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Active Vibration Control of a 2-Story Building Using ESC for Earthquake Mitigation

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***Abstract*— Earthquakes pose a severe threat to structural safety globally, particularly in urban areas near seismic fault lines. This work focuses on the modelling and control of a two-story smart structure with an Active Tuned Mass Damper to reduce seismic vibrations. The structure is designed as a two-degree-of-freedom spring-mass-damper system, with the Tuned Mass Damper located on the second floor to minimise peak displacements during seismic events. A data-driven control technique is proposed that incorporates Extremum Seeking, model inversion, and Proportional-Derivative control. This hybrid controller allows for adaptive performance optimisation without requiring extensive plant models, making it ideal for a variety of seismic action characteristics. The control system is developed and tested in a MATLAB/Simulink environment with real earthquake data, including the 1940 Imperial Valley Earthquake record. Simulation findings show that the suggested controller is successful at reducing structural vibrations, especially on the upper floors, where displacements are often more significant. Compared to passive control systems, the ES-based strategy improves the dynamic response and stability of the structure. This study highlights the potential of intelligent and adaptive control techniques in structural engineering, providing a globally applicable solution for improving seismic resilience in new and existing buildings.**

***Keywords*— ATMD, Extremum Seeking, Vibration Control, Data-Driven Control, Smart Structures.**

I. INTRODUCTION

Turkey lies in one of the world's most seismically active regions, with numerous densely populated cities situated near fault lines (Kanatani et al., 2003). This seismic risk is further aggravated by the presence of weak structures lacking ductile behaviour during strong earthquakes. Historical events, such as the 1964 Alaska and 1999 Kocaeli earthquakes, underscore the destructive potential of these natural disasters. Most recently, on February 6, 2023, Turkey endured a catastrophic sequence of earthquakes: a magnitude 7.8 quake near Gaziantep, followed by a magnitude 7.5 event just nine hours later. These quakes, among the most devastating in the past two decades and comparable to the 1939 Erzincan earthquake, caused widespread destruction, severely impacting local populations and the destruction and loss of life and property are many times greater than the emergency crisis management limits.

To mitigate such risks, the protection and resilience of building structures are critical for post-earthquake recovery, preventing collapses, and ensuring safety. Advanced seismic technologies, including smart structural systems and active control mechanisms, have become indispensable tools for enhancing resilience. In Turkey, urban transformation projects have made it imperative to integrate modern engineering solutions, such as smart buildings, into newly constructed or existing high-rise structures to withstand strong seismic actions. Laboratory experiments remain essential for validating these innovative approaches and ensuring their practical applicability.

Recent developments in material science have led to the emergence of smart materials and adaptive systems, paving the way for smart structures that can monitor and adapt to environmental changes. These innovations are particularly important in infrastructures and urban transformation projects aimed at reducing seismic risks. Smart buildings incorporate intelligent systems and modern control technologies, such as passive, active, and hybrid control mechanisms. Structural dynamics plays a key role in designing these systems, with seismic brakes being widely used to reduce seismic vibrations. Experimental studies using simplified models and hybrid designs, such as adjustable mass dampers, help validate their effectiveness. A conceptual model

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illustrates how combining various control strategies—such as active mass dampers, passive isolators, and servo-controlled mechanisms—can significantly enhance a building's ability to withstand dynamic forces, including earthquakes and wind.

The structural model is idealised using the Tuned Mass Damper (TMD) approach, commonly applied in seismic studies [1] [2]. This method treats each story-floor as a dynamic system, allowing for the simulation and analysis of the building's response. Building on the previous discussions of smart structural systems and real-time monitoring, the proposed system exemplifies a multi-story structure designed to operate with a real-time data acquisition system. This system facilitates experiments on structural behaviour, dynamic response to seismic inputs, and sensory-motor control strategies. The building model is idealised as a second-order dynamic system for each story floor, with the Two-Degree-of-Freedom (2DOF) approach commonly used in seismic studies to simulate and analyse the system's response characteristics.

In the context of vibration control, the optimum design of PID controlled Active Tuned Mass Damper (ATMDs) via modified harmony search presents an advanced approach for optimizing the vibration controller [3]. Recent research has examined the use of Extremum Seeking Control (ESC) in vibration control systems [4]. The works suggested a novel ESC approach for stabilising mechanical systems by evaluating and modifying parameters to reduce vibrations. Similarly, in 2024, researchers looked into using ESC to tune the damping and stiffness of vibration absorbers, hence enhancing performance under harmonic excitation [5]. In addition, research published in 2024 demonstrated the use of ESC to autonomously tune a variable-inertia vibration energy harvester, optimising its efficiency by real-time frequency tracking [6]. These advances demonstrate ESC's potential for adaptive and efficient vibration control.

This study proposes a simplified two-story floor building model for earthquake engineering studies, integrating physical model characteristics and a reduced dynamic model representation to develop and test vibration control algorithms. The approach uses a data-driven control method for real-time vibration control to enhance the building's dynamic response under seismic excitations. An Extremum-Seeking (ES) algorithm that estimates a particular vibration frequency is used in a control strategy incorporating an inner-loop model inversion and an outer-loop Proportional-Derivative (PD) controller to minimise upper-floor vibrations. The system is tested with realistic earthquake acceleration signals, and its effectiveness is validated through MATLAB/Simulink simulations as a preliminary step toward real-time implementation. Unlike conventional buildings relying on passive control, a smart building structure actively adapts to seismic actions, optimising structural stability. This research contributes to the development of advanced active control strategies for earthquake-resistant buildings.

II. Modelling of a Two-Story Structure Using Tuned Mass Dampers

The use of mechanical analogies greatly simplifies the representation of complex systems. For instance, the dynamics of a single-story floor can be approximated using simple spring-mass models. Fig. 1 illustrates the structural models and their equivalents: a) a schematic of the 2DOF shear frame system, and b) the corresponding 2-story-floor CAD model. Fig. 2 illustrates a system in which a spring and damper mechanism is connected to a second system, adjusted according to the dynamic characteristics of the structure. This control system can be seen as a combination of a pure active system, such as an ATMD, and a Passive Mass Damper (PMD) element, often referred to as Hybrid Mass Dampers (HMDs). Smart systems and active control technologies are significant areas of development in modern engineering. Laboratory experiments are essential for increasing the reliability of control systems and for their practical applications. Various devices are used for structural active control, among which the ATMD is widely modelled and implemented. The ATMD used in this work operates with a single-degree-of-freedom mass, spring and damper system (as shown in Fig. 2). It consists of a mass that can move in response to seismic effects, generating a force, U_a, at the second floor, which is used to produce real-time action to the control algorithms to reduce paper floor amplitude vibrations.

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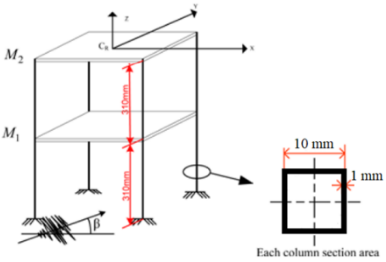
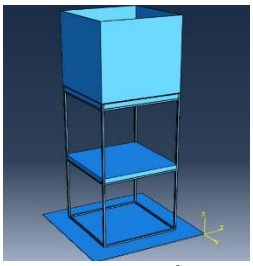


a)



b)

Fig. 1 Structural models: a) Schematic of 2DOF shear frame system, and b) 2-story-floor CAD simulation

The 2DOF story-floor dynamics can be written as follows:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = M\,\ddot{x}_g\,(\mathrm{t}) \qquad (1)$$

Here, M, C, and K are the mass, damping, and stiffness matrices, respectively. The equivalent viscous damping matrix is calculated by the Rayleigh damping method, where the coefficients α_M and α_k are calculated according to (2), (3) and (4). The equivalent critical damping ratio is assumed identical in both modes considered ($\zeta = \zeta_i = \zeta_j$). Combining two distinct modes *i* and *j*.

$$\alpha_M = \frac{2\zeta\omega_i\omega_j}{\omega_i+\omega_j}$$
$$\alpha_k = \frac{2\zeta}{\omega_i+\omega_j} \qquad (2)$$

where ω_i and ζ_i are the critical damping ratio and the circular frequency for mode "i ". The circular frequencies ω_i and ω_j correspond to the first and second modes, respectively. The lumped mass matrix is given by:

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \qquad (3)$$

$$K = \begin{bmatrix} K_1 & -K_1 \\ -K_1 & K_1 + K_2 \end{bmatrix} \qquad (4)$$

$$C = \alpha_M \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} + \alpha_k \begin{bmatrix} K_1 & -K_1 \\ -K_1 & K_1 + K_2 \end{bmatrix} \qquad (5)$$

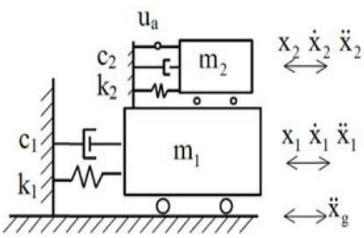


Fig 2. Active tuned mass damper representation.

The dynamic response of the structure is evaluated in this study using the 1940 Imperial Valley ground motion as an input excitation. Realistic seismic behaviour simulation is made possible by the data, which was gathered at 0.02 s intervals for a total of about 28 s. It is perfect for verifying the functionality of vibration control systems like the ATMD modelled in this work because of its extensive use in structural dynamics.

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Because of its track record of accurately simulating structural responses under dynamic loads, the IDARC 2D platform [7] was chosen for this work. It is ideally suited for examining how buildings behave during earthquakes due to its capacity to mimic intricate geometries and time-dependent seismic inputs. The 1940 El Centro ground acceleration record (NS component) is used to assess each story floor's vibrational properties, offering important information for structural control and design enhancements. Fig. 3 shows the earthquake-grown acceleration given as input to the simulation. Story capacity curves (story shear versus story drift graph) for the first and second story floors are plotted in Fig. 4. The time history for the response of the first and second stories is shown in Fig. 5. In each column, the displacement, velocity and acceleration response of each story is plotted.

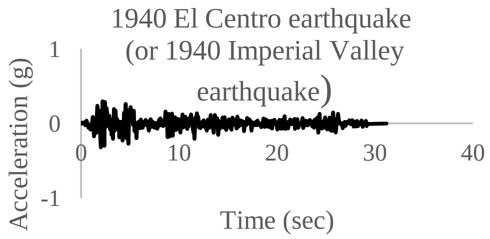

Fig. 3: Input earthquake record.

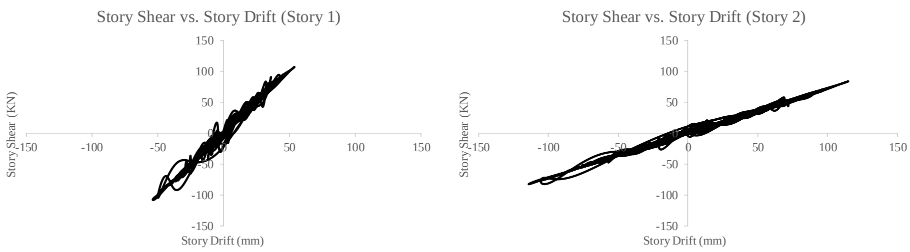

Fig. 4: Story shear versus story drift graph.

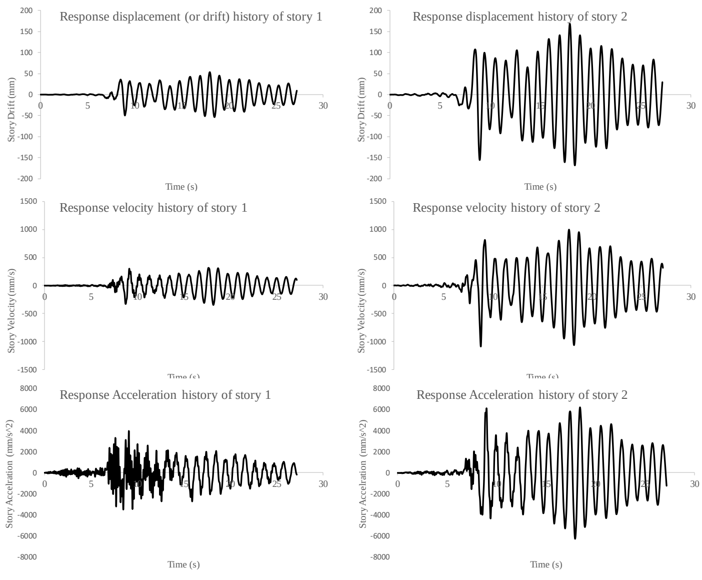

Fig. 5 Displacement, velocity and acceleration response of the first and second-story floors.

Building on the advancements in smart materials and adaptive systems, this work aims to propose an algorithm in order to enhance the resilience of structures. By incorporating real-time sensory systems and actuating mechanisms to monitor and control the building's response to external forces, including seismic activity. The integration of smart structures with real-time sensors is essential for measuring the deformations caused by forces like earthquakes and for tracking the distribution of loads across the system. One key component of the implementation of a seismic signal detector is that it will identify seismic events and allow

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the system to differentiate between periods with and without seismic activity. During non-seismic periods, the system will remain in a passive state, and actuators will be deactivated, ensuring the building behaves like a normal structure.

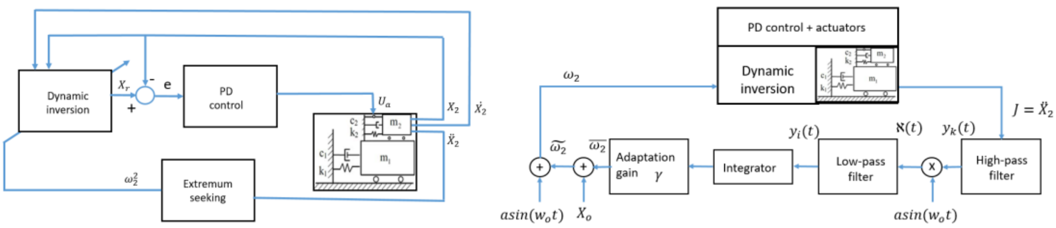
The building has been simulated using MATLAB/Simulink, and the main simulation parameters for the spring-mass-damper model that represents a TMD system are compiled in Table 1. In order to simulate inter-story dynamics under seismic excitation, this idealised two-degree-of-freedom structure is made up of two-story masses joined by springs and dampers. The parameters for each floor include the mass values, spring stiffness, damping coefficients, gravitational acceleration, and numerical integration parameters such as total simulation time and sampling time.

Table 1. Simulation Parameters for the TMD Model

Parameter	Description	Value	Unit
ts	Total simulation time	60	s
h	Sampling time	0.002	s
g	Gravitational constant	10	m/s²
$\mathbf{k_1}$	Spring constant (story 1)	7×10^9	N/m
$\mathbf{k_2}$	Spring constant (story 2)	1.4×10^{10}	N/m
$\mathbf{c_1}$	Damping coefficient (1st)	151200	Ns/m
$\mathbf{c_2}$	Damping coefficient (2nd)	302400	Ns/m
$\mathbf{m_1}$	Mass of story 1	131.2×10^6	kg
$\mathbf{m_2}$	Mass of story 2	131.2×10^6	kg

III. EXTREMUM SEEKING-BASED ACTIVE VIBRATION CONTROL

The vibration control is based on Extremum Seeking Control (ESC), which is an adaptive, model-free optimisation method used to tune system parameters in real-time. It continuously perturbs an input signal, measures system response, and adjusts control variables to minimise or maximise a given performance criterion. ESC is used to estimate the dominant vibration frequency ω_2 of the second-story floor of the building during the excitation coming from an earthquake. The system then generates a new reference and tracks it. By dynamically adjusting the control frequency, ESC enables the inner-loop model inversion to remain effective, ensuring vibration damping. This enhances the performance of the PD controller in the outer loop, leading to improved seismic resilience by actively adapting to structural dynamics. The objective is to minimise the top-story displacement of structures under dynamic forces. The results demonstrate that the proposed method effectively reduces structural vibrations, outperforming passive TMDs. Fig. 6(a) illustrates the Control strategy based on an ESC controller.



(a) (b)

Fig. 6 Vibration Control strategy: (a) method based on an ESC controller, and (b) the ESC block diagram.

Frequency-based extremum seeking, where $\omega_{2(t)}$ is the independent estimated signal, $J = \ddot{X}_2$ is the minimized signal, $y_k(t)$ is the signal coming from the high-pass filter, w_o stands for the designed frequency, $\aleph(t)$ is the signal to the low-pass filter, $y_i(t)$ is coming from from the low-pass filter, γ is the adaptation gain, $\overline{\omega_2}$ is the signal after multiplying the adaptation gain, X_o is call the bias signal, $\widetilde{\omega_2}$ is the signal after bias and a is the amplitude of the sine wave. Figure

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The results of the simulated algorithms are presented through the following plots; the frequency estimation convergence plot (estimated frequency vs. time) in Fig. 7, and the performance index plot (cost function vs. time) in Fig. 8. The comparison plot (ESC vs. free vibration) – peak displacement reduction vs. time is shown in Fig. 9. These figures demonstrate the effectiveness of the algorithm in estimating a frequency for model inversion, the convergence of acceleration to zero (Fig. 8), and the comparison of vibration amplitudes with and without vibration control. Fig 10. Gives an idea of the necessary generated force U_a to be provided by the actuators at the 2DOF building upper floor.

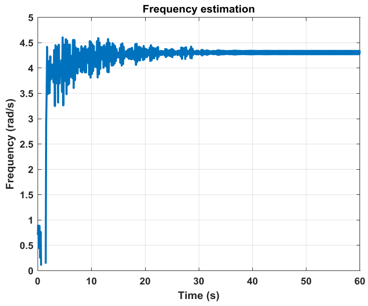

Fig 7. Estimated frequency

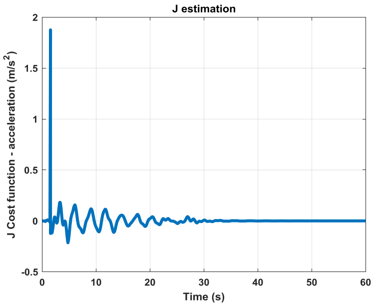

Fig 8. Acceleration convergence to zero

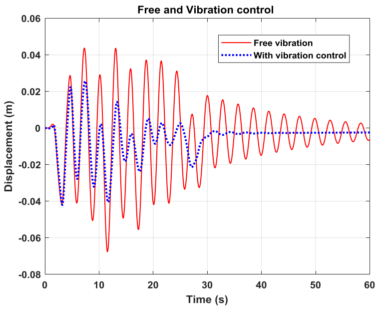

Fig 9. 2DOF building seismic response: upper floor displacement with and without vibration control.

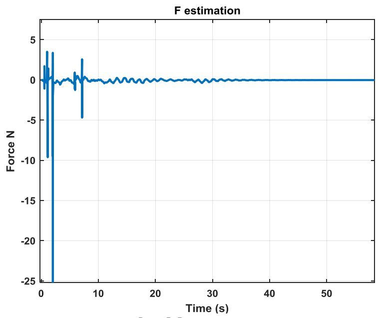

Fig 10. 2DOF building seismic response: the required force U_a generated at the upper floor.

IV Conclusion:

This study presents a simplified two-story building model with real-time vibration control for earthquake engineering. Using Extremum Seeking Control (ESC) and model-based strategies, the system estimates and tracks the dominant vibration frequency, minimising top-story displacement responses. The approach integrates inner-loop model inversion and an outer-loop PD controller, ensuring adaptive seismic response. Simulation results confirm effective frequency estimation, acceleration convergence, and vibration reduction. Future work will focus on real-time implementation, refining actuation dynamics, and enhancing measurement accuracy for improved earthquake resilience. This research advances intelligent active control systems for earthquake-resistant structures.

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