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Nonlinear design and sizing of semi-active resetable dampers for seismic performance

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ABSTRACT

Semi-active resetable devices can be used in a wide range of structures to reduce damage due to seismic loading. The specific benefits of these devices in reducing displacement, base shear, or both have been illustrated using linear and experimentally validated nonlinear device models, as well as in a range of large to full scale experiments. However, designing the specific device dimensions to obtain a specific device force-displacement capacity and response is difficult and no set design approach exists. More importantly, there is no design approach for specifying device dimensions to both meet a desired force-displacement capacity and linear or near linear device hysteresis loop shape.

In this research a design procedure is developed and presented by example that allows an device dimensions to be sized so that its response approximates the desired ideal linear responses and the desired force or stiffness (force-displacement) capacity. This method is validated by systematically by comparing device designs with equivalent ideal linear models to assess how well they meet design goals, using an experimentally validated nonlinear model. Methods are presented for the most common device control laws in terms of the basic device dimensions. Errors were generally less than 10%. The overall approach is seen to deliver the device dimensions for a highly linear device response that meets design specifications, and is the first generalised design approach presented for these semi-active resetable devices or any similar semi-active device.

1. Introduction

Semi-active control is emerging as an effective potential method of mitigating structural damage from large environmental loads, such as wind loading and seismic excitation [1–12]. It has two main benefits over active and passive solutions. First, a large power/energy supply is not required to obtain significant response reductions. Second, semi-active systems provide the broad range of control that tuned passive systems cannot [6,10], making them more robust and better able to respond to changes in structural behaviour due to nonlinearity, damage or degradation over time. Semi-active systems are also strictly dissipative and do not add energy to the structural system so that instability is not generated [8]. More specifically, semi-active systems in general utilize the building motion to generate resistive forces [2,6,10,13,14], and semi-active devices focus on managing these forces to dissipate energy in a controlled manner (e.g. [2,7,11]).

Semi-active devices with resettable hydraulic spring elements add a nonlinear stiffness to the structure without altering the damping [2,9,15]. Piston displacement stores energy by compressing a working fluid. Energy can then be released via actively controlled valves using different device-specific control laws, dissipating energy and reducing structural response.

In particular the independently controlled two chamber resetable device of Chase et al. [2] offers the unique opportunity to sculpt or re-shape the device and structural hysteresis loops to meet specific design needs. For example, given a sinusoidal input, a typical viscously damped, linear structure has the hysteresis loop definitions schematically shown in Fig. 1a, 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. Fig. 1b shows the same behaviour for a simple resettable device where all stored energy is released at the peak of each sine-wave cycle and all other motion is resisted, per the original device control approach [15]. This form is denoted a “1–4 device” as it provides damping in all four quadrants. A stiff damper will thus dissipate significant energy. However, the resulting base-shear force is increased. However, 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 Fig. 1d. In this case, the semi-active resettable damper force reduces base-shear demand by providing damping forces

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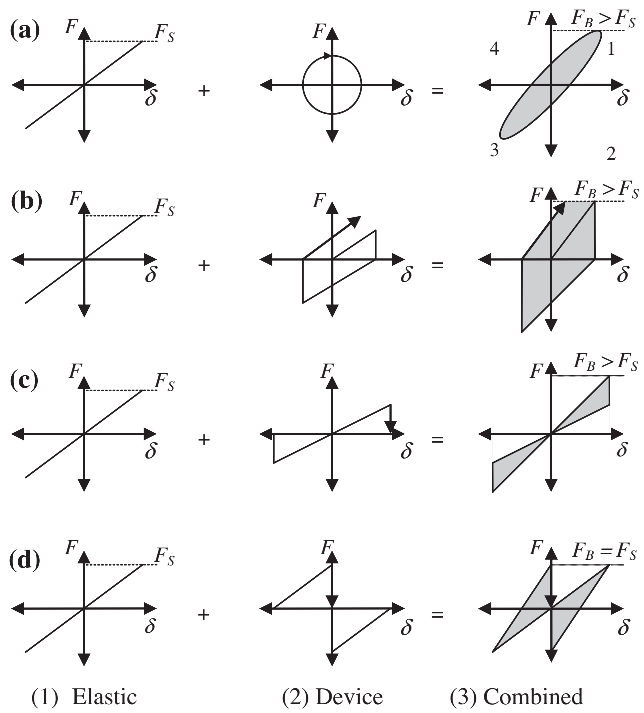

Fig. 1. Schematic hysteresis for (a) viscous damping, (b) a 1–4 device, (c) a 1–3 device, and (d) a 2–4 device. F_B = total base shear, F_S = base shear for a linear, elastic structure. $F_B > F_S$ indicates an increase due to the additional device.

only in quadrants 2 and 4 and is denoted a "2–4 device". Fig. 1c shows a damper that resists motion only away from equilibrium and increases base shear, a "1–3 device" with peak energy storage occurring at the peak displacement position. Note that the 1–3 and 2–4 control laws can only be implemented with independent valve control of each device chamber, as illustrated in Fig. 2 [2,16,17].

Although earthquake records are random signals and vary significantly from the harmonic response used to illustrate device types in Fig. 1, the control implementation does not change. The only feedback measurement required for implementation is displacement information across the device to determine position and velocity. This information defines the current quadrant of the displacement–velocity plot, and consequently the required valve position for a given semi-active control law.

Equations to model the ideal and nonlinear behaviour of these semi-active resettable devices have been developed by Mulligan et al. [17] and Rodgers et al. [4] and have been verified and validated using data from experimental prototypes and large scale experiments [16,17]. The resulting model includes the following dominant and fundamental nonlinear dynamics:

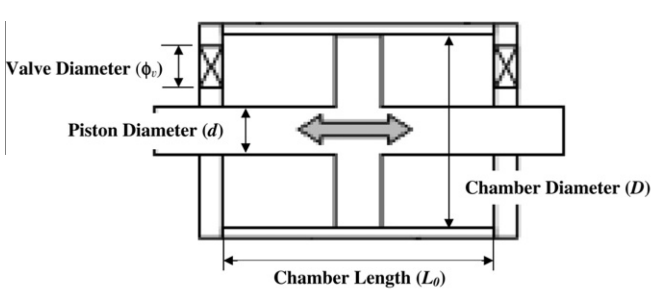

Fig. 2. View of a typical semi-active resettable device where each chamber is independently controllable by its own valve, contrary to initial designs [15] that coupled the chambers and controlled them both with 1 valve, limiting the potential device uses [2]. The device dimension parameters used, are also shown.

1. Ideal/Perfect gas law (or similar for other working fluid) for air behaviour in chamber.
2. Friction between moving parts.
3. Flow rates into and out of the device via the valves (including valve sizes).
4. Valve operation delay.

A main drawback of any semi-active device is the inherent nonlinearity observed in their dynamics (e.g. [2,6,7,9–11]). More specifically, in virtually all prior resetable device research, ideal, linear models of the device types, as shown schematically in Fig. 1, have been used to create various analyses, experiments, design spectra and guidelines (e.g. [1–5,15,18–21]). However, the linear and nonlinear behaviours can be very different, especially at the beginning and end of each stroke and depending on device control law [16,17]. For a given working fluid, the nonlinear behaviours are a function of specific device dimensions, whereas, ideal linear models need only to specify and effective (linear) device stiffness. In contrast, nonlinear, real devices have variable stiffness across a stroke [17]. Hence, there is a large gap between ideal devices and the analyses and guidelines that use them and actual device implementations.

This paper bridges that gap by relating specific device dimensions to device performance. Thus, for a given ideal, linear model stiffness a near equivalent nonlinear device may be specified with the desired stiffness and force capacity. To accomplish this task, the paper first presents the linear and nonlinear device models. Nonlinear dynamics are then related to device dimensions, and equivalences to ideal linear stiffness are developed. Case examples are presented to validate this overall development.

2. Device dynamics and modelling

2.1. Structure model

A simple structure can be modelled as a single degree of freedom mass with an internal viscous damping of 5%. This model is commonly used in spectral analyses and simplified analyses in design codes and standards [22]. Fig. 3 shows this model schematic with a semi-active resettable device. For spectral analysis, the natural period of the structure is changed from 0.1 s to 5.0 s by 0.1 s increments. The stiffness is 30,000 N/m, and the natural period is changed by modifying the structural mass.

2.2. Ideal linear device control and modelling

The linear model is basically a linear resettable spring. Simple and easily understood, the control rules can be easily computed for analysis in finite element or other simulation software. Importantly, the actual characteristics of real device models, such as specific dimensions, valve dynamics and working fluids, do not need to be considered. Hence, it makes the analysis to determine the desired device capacity straightforward. However, real device

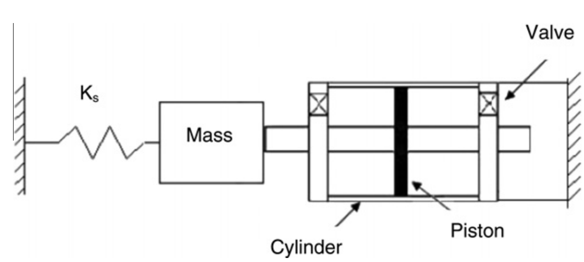

Fig. 3. Elastic Single Degree of Freedom (SDOF) system model with semi active resetable device.