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A Novel Nonlinear Control System with Emphasis on Nonstructural Performance

Xin Xu

Graduate Student, Department of Civil, Structural & Environmental Engineering, University at Buffalo

Research Supervisor: Gary Dargush, Professor

Summary

Most control techniques in the structural engineering literature are aimed at improving performance of the primary structural part, but they may have limited or reverse effect on the nonstructural component during strong seismic events. In this paper, we emphasize the nonstructural performance using a cubic nonlinear active control system optimized in the frequency response functions of an SDOF nonlinear isolator. An eight-story base isolated benchmark building recently proposed by the ASCE community is studied as a demonstration. Both the structural and nonstructural performance indices are proposed in this research. We compare our cubic control effect with that of an LQG-based semiactive damping control system. It is shown from the simulation results that, in most design cases, the cubic control system has much better nonstructural performance while still maintaining good performance of the primary structural part. Further research of this cubic control system is also addressed.

Introduction

It is apparent, as demonstrated in the extensive literature on the subject, that the engineering profession has now recognized the importance of the seismic design of electrical and mechanical equipment, pipelines, parapets, elevators, tanks, and other nonstructural elements that are usually attached to the walls and floors of large multistory buildings, nuclear power plants, industrial facilities, and offshore platforms. More importantly, it also has been recognized that after the occurrence of a strong earthquake the survival of these so called secondary systems may be vital to provide emergency services, as it is the case for equipment in power stations, hospitals, or communication facilities. Up to now, the most accepted performance indices with respect to the nonstructural components attached to buildings are the peak and root-mean-square (RMS) absolute floor accelerations.

Base isolation, the most mature passive control technique, has been used widely to protect these critical facilities. But certain severe seismic events, such as some near fault earthquakes dominated by high frequency ground acceleration, will increase the isolation deformation, and also increase the superstructure absolute accelerations which are vital to the nonstructural seismic performance. Passive control devices, such as viscous dampers, may be used to augment damping (Soong and Dargush 1997) at the isolation level to reduce the isolation deformation, but heavy damping may increase superstructure accelerations and drifts (Gavin and Aldemir, 2001). Other optimal control systems, developed mainly in automatic control engineering, have been recently introduced to the structural engineering profession, such as the Linear Quadratic Gaussian (LQG), Clipped-optimal and Skyhook semiactive control using Magneto-Rheological (MR) fluid dampers. The control effects of a base-isolated benchmark building employing these very mature and practical active/semiactive control systems are studied and compared in a recent paper (Nagarajaiah and Narasimhan 2004). The results show that, while all of these control systems can suppress the structural vibration, none of them can significantly reduce the floor acceleration demands and some of them may even have a reverse effect on the nonstructural performance. It should be also noticed that, LQG is a linear, full-state feedback control law and the Clipped-optimal and Skyhook are just heuristic nonlinear output feedback.

In this paper, we emphasize the nonstructural performance using a novel and more rigorous nonlinear output feedback control system. In the next section, we will describe the Krylov-Boguliubov "averaging method" for obtaining analytical frequency response functions (FRFs) that approximate the periodic solution of second-order nonlinear differential equations containing cubic terms that we add in the controller intentionally. In nonlinear dynamics, this method has a wide range of applicability by enabling one to study the so-called "slowly varying" oscillation that is an extension to the linear oscillation theory commonly used by structural engineers today. The set of parameters where the single-degree-of-freedom (SDOF) oscillator behaves regularly are found, and the nonlinear oscillator is optimized for obtaining minimum relative deformation and absolute acceleration based on its FRFs. Thus we basically take a frequency domain approach to design the optimal nonlinear controller.

Furthermore, a base isolated building has some unique characteristics for which the SDOF nonlinear oscillation theory can apply. The natural vibration frequency of the "isolation mode" can be shown to be much lower than those of the "structural modes", thus the dynamics of the MDOF base-isolated building can be estimated by a simpler analysis treating the superstructure as rigid (Chopra, 1995). Although the demonstrated building is a 3D model, we can still approximately treat it as an SDOF oscillator in each X and Y direction when designing the controller. Simulation results of the realistic structure verify the proposed nonlinear control system.

Method of Control Systems Design

The frequency response functions of both the relative deformation and absolute acceleration normalized by the corresponding sinusoidal base excitation counterpart for an SDOF linear oscillator have been well established and are replotted as the thin curves in Fig. 1 below. It should be noticed that, while heavy linear damping can significantly reduce the dynamic response near its resonant frequency, it increases the absolute acceleration throughout the high frequency range of the input (normalized frequency w/w1>1.41). Thus, when a base isolated building that always has a low first natural frequency undergoes a strong ground motion containing high frequency contents (>1 Hz), it will provide poor acceleration performance if it is heavily damped. To overcome this dilemma, we introduce algebraic cubic damping and stiffness terms in the equation of motion and use the averaging method (Vidyasagar, 1993) to obtain the analytical FRFs as the dotted curves shown below. Distortion of the FRFs for nonlinear systems is well known. We optimize their shapes to obtain the minimum response and meanwhile obtain the optimal set of parameters, p and ksi3, that control the cubic stiffness and cubic damping terms, respectively.

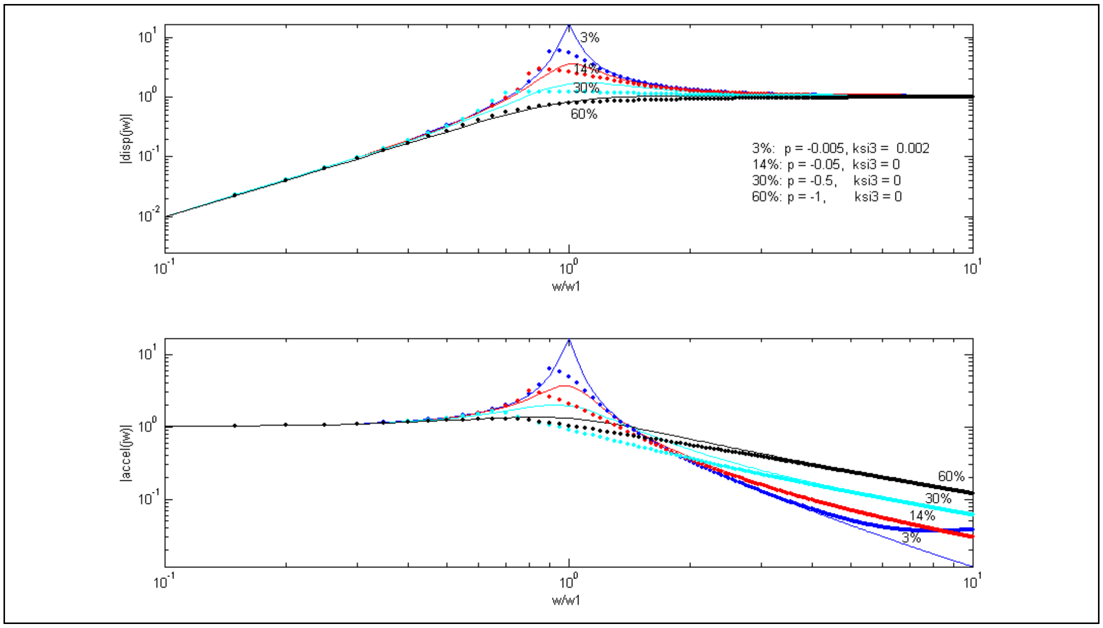

Figure 1. FRFs for linear and nonlinear oscillators with different linear damping ratio

These FRFs are all obtained to avoid the jump phenomenon when the FRFs become over-distorted and all of them are verified by the numerical integration in the time domain. It is clear from these FRFs that, the optimal control parameters are p= -0.5, ksi3=0 at this stage, corresponding to an intermediate damping ratio of 30% or so. This oscillator can attain the same steady state response near the resonant frequency as that of a heavy linear damping (60%) oscillator and also can keep the response in the high frequency range as small as that of a lightly damped oscillator. In addition, the distorted resonant frequency of this nonlinear oscillator shifts to 0.22 Hz without changing its linear stiffness and is farther away from the dominant frequency of most near fault earthquakes than the uncontrolled building (0.33 Hz). It should be emphasized that, in this paper the nonlinear controller is also Lyapunov stable by saturating the controls to keep the oscillator restoring force effective all the times. It should be further emphasized that all the nonlinear FRFs we obtained are dependent on the magnitude of the sinusoidal base excitation. Thus, when detailing the controller, we treat the whole input as a single sinusoidal excitation at its dominant frequency (1 Hz) so as to choose an appropriate input magnitude from the acceleration signals.

To compare our nonlinear control effect, the author also designed a set of semiactive viscous fluid dampers using the Hrovat algorithm (Hrovat et al., 1983) to trace the active LQG controller developed by Nagarajaiah et al. (Nagarajaiah and Narasimhan 2004b). The controller output voltage (0-10V) for each semiactive damper can be designed to be linearly dependent on the required damping coefficient between the upper and lower parameter bounds of the damper at each time instant to trace LQG. The simulation results show that our semiactive control system has almost the equivalent control performance as the active LQG control system. (Xu et al. 2004).

Benchmark Building Demonstration and Simulation Results

The configuration of the eight-story base isolated benchmark building is shown in Fig. 2.

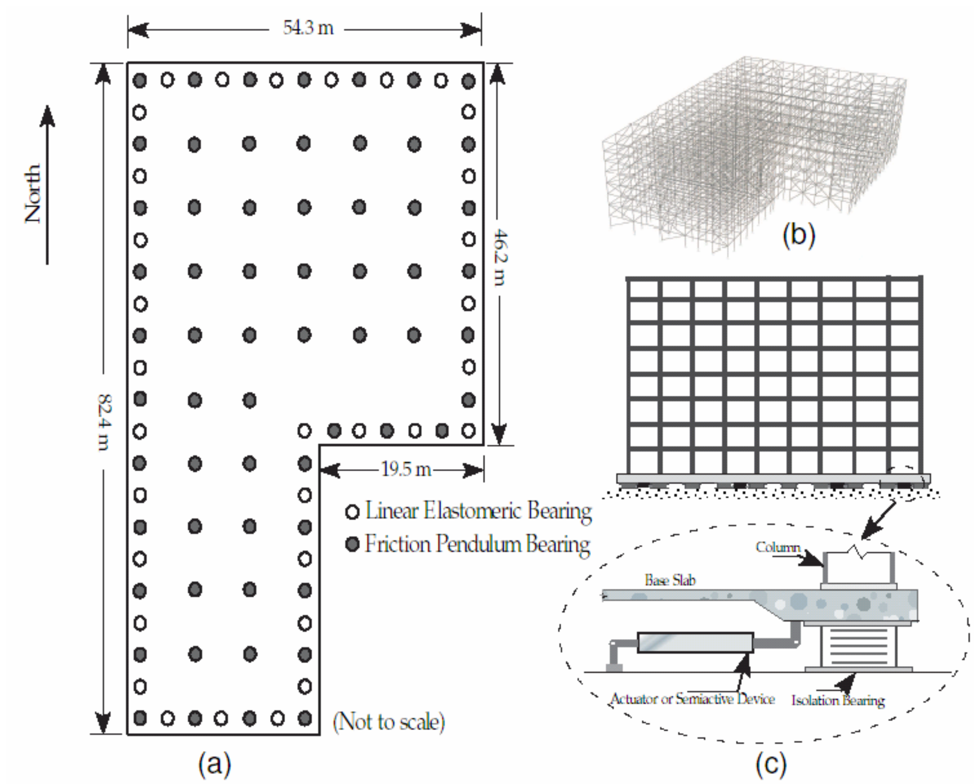

Figure 2. (a) Isolation Plan, (b) FEM Model of Superstructure, (c) Elevation View with Devices (adapted from Nagarajaiah and Narasimhan 2004)

There are seven bi-directional historical near fault earthquakes designated for this benchmark study. The results of the effectiveness for our nonlinear control (Nonlinear) and semiactive control (SAVD) systems are presented in Table 1. Time history response in the EW direction for the Newhall earthquake acting on the building is shown in Fig 3. The force-displacement loops for the two control systems are also shown in Fig 4.

Table 1. Results for Nonlinear Control and SAVFD Control Systems

	Case	J1	J2	J3	J4	J5	J6	J7	J8	J9
Newhall	**Nonlinear**	0.88	0.88	0.85	0.92	0.93	0.13	0.66	0.82	0.51
	SAVD	0.89	0.88	0.79	0.94	0.98	0.10	0.67	0.83	0.45
Sylmar	**Nonlinear**	0.77	0.80	0.81	0.84	0.88	0.12	0.65	0.71	0.50
	SAVD	0.89	0.91	0.89	0.94	0.95	0.10	0.70	0.82	0.47
ElCentro	**Nonlinear**	0.87	0.86	0.58	0.75	0.78	0.13	0.56	0.57	0.47
	SAVD	0.95	0.93	0.79	0.80	0.82	0.09	0.74	0.72	0.41
Rinaldi	**Nonlinear**	0.92	0.92	0.80	0.92	0.96	0.14	0.65	0.64	0.49
	SAVD	0.97	0.96	0.90	0.94	0.96	0.08	0.72	0.75	0.47
Kobe	**Nonlinear**	0.71	0.70	0.71	0.71	0.94	0.13	0.63	0.62	0.50
	SAVD	0.84	0.84	0.77	0.85	0.89	0.10	0.71	0.73	0.45
Jiji	**Nonlinear**	0.89	0.88	0.89	0.88	0.89	0.11	0.65	0.74	0.40
	SAVD	0.87	0.87	0.83	0.88	0.89	0.07	0.74	0.82	0.38
Erzinkan	**Nonlinear**	0.80	0.82	0.72	0.77	0.80	0.12	0.67	0.65	0.48
	SAVD	0.94	0.96	0.74	0.80	0.93	0.09	0.74	0.78	0.48

J1-J9 are nine performance indices defined for the benchmark problem and are briefly explained as follows. J1: Peak base shear (isolation-level) in the controlled structure normalized by the uncontrolled structure. J2: Peak structure shear (at first story level) in the controlled structure normalized by the uncontrolled structure. J3: Peak base displacement in the controlled structure normalized by the uncontrolled structure. J4: Peak inter-story drift in the controlled structure normalized by the uncontrolled structure. J5: Peak absolute floor acceleration in the controlled structure normalized by the uncontrolled structure. J6: Peak force generated by all control devices normalized by the peak base shear in the controlled structure. J7: RMS base displacement in the controlled structure normalized by the uncontrolled structure. J8: RMS absolute floor acceleration in the controlled structure normalized by the uncontrolled structure. J9: Total energy absorbed by all control devices normalized by energy input into the controlled structure.

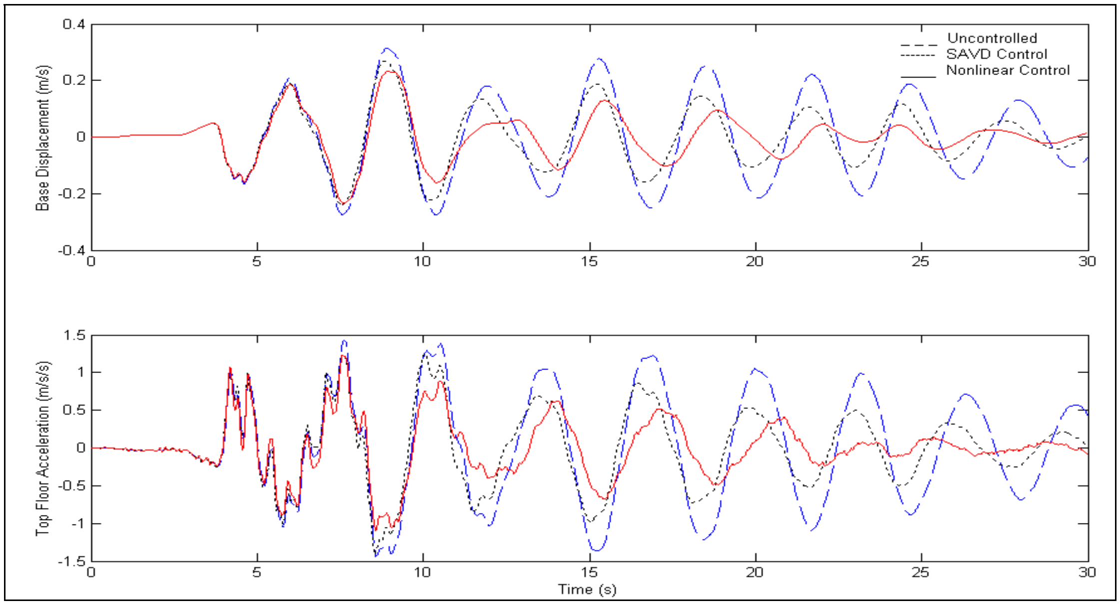

Figure 3. Time history responses of base displacement and top floor acceleration at the center of mass of the base and the top floor respectively in the EW direction for Newhall earthquake

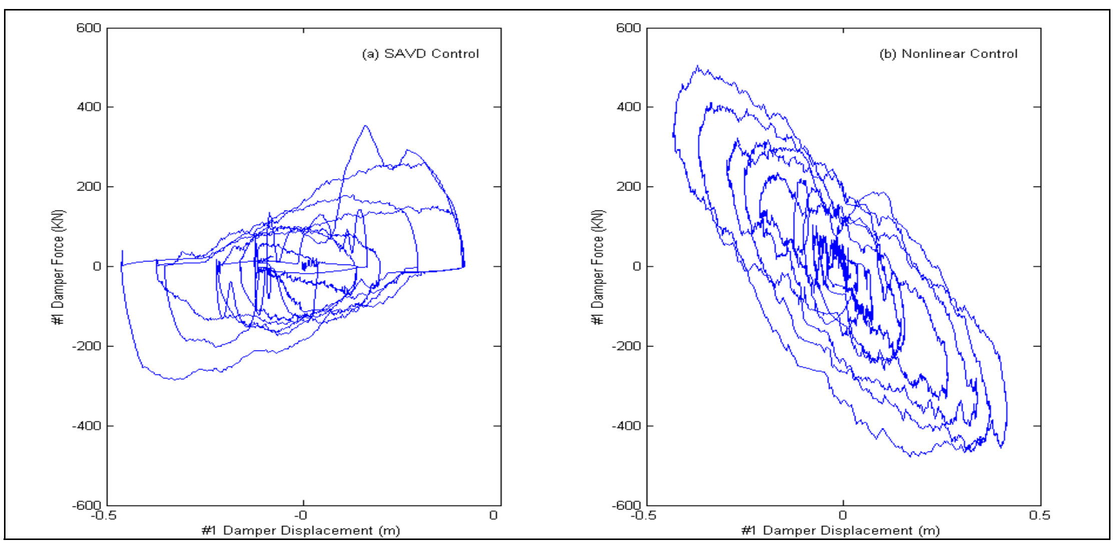

Figure 4. Force-Displacement Loops of #1 Control Device: (a) SAVD Control System, (b) Nonlinear Control System

Conclusions and Future Work

Our semiactive viscous damping control system shows that, the LQG control is mainly in the form of time varying damping force. Other control laws, such as Clipped-optimal and Skyhook, also provide time varying damping force. However, the nonlinear control system providing restoring forces has better performance of absolute floor acceleration, especially if the RMS evaluation criterion is considered, while still maintains good performance of isolation deformation. This result is in good agreement with the analytical nonlinear frequency response functions and therefore this control system is very suitable to protect nonstructural contents in a critical base isolated structure. Also, from the force-displacement loops, we can see that the SAVD system has almost I, III quadrant forces in the control device while the nonlinear control system has II, IV quadrant forces in the control device. Thus, this nonlinear control law cannot be traced well by the smart viscous fluid dampers. Finally, the optimization of the cubic control system containing other nonlinearities, such as the phase II base isolated benchmark building with friction pendulum bearings or lead rubber bearings, merits further study.

Acknowledgements

This research was primarily supported by the Earthquake Engineering Research Centers Program of the National Science Foundation, under award number EEC-9701471. This financial support is gratefully acknowledged.

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