

Development of a Real-Time Two-Layer Adaptive Control System for Reducing Seismic Responses of High-Rise Structures Using Hyper-Adaptation and the Extremum Seeking Algorithm

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ABSTRACT

In this study, a real-time adaptive control framework with a two-layer architecture is proposed for mitigating the seismic responses of tall buildings exhibiting nonlinear behavior. The proposed structure consists of a baseline adaptive controller and a supervisory hyper-adaptive layer that adjusts the adaptation parameters online using a filtered extremum-seeking algorithm. The baseline controller generates the control signal based on output-feedback adaptive laws, while the hyper-adaptive layer determines the direction and rate of updating the controller gains by estimating the instantaneous approximate gradient of the performance function. This mechanism, without relying on an accurate structural model or prior identification, enables dynamic adaptation to sudden or gradual changes in system dynamics, nonlinear behaviors such as hysteresis, and structural uncertainties. The iRT-SAC framework is designed to guarantee boundedness of the adaptive parameters and closed-loop stability under challenging operating conditions, while minimizing the need for manual retuning or remodeling. To evaluate its performance, the proposed method is implemented on the 20-story benchmark structure of Ohtori et al. and compared with reference controllers including LQG, H_{∞} , fuzzy control, and Clipped-LQG. The results demonstrate approximately 60% reduction in interstory drift and preservation of closed-loop stability in the presence of severe uncertainties and nonlinear behavior. Overall, iRT-SAC represents a model-free, robust, and practically deployable adaptive control framework for tall and complex structures.

KEYWORDS

Simple Adaptive Control (SAC), Hyper-Adaptation, Model-Free Control, Extremum Seeking Algorithm, Nonlinear Benchmark Structure.

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1. Introduction

Severe seismic events pose persistent threats to civil infrastructure, causing excessive responses and economic losses, and driving the development of advanced vibration mitigation technologies [1]. Structural control systems are typically categorized as passive, active, semi-active, and hybrid [2]. Passive systems offer simplicity and energy independence but lack adaptability, while active systems provide stronger reduction capacity yet depend on precise models and control parameter tuning, which limits robustness under uncertainties [3].

Intelligent control methods using neural networks, fuzzy logic, or data-driven learning have shown improved adaptability but still face difficulties such as noise sensitivity, heavy computation, and demanding training, hindering real-time operation [4]. Adaptive control schemes can handle nonlinear and time-varying structural behavior; however, most employ constant learning rates, slowing convergence under strong excitations [5].

Extremum Seeking (ES) enables model-free online optimization through direct performance feedback. Building upon this concept, this paper proposes an intelligent real-time self-adaptive control (iRT-SAC) strategy combining the SAC framework with a meta-adaptive ES layer. The proposed controller simultaneously adjusts learning rates and multi-objective weighting factors (tracking accuracy, control effort, and adaptive-parameter variation), enabling robust, model-free, and computationally efficient seismic response control.

2. Methodology

The proposed iRT-SAC framework extends the Simple Adaptive Control (SAC) paradigm for real-time mitigation of seismic responses in nonlinear structures with uncertain dynamics. Controller gains are updated directly from tracking errors without explicit system identification, enhancing robustness and practical applicability.

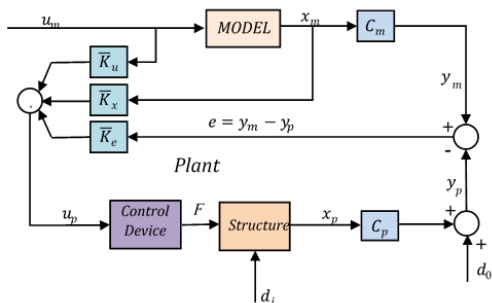


Figure 1. Block diagram of the SAC adaptive controller.

To further improve adaptability, a meta-adaptive Extremum Seeking (ES) layer is integrated into SAC. This layer continuously tunes learning rates and weighting factors of a multi-objective cost function incorporating RMS tracking error, control energy, and adaptive-parameter variation. The ES algorithm executes model-free optimization by injecting small perturbations for gradient estimation based solely on measured outputs, ensuring low computational demand and stable adaptation.

The controller's performance is verified using a nonlinear 20-story benchmark model and compared with reference methods. Results confirm low computational cost independent of structural size, with per-step runtime well below the sampling interval, thereby ensuring feasibility for real-time implementation on standard control hardware.

3. Numerical Study

The proposed iRT-SAC controller is examined on a nonlinear 20-story steel moment-resisting benchmark structure equipped with an active tendon system, representing severe seismic conditions with stiffness degradation, plastic hinges, and local damage effects. Analyses follow the benchmark protocol in the north-south direction using a 20-DOF reduced-order model, where floor displacements denote main response coordinates. Modal damping ratios of 2% are assigned to the first and fifth modes. Accelerometers are placed at Floors 4, 8, 12, 16, and 20, and actuators rated at 1000 kN are distributed along the height.

Nonlinear time-history analyses are performed using the Newmark- β scheme with a 0.005 s time step, ensuring unconditionally stable computations. Performance is evaluated through normalized benchmark indices (J_1 - J_{14}) related to displacement, acceleration, device efficiency, and control effort—values below unity reflect improvement over the uncontrolled case. Four historical earthquakes (El Centro 1940, Hachinohe 1968, Northridge 1994, and Kobe 1995) under multiple intensity levels are considered to verify robustness across both linear and nonlinear response regimes.

In the ES layer, the perturbation frequency is kept at 8 Hz—beyond dominant structural modes—for proper time-scale separation, with amplitude below 0.1% of adaptive gains. The controller runs via matrix multiplications and direct adaptive updates, requiring neither inversion nor optimization routines. The average computation time per step is 0.5 ms, well below the 5 ms sampling interval, confirming real-time compatibility for DSP/FPGA-based implementations.

4. Results and Discussion

The effectiveness of the dual-layer iRT-SAC controller was validated through nonlinear simulations of a 20-story benchmark structure with active tendons. By integrating an ES-based meta-adaptive layer into the SAC framework, the system enables continuous online parameter tuning without a precise structural model, even under nonlinear stiffness degradation. Performance was compared against LQG [6], fuzzy control [7], Clipped-LQG [8], semi-active MPC [8], semi-active H_∞ [8], and OSAC [9] controllers using standard benchmark data.

Under the El Centro record, both maximum interstory drift ratios and absolute floor accelerations (Figure 2) were markedly reduced compared to the uncontrolled structure. The consistent reduction pattern across floors indicates effective redistribution of control forces, avoiding local damage concentration. Notable improvements in lower stories reflect enhanced global vibration suppression, attributed to adaptive learning-rate and cost-function optimization.

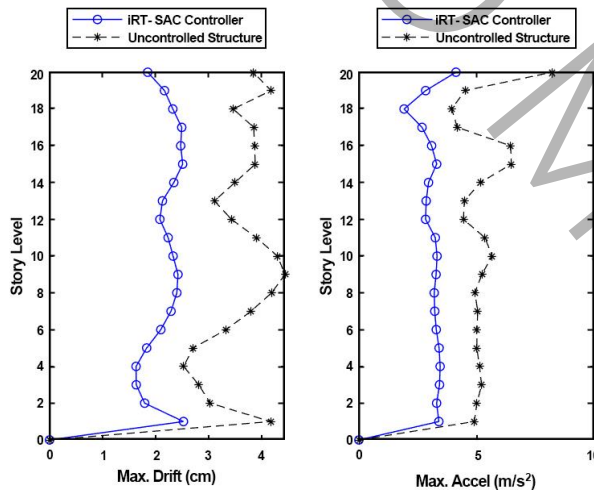


Figure 2. Maximum interstory drift and absolute acceleration of the structure under uncontrolled and iRT-SAC controlled cases, based on the El Centro earthquake record scaled by a factor of 1.5 relative to the original recorded motion.

The iRT-SAC controller achieves simultaneous mitigation of displacement and acceleration while maintaining actuator forces within practical limits. The extremum-seeking meta-adaptive layer continuously refines controller parameters, ensuring stable performance across varying seismic intensities. Integrating model-free optimization with adaptive control improves robustness against modeling uncertainties and nonlinear effects, confirming the framework's suitability for real-time structural applications.

5. Conclusions

The proposed dual-layer iRT-SAC controller was tested on a 20-story benchmark structure under four historical earthquakes. It outperformed conventional controllers (LQG, fuzzy, H_∞ , Clipped-LQG, OSAC, MPC) by achieving over 60% reduction in structural responses, while keeping actuator demands and plastic deformations within safe limits. Through its meta-adaptive layer, iRT-SAC adjusts learning rates and cost weights online, ensuring stability and model-free adaptation. The approach provides a simple, efficient, and reliable solution for real-time seismic control of high-rise structures.

6. References

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