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A NONLINEAR CONTROL STRATEGY FOR BUILDING STRUCTURES

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ABSTRACT

A nonlinear control strategy which can be readily implemented in a semi-active fashion has been developed. This control scheme fully utilizes the energy-dissipation capabilities of the control devices and does not require any sensors. The scheme is always stable and robust and does not have the time-delay problem. For implementation, a screw-jack-type semi-active actuator, which does not require any power to operate, has been developed. The actuator is installed in a bracing mechanism which minimizes the force demand on the actuator. It is shown that the performance of the nonlinear control strategy is superior to that of the linear optimal feedback control law when full bracing control is used.

KEYWORDS

Active control; building vibrations; earthquake response; nonlinear control; semi-active device; screw jack.

INTRODUCTION

The use of active control to mitigate building vibrations has gained much attention in the field of earthquake engineering in recent years. Its main advantage is that active devices are often structurally less invasive than passive devices (Soong, 1987). For example, a single active device, such as an active mass damper, can be designed to influence a number of vibration modes. Hence, active control is most suited for tall and slender structures, where the response can be influenced by a number of natural modes. Active control systems have been implemented in a number of buildings in Japan (Kobori et al., 1991; Soong and Reinhorn, 1993). However, all these systems were designed only for wind and moderate earthquake forces. The use of active control to counteract large earthquake forces has always been controversial for a number of reasons. Large control forces are not only difficult to realize, they could also be as detrimental as earthquake forces if the control system happened to malfunction.

In any respect, linear control laws may not utilize the energy-dissipation capability of a control device in a most effective manner. For example, with a constant velocity-feedback gain, the dissipative force vanishes at the same rate as the velocity. If one designs a control system for a severe but rare seismic event, large control forces may only be occasionally activated during a moderate earthquake, while most of the time, the control forces developed will fall far below the full capacities of the devices. Hence, this may not be a most efficient control strategy for wind and small earthquake forces. On the other hand, if a control system is designed for a moderate excitation force, the forces developed in the control devices will soon reach a saturation state when an exceptionally strong excitation is encountered, and, thereby, the performance of the system may deteriorate, as the stability of a linear control law is generally not guaranteed under force saturation.

A nonlinear control strategy that can be implemented with a semi-active concept is presented in this paper to eradicate the aforementioned drawbacks of linear active control schemes.

NONLINEAR CONTROL LAW

It is desirable to have a control system that is designed for the worst anticipated event and is yet able to mobilize its full capacity under small and moderate excitations that may occur frequently during the lifetime of the structure. To this end, the following nonlinear control law is proposed.

$$u_i = \begin{cases} F_{vi}(\dot{y}_i - \dot{y}_{i-1}) & \text{if} \quad |u_i| < u_s \\ u_s \operatorname{sign}(u_i) & \text{if} \quad |u_i| \geq u_s \end{cases} \tag{1}$$

in which $\dot{y}_i$ is the velocity at story i, u_i is the interstory control force, F_{vi} is the velocity-feedback gain for the control device, and u_s is the force limit at which saturation occurs. To achieve the above-mentioned control objective, the control gain, F_{vi}, has to be large enough to mobilize the maximum control force at low excitation levels, and the saturation point, u_s, has to be selected in accordance with the amount of response reduction that needs to be achieved under the worst anticipated event as well as with the mechanical constraint of the device. The force saturation can also be considered as a safety fuse that prevents the transmission of large control forces to other members of the structure.

The above nonlinear control scheme has a number of desirable features. Since the saturation limit is part of the design consideration rather than a mere mechanical constraint, the performance of such a system is, thus, more predictable than that resulting from a linear control theory. Since the nonlinear control law is based on local velocity feedback, it is always stable and robust, which has been proven mathematically. One major advantage of the nonlinear control strategy is that it can be implemented with semi-active devices. As will be described in a later section, a semi-active actuator which does not require any power consumption has been developed and successfully tested for this control strategy. Since each device can be controlled in a decentralized manner, the problem of time delay is minimized. It must be pointed out that a constrained optimal control scheme has been studied by Indrawan and Higashihara (1993) to achieve the same design objective delineated here. However, that scheme cannot be easily applied to multiple-degree-of-freedom structures and it requires the knowledge of the excitation time history *a prior*. The nonlinear control law presented here is similar in certain respects to a bang-bang control. Nevertheless, its main distinction from a bang-bang control is that the control force developed in this scheme varies continuously.

COMPARISON OF LINEAR AND NONLINEAR CONTROL LAWS

For building applications, a most effective control law is considered as one which can limit the story drift to a target level with a minimum amount of control effort. Hence, to evaluate the effectiveness of different control laws, two dimensionless indices, which reflect the above performance measures, are introduced. They are the drift reduction factor (DRF) and the normalized control force (NCF) defined as follows.

$$DRF = \frac{\Delta^u{}_{\max} - \Delta^c{}_{\max}}{\Delta^u{}_{\max}} \tag{2}$$

$$NCF = \frac{u_{\max}}{\langle 1 \rangle \mathbf{M} \{1\} \ddot{x}_{0,\max}} \tag{3}$$

in which $\Delta^u_{\max}$ and $\Delta^c_{\max}$ are the absolute maxima of story drifts that occur in the uncontrolled and controlled structures, respectively, $u_{\max}$ is the absolute maximum of the control forces developed, $\ddot{x}_{0,\max}$ is the horizontal peak ground acceleration, $\{1\}$ is a vector of unity, and $\langle 1 \rangle$ is a unit row vector. With linear control laws, the normalization introduced in Eq. 3 eliminates the influence of the level of ground motion and of the mass of the structure on the control effort required, and, thereby, allows an objective comparison of the efficiencies of various control strategies. Even though power requirement is an important consideration in active control, it is not an issue for passive and semi-active control devices. Therefore, it will not be considered here.

The efficiency of the nonlinear control law is compared to those of linear optimal control schemes with a single-degree-of-freedom structure. The structure has a mass of 2.95 kN sec^2/m and a stiffness of 1.96x10^3 kN/m. Damping is assumed equal to 2.26% of the critical. To implement the nonlinear control law in an effective manner, a high velocity-feedback gain, F_{vi}, of 5.3x10^3 kN-sec/m is chosen. This is to maximize the energy dissipation by ensuring that the control force will readily approach the saturation state for the range of saturation limits considered here. By fixing the velocity-feedback gain and gradually raising the force saturation point, u_s, both the *DRF* and *NCF* will increase. This results in an efficiency curve for the nonlinear control scheme. It should be noted that in the case of the nonlinear control, the efficiency curve depends on the velocity gain as well. Nevertheless, if the velocity gain is high enough, as it is in this case, the efficiency curve will eventually approach an upper bound and become insensitive to the velocity gain. This control scheme is compared to the classical optimal feedback and feedforward-feedback controls in Figs. 1 and 2. It can be observed that the nonlinear control law is superior to the linear feedback control law for the El Centro and Sylmar records, especially, when the allowable *NCF* is low. Evidently, the classical optimal feedforward-feedback control, which requires the knowledge of the excitation time history *a priori*, always appears to be the most effective scheme when compared to the other two. However, as shown in the figures, the performance of the nonlinear control scheme approaches that of the feedforward-feedback control.

CONTROL MECHANISMS

Semi-Active Actuator Design

A semi-active actuator has been developed for implementation with the aforementioned nonlinear control strategy. The semi-active actuator consists of a conventional DC motor connected to a "resistive load variable circuit" for variable damping. The principle of operation can best be seen in the cross-sectional view of Fig. 3. The device has a resistive load controlled screw-jack strut. Within the cylinder are a ball screw and nut that serve to convert the linear motion into rotational motion of the ball screw and motor.

When an external loading is applied to the actuator, the loading will rotate the ball screw and turn the motor; thus, it will result in extension or retraction of the actuator. During its extension or retraction, the actuator provides the resistance of an electromagnetic damping force. In this process, the viscous-like damping is caused by the motor shunted to a resistive circuit. The resisting force of the actuator is a function of the external resistance. During the actuator operation of extension and retraction, different damping can be created by changing the electrical resistance. This operation is basically an uncomplicated passive energy absorption. More advanced active operations of the actuator can be implemented to meet specific requirements. A semi-active operation to limit and preserve the actuator load to a magnitude lower than the prescribed load level can be achieved by limiting the current generated by the motor through a circuit. Thus, the actuator has features to operate passively, semi-actively, or actively as needed.

The circuit being considered limits the current to preset levels to avoid excessive loading during the actuator operation. The circuit is connected to the motor armature lines, and it is activated to clip off the excessive current near to a constant, resulting in a constant load during operation. For a current value generated by the motor which is lower than the prescribed current, the current response would be proportional to the motor

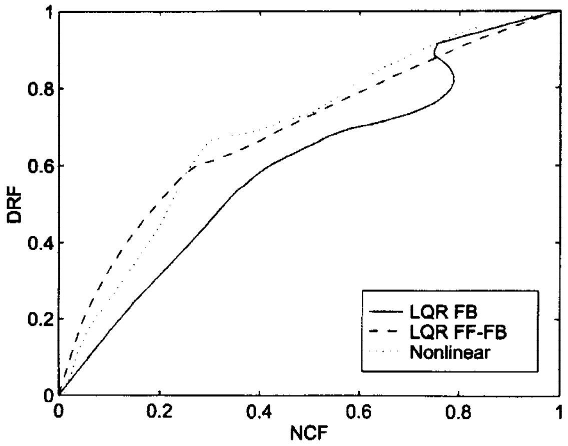


Fig. 1. Comparison of linear and nonlinear control schemes (1940 El Centro)

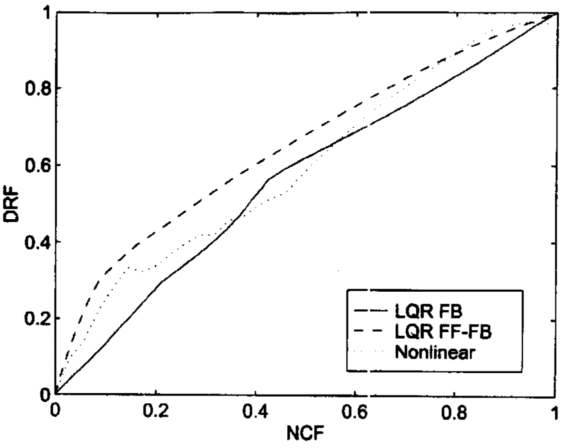


Fig. 2. Comparison of linear and nonlinear control schemes (Sylmar, 1994 Northridge)

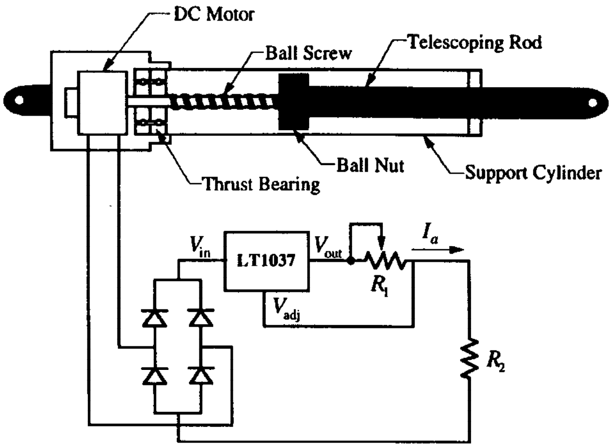


Fig. 3 Semi-active damper

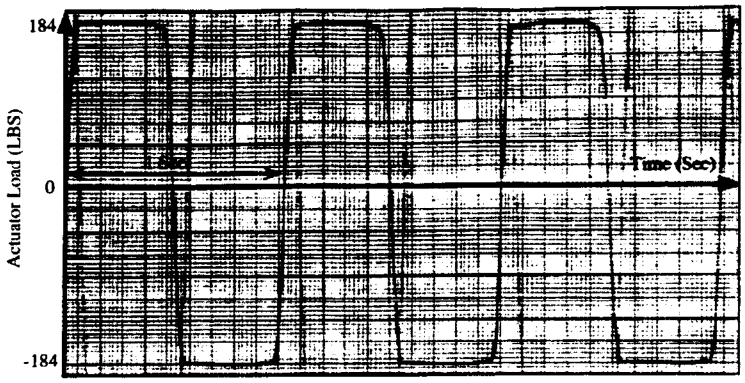


Fig. 4 Response of semi-active damper under sinusoidal displacement

speed. A proposed circuit is shown in Fig. 3. In this circuit design, a 3-terminal adjustable positive regulator is used as a current limiter. The regulator (LT1037) which is commercially available is used for its high current rating (10 Amps). The regulator adjusts its output voltage to maintain a constant 1.25 Volt from the output to the adjustment terminal. A variable resistor R_1 is used to adjust the current limit. The load resistor R_2 provides additional heat dissipation capabilities. Both the regulator and load resistor are operated with a proper heat sink. The time history of the damping force generated by such an actuator under a prescribed sinusoidal motion is shown in Fig. 4.

Bracing System

Since large damping coefficients are required in the proposed control strategy and also large damping forces are needed for structures subjected to strong earthquakes, the bracing system shown in Fig. 5 is proposed here. This design is an attractive approach for a number of reasons (Kang et al., 1994; Kang, 1994). The primary reason for this actuator placement is that the actuators are not in the direct load path and accordingly the required operational loads in the actuators are substantially reduced. This system consists of four rigid struts of equal length pinned together and symmetrically placed with an initial geometric offset, δ_o. The mechanism amplifies the structural damping force as well as the equivalent damping coefficient provided by the actuator. The resulting amplification at the structural level depends on the geometry of the bracing mechanism as shown in Fig. 6. The amplification of the damping coefficient provided by an actuator is shown in Fig. 7 for various geometric ratios. It can be seen that for most applications, it is in the range of 10 to 40 times.

CASE STUDY WITH A TEN-STORY BUILDING

To examine the practicality of the aforementioned control laws, a ten-story moment-resisting steel frame designed by Anderson and Naeim (1984) is selected for case study. The design of the frame and its dynamic properties are shown in Fig. 8. The mass at each floor is 98 kN-sec^2/m (0.5590 kip-sec^2/in), with the roof mass being 81.6 kN-sec^2/m (0.4658 kip-sec^2/in). Rayleigh damping is used, with the damping ratios for the first two modes set to 5%, as shown in Fig. 8. This damping could be slightly higher than what is normally encountered in buildings. Nevertheless, a higher damping is expected to result in a more conservative assessment of a control system, whose efficiency is usually reduced by the inherent damping of a structure.

The efficiency of the nonlinear control law in the ten-story frame is examined with a semi-active control device installed in the diagonal brace of every story. A velocity gain of 149 kN-sec/mm (850 kip-sec/in) is selected for each device. This large control gain is intended to exploit the full capacity of the control devices over a range of the *NCF* chosen. A *DRF*-vs.-*NCF* curve is generated by increasing the force saturation limit. The result obtained with the El Centro record is shown in Fig. 9 and is compared to the performance of linear optimal control laws. It can be seen that the feedforward-feedback control is better than the other two. However, the performance of the nonlinear control law is superior to that of the linear feedback control and is close to that of the feedforward-feedback control as long as the *NCF* is around 0.2 or below. The nonlinear control and linear feedback control have almost the same performance when the *NCF* exceeds 0.4. It is interesting to note that the linear feedback control with a large control gain (which is comparable to that of the nonlinear control) and force saturation has the same performance as that of the nonlinear control when the NCF is below 0.1; nevertheless, the performance of the linear feedback control with force saturation deteriorates substantially when the NCF goes beyond 0.2. This could be related to the stability of the linear control scheme, which is not guaranteed when saturation occurs.

CONCLUSIONS

The nonlinear control law introduced here is simple to implement and robust. In the examples shown, it has a performance at least equivalent to, if not better than, the linear optimal feedback control law, while the

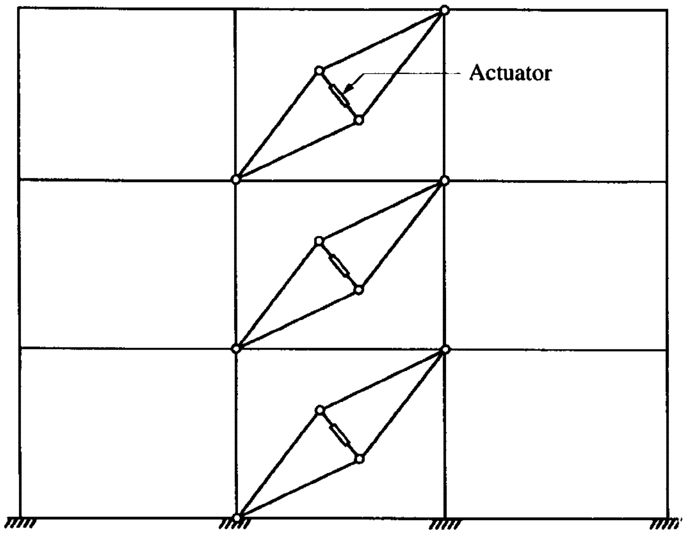
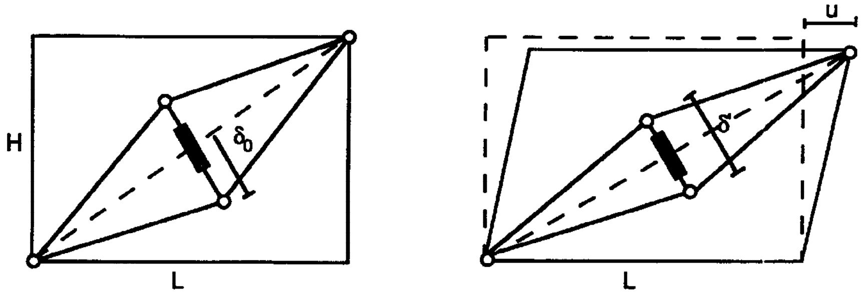


Fig. 5 Semi-active bracing system



$$\alpha = \frac{L}{H};\ \beta = \frac{\delta_0}{H};\ \mu = \frac{u}{H}$$

$$\text{Damping Amplification}: \frac{C_u}{C_\delta} = \left[\frac{\alpha}{\sqrt{4\beta^2 - 2\alpha\mu}}\right]^2$$

Fig. 6 Damping amplification mechanism

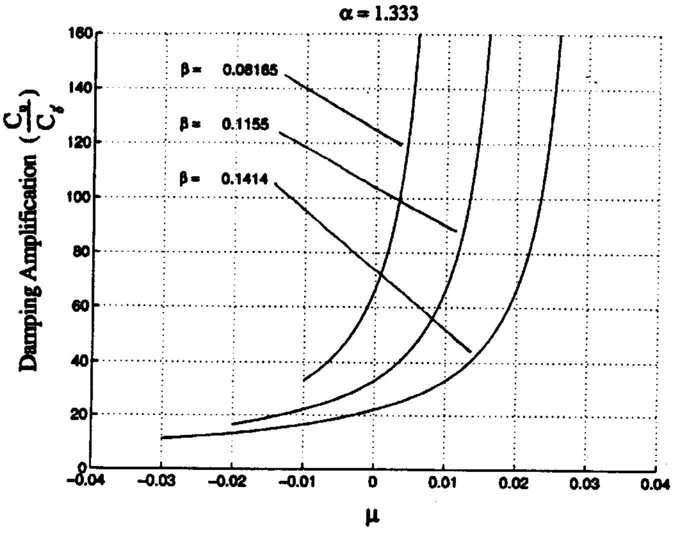


Fig. 7 Damping amplification curves

MODE	ω_i (rad/sec)	ξ_i (%)
1	2.59	5.0
2	7.05	5.0
3	11.8	6.9
4	16.8	9.3
5	21.9	12
6	26.2	14
7	30.8	16
8	34.9	18
9	39.6	21
10	45.2	24

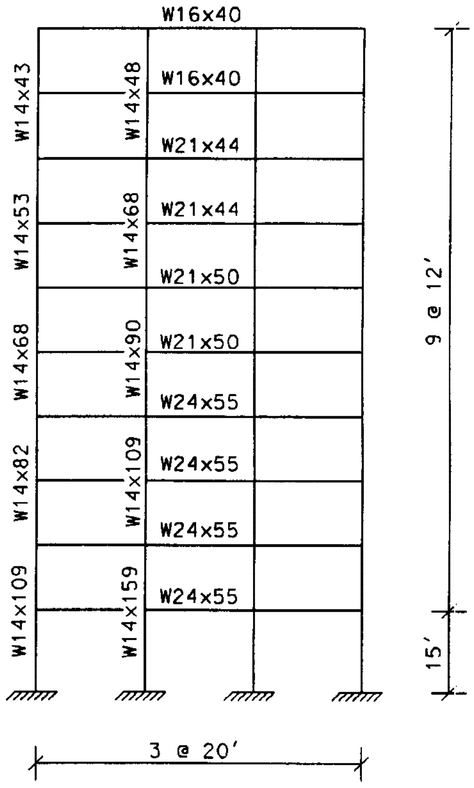


Fig. 8 Ten-story prototype steel frame

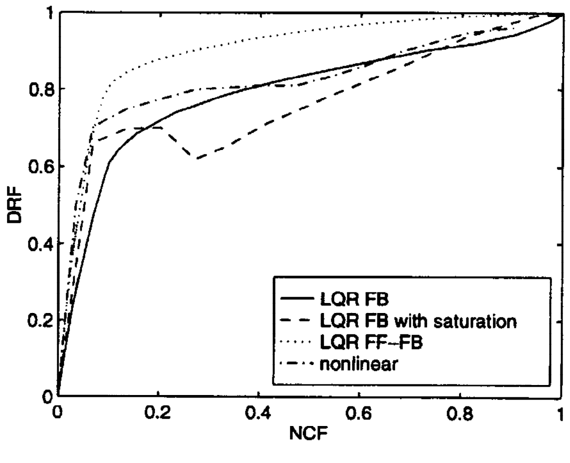


Fig. 9 Comparison of linear and nonlinear control with ten-story frame (1940 El Centro)

sensing, stability, and time-delay problems of the latter have been eradicated. When only relatively small control forces are permitted, the nonlinear control law appears to be far more efficient than the linear feedback control law. Furthermore, an efficient semi-active control mechanism that can be implemented with the nonlinear control strategy has been proposed. The semi-active device does not require any power to operate.

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