Engineering Structures 167 (2018) 256–271

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Adaptive causal realization of rate-independent linear damping

Ashkan Keivan[a], Brian M. Phillips[a,*], Kohju Ikago[b]

[a] Department of Civil and Environmental Engineering, University of Maryland, College Park, United States
[b] International Research Institute of Disaster Science, Tohoku University, Sendai, Japan

ARTICLE INFO

Keywords:
Rate-independent linear damping
Adaptive control
Semi-active control
Real-time hybrid simulation
Base isolation
Inter-story isolation

ABSTRACT

This paper proposes an adaptive approach to achieve an accurate causal realization of rate-independent linear damping (RILD). RILD provides direct control over displacement, a benefit to low-frequency structures subjected to earthquake ground motion. The damping force generated by RILD is higher (lower) than that of linear viscous damping at lower (higher) frequencies, resulting in effective reduction of displacement and acceleration. The RILD force is proportional to displacement that is advanced in phase by $\pi/2$ radians, a noncausality that has limited its practical application. Adaptive controllers are proposed to approximate ideal (noncausal) RILD based on the dominant response frequency estimated in real-time and a filter-based causal model for RILD. By estimating the dominant response frequency, the displacement phase advance is more accurately applied.

The adaptive control approach is demonstrated through the real-time hybrid simulation (RTHS) of a 5-story base-isolated building and a 14-story inter-story isolated building. A magnetorheological (MR) damper is added to the isolation layer of each structure to provide supplemental control mimicking ideal RILD. The MR damper is experimentally represented while the remainder of the structure is numerically simulated in the RTHS loop. The desired damping force is tracked by the semi-active damper, which is naturally in phase with velocity and has a controllable magnitude. The results compare well to noncausal numerical simulations in both damping forces and structural responses. Results also show clear improved seismic performance of the adaptive algorithms as compared to non-adaptive causal approximations of RILD and passive-on and off damper controllers (i.e., nonlinear hysteretic damping).

1. Introduction

Base isolation is a widely used passive control method where flexible bearings are placed between the structure and foundation to shift the dominant natural frequency of the structure below the frequency content of the expected ground excitation [1,2]. Base isolation greatly reduces base shear, inter-story drifts, and story accelerations at the cost of increased base displacement [3–5]. The performance of base-isolated structures can be compromised by excessive base displacement, leading to damage of the isolators or moat wall impact. The 2011 Great East Japan earthquake produced large displacements in low-frequency structures previously thought to be safe [6,7]. Supplemental control (e.g., hysteretic or viscous dampers), can maintain the response reduction of base isolation while restricting base displacements to within an acceptable level [8–10]. These systems are referred to as hybrid isolation.

Traditional supplemental damping has some notable shortcomings when applied to protect low-frequency structures. Nonlinear hysteretic dampers such as steel yielding dampers work well for moderate displacements, however produce low equivalent damping ratios for small and large displacements as shown in Fig. 1b. Viscous dampers can be tuned to provide the desired energy dissipation for a target frequency range (Fig. 1a). However, viscous dampers will then provide inadequate damping at lower frequencies and excessive damping (and accelerations) at higher frequencies. A robust hybrid isolation solution must provide seismic protection under a wide range of response amplitudes and frequency content. [11,12]

Rate-independent linear damping (RILD) provides a damping force proportional to displacement (advanced in phase by $\pi/2$ radians), making it attractive to directly suppress displacement responses. Because it is also frequency independent, it is not sensitive to high frequency ground motion components which could amplify acceleration responses [13]. RILD is also known in the literature as linear hysteretic damping, complex-value stiffness, structural damping, and solid damping [14–16]. Crandall [17] first noted that ideal RILD is noncausal. Crandall [18] further investigated the performance of

Abbreviations: RILD, rate-independent linear damping; RTHS, real-time hybrid simulation; CFB, causal filter-based (model)

* Corresponding author at: 1173 Martin Hall; 4298 Campus Drive; College Park, MD 20742, USA.
E-mail address: bphilli@umd.edu (B.M. Phillips).

https://doi.org/10.1016/j.engstruct.2018.04.019
Received 28 July 2017; Received in revised form 6 March 2018; Accepted 6 April 2018

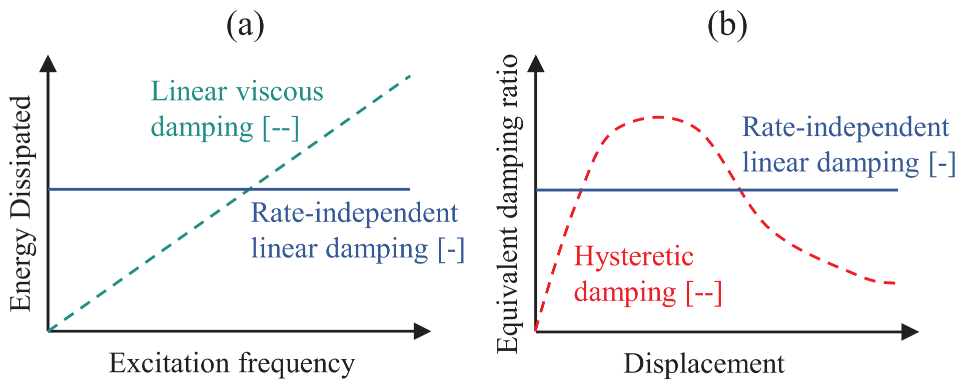

Fig. 1. Rate-independent linear damping versus other damping types.

damping devices using transfer functions in the frequency domain and impulse response functions in the time domain, concluding that a damper with frequency-independent energy dissipation violates causality requirements. Ideal RILD is proportional to displacement advanced in phase $\pi/2$ radians, a noncausality that has limited its practical application. As a result, a causal approximation is required to implement this type of damping in real structures.

The first successful causal RILD model was presented by Biot [19]. This visco-elastic model consists of a linear spring in parallel with an infinite number of Maxwell elements (spring-dashpot links). Makris [20] proposed a causal hysteretic element that generates frequency independent energy dissipation. In this approach, an adjustable term is added to ideal RILD to satisfy causality. The model was shown to be the limiting case of the linear visco-elastic model proposed by Biot [19]. Keivan et al. [21] proposed a causal filter-based (CFB) approach to approximate ideal RILD which is accurate at a prescribed frequency, set as the fundamental natural frequency of the structure. The CFB approach is well-suited as a basis for an adaptive algorithm whereby the filter frequency can be updated in real-time based on the actual structural responses.

In this paper, two adaptive controllers are proposed to approximate ideal RILD based on the dominant response frequency estimated in real-time and the CFB model. By estimating the response frequency, the displacement phase advance of $\pi/2$ radians is more accurately applied. The desired damping force is then tracked by a semi-active damper, which is naturally in phase with velocity and has a controllable magnitude.

The adaptive control approaches are demonstrated through the real-time hybrid simulation (RTHS) of a 5-story base-isolated building and a 14-story inter-story isolated building. A magnetorheological (MR) damper is added to the isolation layer of each structure to provide supplemental control mimicking ideal RILD. The MR damper is experimentally represented while the remainder of the structure is numerically simulated in the RTHS loop. The desired damping force is tracked by the MR damper. The results compare well to noncausal numerical simulations in both damping forces and structural responses. Results also show clear improved seismic performance of the adaptive algorithms as compared to non-adaptive causal approximations and passive-on and off damper controllers (i.e., nonlinear hysteretic damping).

2. Background

From Inaudi and Kelly [22], the true time domain and frequency domain representation of rate-independent linear damping are described in Eqs. (1) and (2), respectively.

$$f_d(t) = \eta k \hat{x}(t) \quad (1)$$

$$F_d(\omega) = \eta k i \,\mathrm{sign}(\omega) X(\omega) \quad (2)$$

where k is stiffness, η is the ratio between the loss and storage moduli for the RILD element, i is the imaginary unit, sign( ) is the signum function, and $\hat{x}(t)$ is Hilbert transform of $x(t)$. The Hilbert transform is given by:

$$\hat{x}(t) = \frac{1}{\pi} p.\,v. \int_{-\infty}^{\infty} \frac{x(t)}{t-\tau} d\tau \quad (3)$$

where *p.v.* denotes the Cauchy principal value. Eq. (1) provides insight into the behavior of RILD and its relationship with the Hilbert transform and Eq. (2) illustrates how RILD can be represented in frequency domain analyses.

Due to noncausality of ideal RILD, structures employing RILD require knowledge of the entire input time history [17]. For a general MDOF system, frequency domain analysis is the most straightforward method to solve a noncausal system [23]. In this study, all noncausal numerical simulations are performed in the frequency domain. These reference simulations will serve as a comparison for the causal RILD approximations evaluated through RTHS.

2.1. Comparison of damping types

Three supplemental damping types will be investigated herein, including viscous damping, Coulomb damping, and RILD. The damping models are shown below as applied to a second-order single degree-of-freedom (SDOF) system subject to ground acceleration:

$$m\ddot{x}(t) + f_d(t) + kx(t) = -m\ddot{x}_g(t) \quad (4)$$

where:

$$\text{Viscous: } f_d(t) = c\dot{x}(t) \quad (5.1)$$

$$\text{Coulomb: } f_d(t) = \mu N\, sign(\dot{x}) \quad (5.2)$$

$$\text{RILD: } f_d(t) = \eta k \hat{x}(t) \quad (5.3)$$

Viscous damping has been successfully employed in many civil engineering structures in the form of traditional oil dampers. The restoring forces generated by these dampers are nominally proportional to the velocity of the response, meaning that these dampers only indirectly control displacements. Viscous damping is effective in controlling displacement when the product of the maximum displacement response and the natural frequency of the structure (i.e., pseudo-velocity) match well with the actual maximum velocity response. When the actual maximum velocity exceeds the pseudo-velocity, viscous damping will produce excessive damping forces and subsequently high accelerations in the structure [13].

Coulomb damping is commonly used to represent sliding friction. As with viscous damping, the restoring force is in phase with velocity. In traditional Coulomb damping, the magnitude of the force is constant, equal to the product of the coefficient of friction μ and a constant contact normal force N. Due to a constant slip force, Coulomb damping