.

It is important to note that this ability to add a high pressure source and utilise it for differential response is only possible due to the independent chamber design developed by the authors [8, 9, 12]. Pre-pressurising the chambers with the standard connected chamber design [7, 14] would, by default, result in both the chambers being charged. Hence, the increase in differential pressure between the chambers supplied by the charging would be negated, as both chambers would be once again starting from the same base or initial pressure.

Device and Experimental Setup

A high pressure air source is easily incorporated into the device by the addition of an extra valve per chamber to separate the charging and venting of each chamber. The device thus has two valves per chamber or four valves per each device, as shown in Figure 4. The addition of an extra valve per chamber slightly increases the complexity of the device control. However this complexity is balanced by the potential benefits in increased response forces and manipulation ability over the hysteretic response.

For the purpose of the development and experimental testing of these high pressure devices the high pressure air is provided via a laboratory air supply through a pressure regulator. In situ devices would have a pressure vessel to provide the necessary air mass and pressure for an earthquake event. There are typically a small number of large ground motion peaks during each earthquake event therefore a relatively small vessel can contain sufficient air capacity for an individual event with the vessels typically requiring recharging following each event.

The four valve configuration allows significantly more complex valve control laws to be implemented than the two

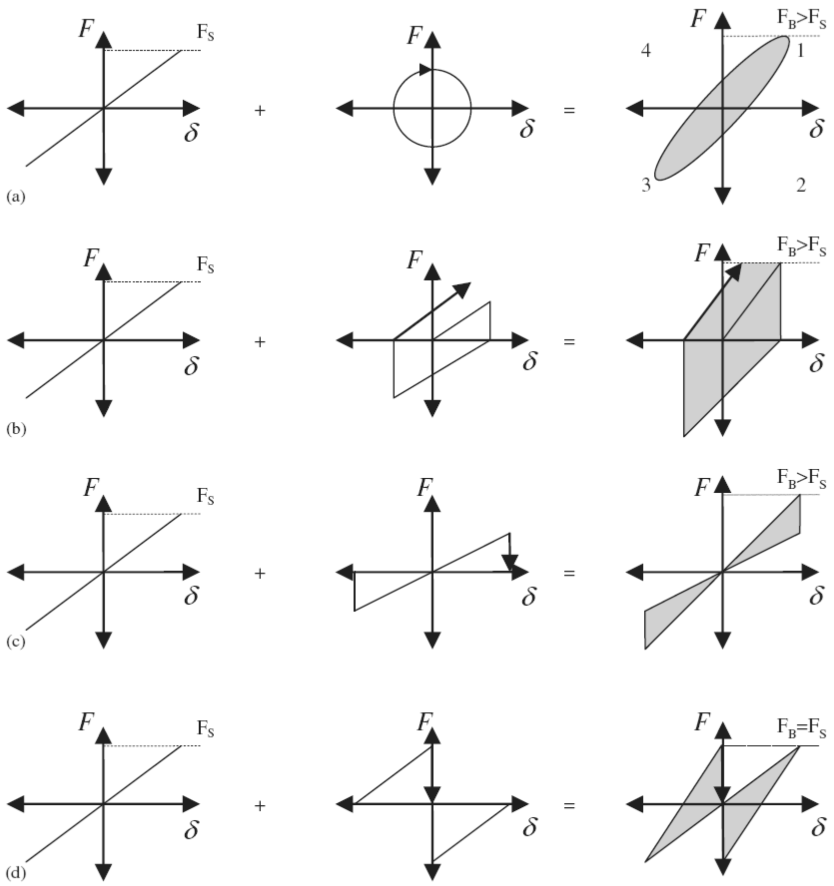

Figure 2. ***Schematic hysteresis for a) viscous damping; b) a 1-4 device; c) a 1-3 device; and d) a 2-4 device. Quadrants are labelled in the first panel, and F_B = total base shear, F_S = base shear for a linear, undamped structure. F_B > F_S indicates an increase due to the additional damping.***

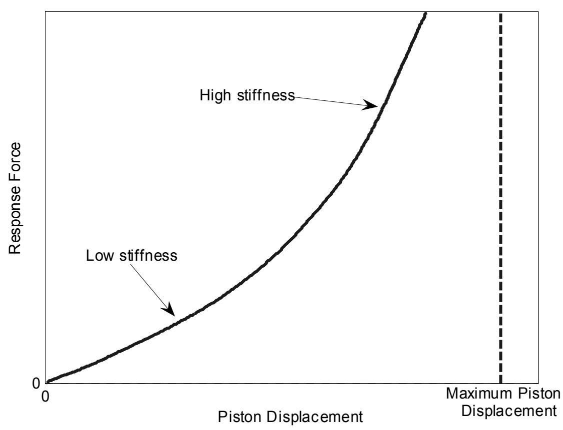

Figure 3. ***Force-displacement response of device showing low and high stiffness regions. The maximum piston displacement is indicated.***

valve device configuration. The 1-4, 1-3 and 2-4 control laws are all investigated with added pressure along with other more complex cases [8, 9]. The different control laws (1-4, 2-4, 1-3) reflect the different quadrants in which they provide dissipation in a force-displacement hysteresis loop. In particular, linear structures exist largely in quadrants 1 and 3, and thus any added dissipative forces there raise the total force on the foundations.

The specifics are detailed elsewhere in Chase *et al.* [8]. However, the main difference is that 1-4 control resists all motion, 1-3 control resists motion only when moving away from zero displacement, and 2-4 control resists motion only when moving towards zero displacement. As a result, 2-4 control can reduce both structural response, as well as base shear forces. Note that this behaviour of resisting only certain directions of motion is enabled only by the addition of independent valves in each chamber.

However, the complexity is increased by the relative timing between pre-pressurising the active chamber and the normal increase in pressure due to the active chamber volume decreasing with piston motion. Some configurations are obviously not beneficial such as having the inlet and outlet valve of a chamber open at the same time allowing the high pressure air to flow through the chamber. In addition, the level or amount of added pressure input becomes an added variable in determining and modelling the overall device response.

An increase in response or reaction force is produced by the resetable devices when the active chamber volume is reducing,

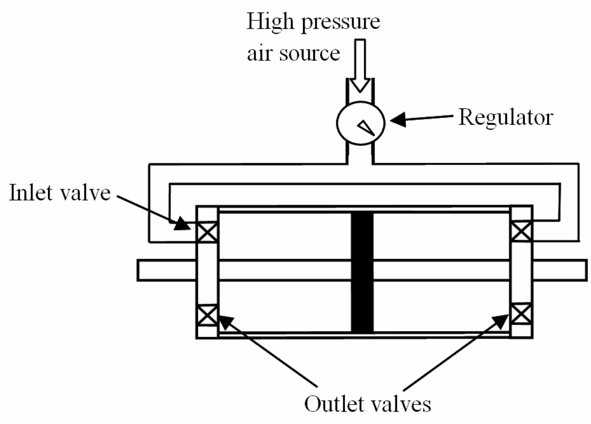

Figure 4. High pressure device schematic indicating inlet and outlet valves and high pressure air source.

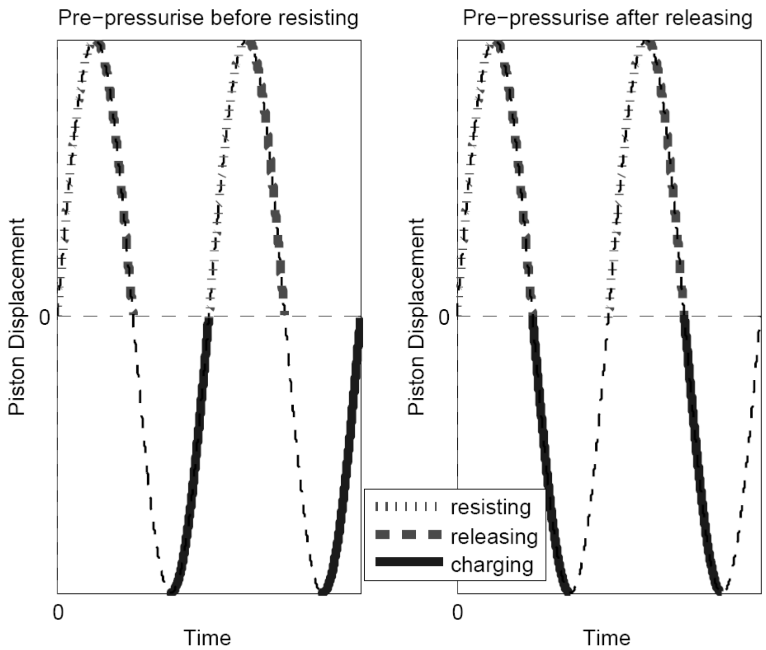

Figure 5. Configuration of charging the active chamber for pre-pressurising immediately prior to or following resisting motion.

compressing the air and increasing the pressure. A high pressure air source is an alternative means of increasing the active chamber pressure, referred to here as pre-pressurising. The time at which the active chamber is pre-pressurised within the piston motion cycle is an important consideration in achieving the desired device hysteretic response. The active chamber can be pre-pressurised immediately prior, immediately after or all the time the active chamber pressure is not increasing purely due to a reduction in volume.

Pre-pressurising the active chamber results in a relatively rapid or stepwise increase in the active chamber volume, which in turn results in a stepwise increase in the response force. The currently utilised valves are either open or closed and do not offer the option of controlling the orifice size, thus the pre-pressurising occurs rapidly. Further manipulation over the hysteretic behaviour is feasible given controllable air mass flow rate (orifice size) valves.

The relative timing of pre-pressurising and pressure releasing of each chamber affects the response. There are basically three configurations developed for pre-pressurising the active chamber:

1. Pre-pressurising on the quarter cycle directly prior to total pressure and energy release.
2. Pre-pressurise on the quarter cycle directly following total pressure and energy release.
3. Pre-pressurise on all quarters that are not pressure and energy releasing.

Figure 5 illustrates the relative timing of charging and releasing pressure from the active chamber based on the 1-3 control law. The plot on the left indicates the active chamber is pre-pressurised during the quarter cycle immediately prior to when the device is resisting piston motion. In contrast, the plot on the right indicates the active chamber is pre-pressurised immediately following pressure and energy release from the active chamber. The control used may fit into more than one of these options depending on the release configuration.

Pre-pressurising results in a rapid increase of the base pressure in the chamber, so it can be thought of as a stepwise change in the total force response. Therefore, option 1 results in a stepwise change in the force immediately following a reset. Options 2 and 3 result in a stepwise change in the force

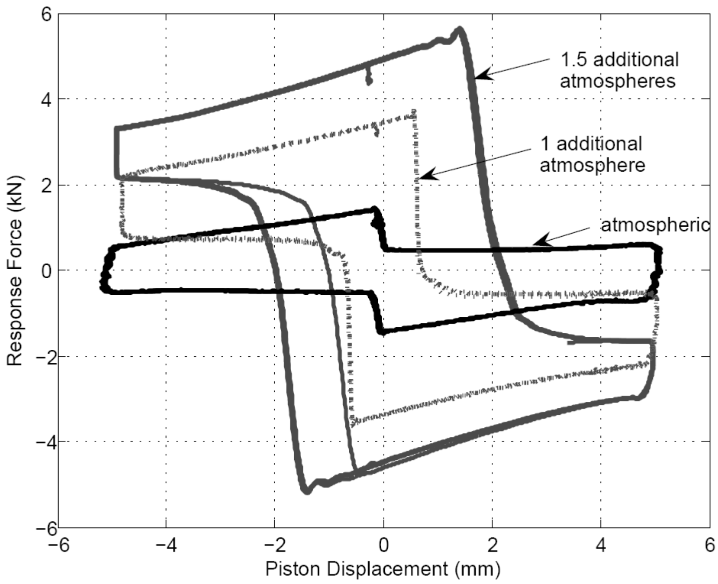

Figure 6. ***Comparison of devices working from atmospheric, 1.0 additional and 1.5 additional atmospheres of pressure. The response force more than doubles for each additional atmosphere of pre-pressurising the device. For this control law case, based on the 2-4 law resisting motions only toward equilibrium, pre-pressurising the cylinder elongates the force-displacement hysteretic response along the vertical, force axis.***

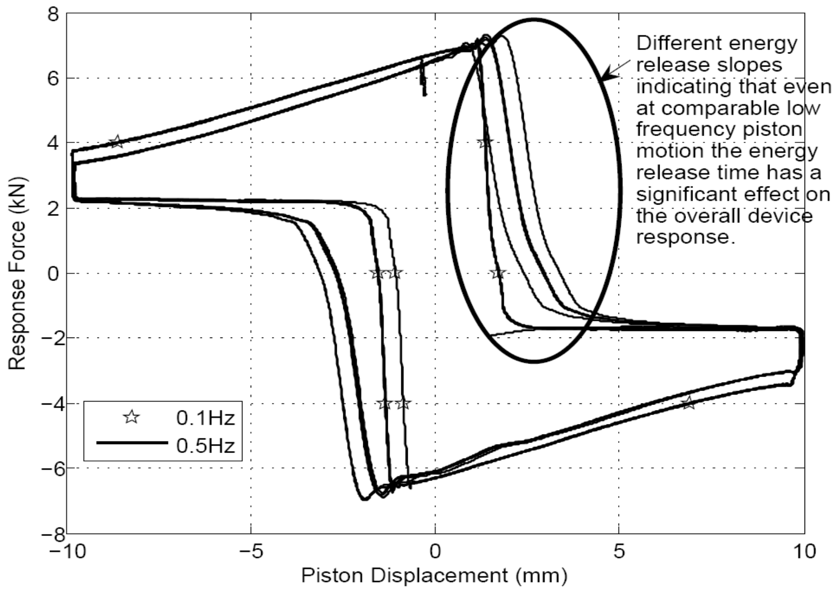

Figure 7. ***A large amount of air mass in the device leads to long energy release or reset times. The energy release time, indicated by a non-vertical line from peak force to the constant level, includes more of the overall motion with faster piston input motion, as illustrated here with piston motion of 0.1 and 0.5Hz.***

immediately prior to a reset. The distinguishing feature between options 2 and 3 is that option 3 continues to pre-pressurise the chamber for the whole cycle when the pressure is not being released. Thus, this option results in the device response being heavily dependent on the value of the pressure source rather than on the piston displacement.

The response of the high pressure devices are tested for a variety of input piston motions, valve control laws and additional pressure source values. The piston motion is sinusoidal with varying amplitude and frequency. The range of possible control laws with four valves per device is extensive. Most valve configurations utilised were pre-determined based on either systematic extensions from analysis of the two valve configuration or other desired outcomes. However, some of the valve configurations were impromptu, which resulted in some interesting and unusual device hysteresis loops. Some of the control laws utilised are direct extensions of the original and basic control laws [7, 9] utilised with the single valve per chamber devices working from atmospheric pressure. Other control laws were developed prior to testing, while others were improvised during testing based on the device response and desired outcomes.

The device is mounted and held in a dynamic test rig that provides the required commanded piston displacement [13]. Motion and force response are measured and returned to the data collection computer to complete a full feed-back loop. All input and response data is recorded for post experiment processing and analysis.

The comprehensive device model developed [9, 13] was augmented to incorporate the high pressure air source. This

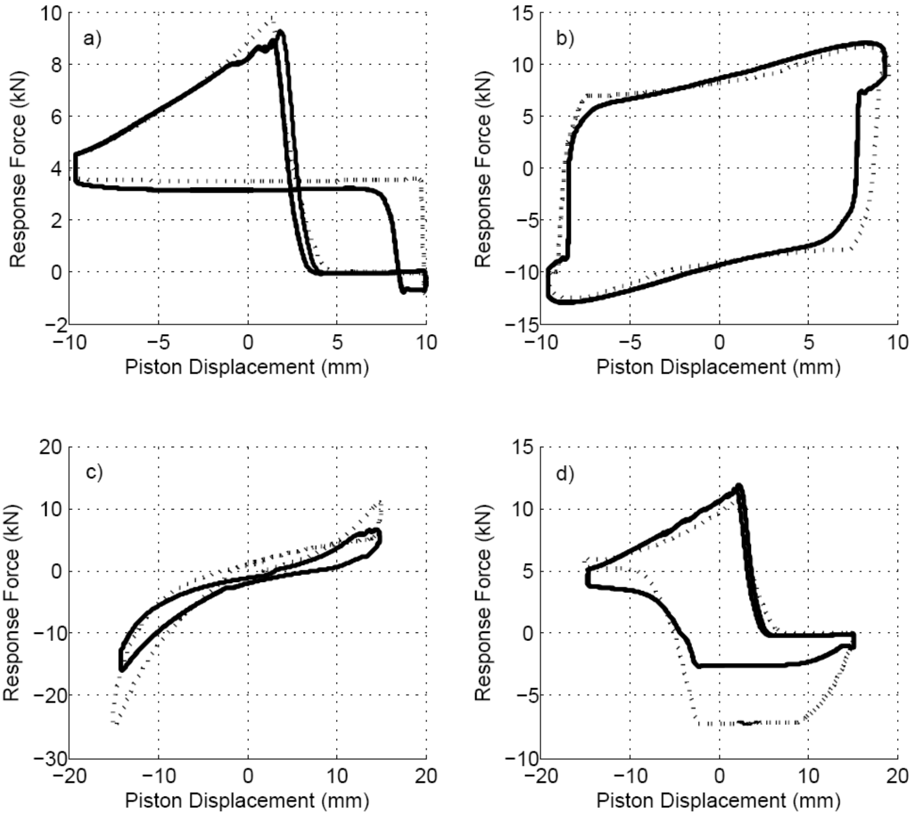

Figure 8. ***Device response to numerous control laws, some of which are one sided devices where one chamber is pre-pressurises while the other is held closed or works from atmospheric pressure. Experimental results are indicated with a solid line, while modelled results are shown with a dashed line.***

inclusive model increases the understanding of how the high pressure source alters the device behaviour. Specifically, this validated model allows rapid examination of changes to the hardware of the device, such as the valve orifice size and opening rates that are fundamental to the device behaviour. The validated model captures the dynamics of this device configuration in all but the most complex and convoluted cases.

RESULTS AND DISCUSSION

The addition of a high pressure air source increased the response force of the devices compared to response forces working from atmospheric pressure. In general, the addition of 1.0 atm (100 kPa) of pressure to the active chamber, more than doubles the maximum force produced by the device. Figure 6 shows a comparison of the device under 2-4 control working from atmospheric pressure and with an additional 1.0 and 1.5 atmospheres of pressure. The maximum force increases from approximately 1.5 kN for the atmospheric supply pressure case to 3.5 kN and 5.6 kN for the high pressure source cases. The additional pressure, in this case, elongates the force-displacement response along the vertical force axis, thus increasing the force provided in the 2nd and 4th quadrants. The response force in the 1st and 3rd quadrants does not change significantly.

The apparent delay between the piston passing the zero position or maximum displacement and when the force begins to increase or decrease is increased with the addition of the high pressure source [8, 9]. This delay is particularly pronounced for the 2-4 control law because when the valve is opened to release the air, the pressure in the active chamber is a balance between the increase in pressure from the chamber volume decreasing and a decrease in pressure due to a decrease in air mass inside the chamber. For the high pressure case, the time for the overall chamber pressure to begin to decrease is a significant and noticeable time period due to the relatively large amount of air mass that is required to be released before the pressure decrease from reducing air mass dominates the pressure balance. This time could be manipulated by using different sized or number of valves and once again illustrates the capacity to achieve the desired response from the devices.

In addition, increasing the initial or base pressure of the active chamber also results in significant energy release times, slowing device response and energy dissipation. Long release times result in non-vertical force responses on a force-displacement plot. More specifically, for large energy storage and release, a large air mass must escape during the device reset period. During this time the piston can move a significant distance, particularly for high frequency motion. Therefore, the energy release occurs while the piston is moving, resulting in a curved non-instantaneous force reduction. The device response for 0.1 Hz and 0.5 Hz inputs thus have significantly different energy release response indicating that the energy release time can be a significant portion of the overall cycle time, as illustrated in Figure 7.

A significant energy release time, along with the ability to control the rate, can be advantageous, as it allows further sculpting of the hysteretic behaviour of the device. This sculpting has the potential to produce more optimal device responses for different applications. More specifically, the energy release rate, and hence the slope of the hysteresis plot, can be controlled by the opening size or number of valves operated depending on the desired air flow rate out of the device. Thus, the flow rate can be manipulated during each release period to provide the desired resetting behaviour in terms of the hysteretic response required, as shown for semi-active base isolation in Chase *et al* [15]. In these experiments,

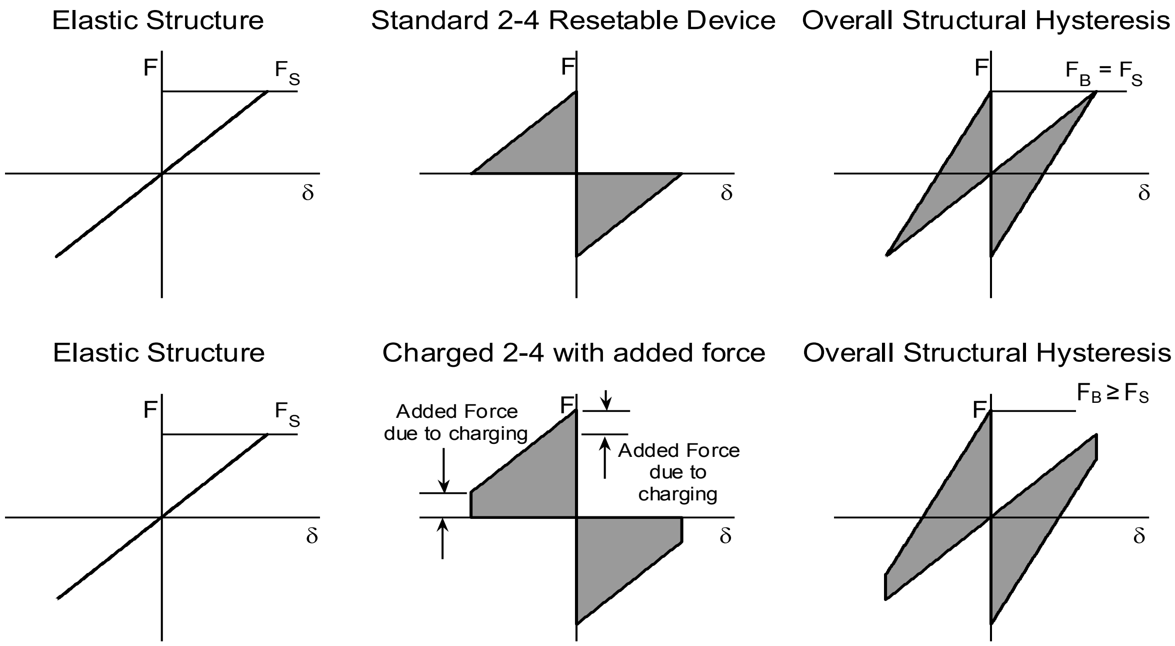

Figure 9. ***Schematic representation of resetable device contribution to overall structural hysteresis. F_B = total base shear, and F_S = base shear for a linear, undamped structure. Note that the addition of force from the charging of the device increases the overall base shear, whereas a standard 2-4 device does not.***

the outlet valves are fixed at the prototype design specification. However, larger valves would have decreased the release time, all else equal. These choices can be controlled via more complex valves or by designs including more valves.

Figure 8 shows the device response under different control laws along with the predicted response from the model developed. In all cases shown, the supply pressure is 2.0 atmospheres. The experimental results are shown with a solid line, while the modelled results are shown with a dashed line. Some of these shapes are achieved by only pre-pressurising one chamber of the device and letting the other work from atmosphere, while others are achieved by holding one chamber closed. Both of these cases make the device effectively a one-sided device, resulting in much higher response forces in one displacement direction that the other. Thus, unique differential behaviour from the device depending on displacement type or direction is possible.

Figure 8a is a one-sided 2-4 controlled device where the active chamber is pre-pressurised immediately following pressure release giving the square response in the 2nd quadrant. Figure 8b is the device using 1-4 control with the active chamber pre-pressurised immediately prior to resisting motion, thus enlarging the area enclosed compared to the conventional device response with 1-4 control. Figure 8c is also based on the 1-4 control law. However, the active chamber is pre-pressurised following pressure release. Finally, Figure 8d is another one sided device with the active chamber using the 2-4 control law. In this case, the active chamber is pre-pressurised immediately prior to resisting motion resulting in the 4th quadrant having a similar result to Figures 6 and 7.

When considering modifications to the resetable dampers it is important to consider the implications on the overall response of a structure fitted with this form of enhanced semi-active damping. Previous research [11] has shown that a resetable device with independent chamber control, such as that shown in Figure 1b, can provide displacement reductions without increasing base shear using the 2-4 control law. The hysteresis loops for a linear structure, 2-4 control law, and overall structural response are shown schematically in the top row of Figure 9. Note that the peak base shear is no larger than the peak structural force.

Interestingly, if the 2-4 control law is modified by the addition of charging of the device chambers, then the resistive force provided by the device will increase. This increase results in an overall increase in the base-shear force back towards its original (uncontrolled value). Thus, the peak base shear occurs at zero displacement, and can match, or exceed, the peak structural force, resulting in a net-zero (no change) or increase in base shear forces for a 2-4 device, as illustrated schematically in the bottom row of Figure 9.

Rodgers *et al* [11] also quantified the reductions in seismic response, and hence reduction in structural force that can be achieved by the addition of resetable dampers to a structure. By reducing the structural response, the total base shear will be reduced, but the addition of resetable damping also imparts damping forces into the foundation and increases the base shear. Overall, the change in base shear from the undamped structure will be a trade off between the response reductions achieved by adding the dampers, and the increase in base shear from the damper reaction forces. The standard 2-4 device does not have this trade off, as it does not increase base shear. As such, the overall structural impact of adding charging to the 2-4 device must be carefully considered.

Therefore, one intriguing outcome is to design a 2-4 device to achieve a "Net-zero base shear design". This approach would use previously defined base-shear reduction factors [11] to predict the reduction in structural response and base shear, and then size the damper forces and chamber charging as in Figure 9 appropriately to achieve a net-zero base shear (no increase, no reduction). This approach would thus result in no change to the overall base shear force, as the damper reaction forces would be offset by the response reductions, but would provide increased reductions in structural response.

In previous work [11], it was seen that although they reduced base shear, 2-4 devices were unable to provide the same reductions as the 1-4 control law. Conversely, 1-4 devices could significantly reduce structural response, but did so at the cost of increased base shear. The addition of charging to the 2-4 control law, and the use of “Net-zero base shear design” would provide the better attributes of both, with larger response reductions than the 2-4 device, without the increase in base shear seen with the 1-4 device.

CONCLUSIONS

Semi-active resetable devices have significant potential to reduce structural damage during seismic events. However, a limiting factor to full-scale implementation with devices using air as the working fluid is the relatively modest response forces in relation to the device size or overall architectural footprint. One method of increasing the response force with no increase in the device size is to charge the device from a high pressure air source.

Charging the active chamber of the device greatly increases the response force with at least a doubling of the response force for each additional atmosphere of base pressure. Charging the active chamber results in an approximate step increase in the response force therefore the timing of charging effects the device hysteresis response. Controlling the charging time thus results in increased manipulation control over the device response, further than that available and possible with the devices working from atmospheric pressure, which in themselves exhibit a large range of hysteretic behaviour not achievable with many other energy dissipation devices.

The analytical model developed shows good agreement with the experimentally observed results in all but some response in the most complex cases. This validated model assists in the understanding and design of resetable semi-active pneumatic devices. The device model is a useful tool and can be used to reduce the large or full-scale tests required and to ensure the experiments conducted are worthwhile.

Increasing the response force without increasing the overall device size or architectural footprint moves resetable devices further towards real, full-scale implementation in structural control methods and systems. Increasing the stiffness of the devices to achieve greater response forces was readily and easily achieved by slight device and control law modifications. The increased manipulation control over the force-displacement hysteretic behaviour achieved by selectively pre-pressurising the active chamber further widens the application scope of the resetable devices. In addition, this manipulation ability serves to demonstrate to structural engineers and designers the possibility available in structural control to aim for the best solution tailored for each structural application.

Finally, the concept of “Net-zero base shear design” is discussed in relation to the charged 2-4 control approach and has the potential to combine the better attributes of individual control laws, increasing response reductions without increasing base shear.

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APPENDIX – CONTROL LAW DEFINITIONS

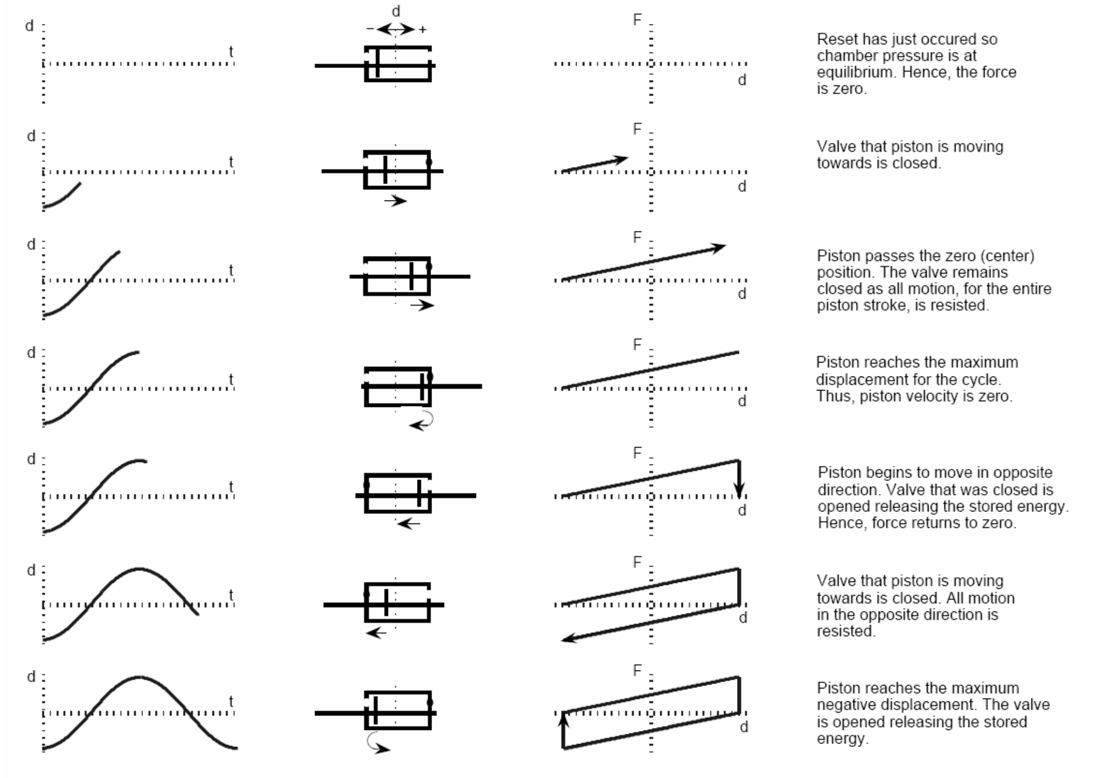

Figure A-1. ***Schematic showing one cycle of device under the 1-4 control law. The first column shows the piston displacement with respect to time. The second column shows a diagram ofthe device indicating the piston motion direction and the valve states. The third column shows the ideal force-displacement response.***

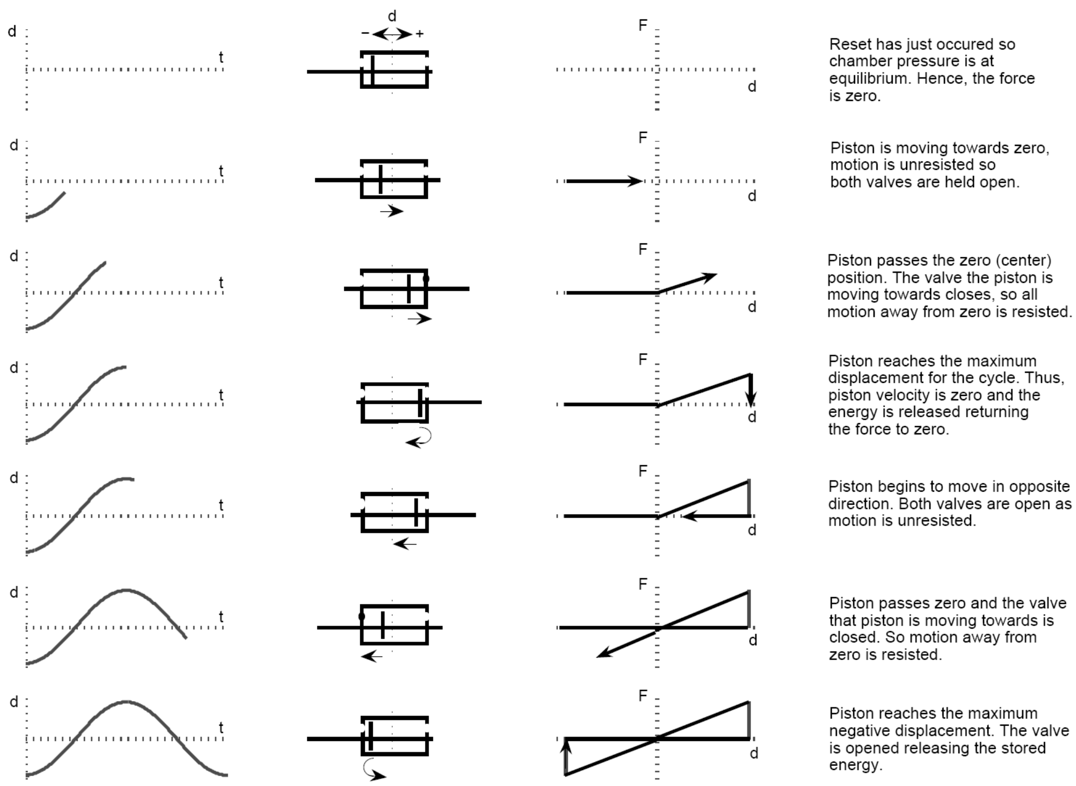

Figure A-2. ***Schematic showing one cycle of device under the 1-3 control law. The first column shows the piston displacement with respect to time. The second column shows a diagram of the device indicating the piston motion direction and the valve states. The third column shows the ideal force-displacement response.***

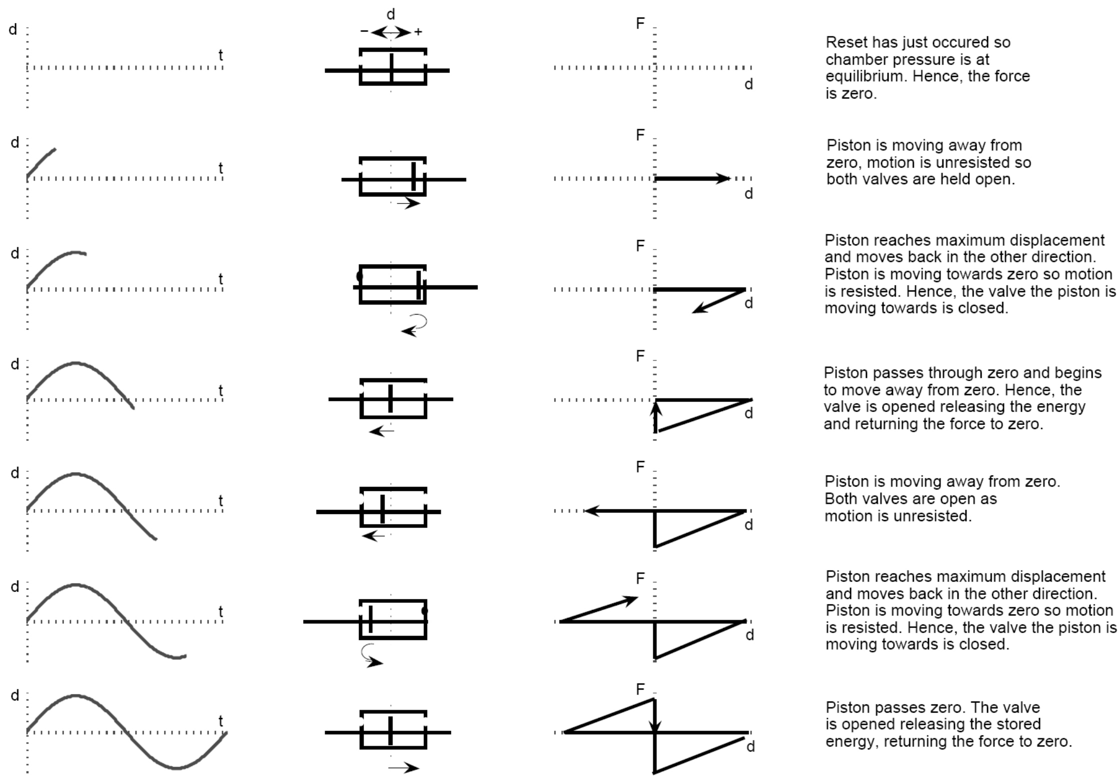

Figure A-3. ***Schematic showing one cycle of device under the 2-4 control law. The first column shows the piston displacement with respect to time. The second column shows a diagram of the device indicating the piston motion direction and the valve states. The third column shows the ideal force-displacement response.***

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