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Optimal Structural Control of Tall buildings using Tuned mass dampers via Chaotic Optimization Algorithm-A Review

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Abstract: Tuned Mass Dampers (TMDs) are generally known to be highly effective in suppressing unwanted structural vibrations induced by random environmental loads. In this paper, optimal design parameters of passive and active TMDs are optimized through an advanced optimization algorithm. To validate its performance, the algorithm was implemented to a 10-story shear frame subjected to severe seismic activity and to a 76-story concrete office building subjected to wind-induced vibration. The outcomes prove that TMDs designed with this technique greatly improve the structural system's capacity to resist dynamic excitations, proving to be useful and efficient in enhancing building stability.

Keywords: Chaos, Tuned mass dampers, Tall building, Structural control, Optimization, Novel Optimization, Particle Swarm Optimization

I. INTRODUCTION

Tall structures, the hallmark of modern urban development, are under peculiar structural challenges due to their vulnerability to dynamic loads such as wind and earthquake [50-64]. Their stability and safety require sophisticated structural control systems above the ordinary techniques. Even though traditional techniques such as base isolators and mass dampers have been satisfactory, they are not that versatile and effective, particularly in evolving environmental conditions [65-78]. This has motivated the study of sophisticated optimization techniques that yield more adaptive, efficient, and economical solutions to better control structure and enhance the resilience of high-rise buildings [25-49].

One of the more widespread solutions to structural control is the application of Tuned Mass Dampers (TMDs), passive energy dissipation systems that are intended to oppose vibrations by oscillating in opposition of motion to structural movement [65-78]. Originally proposed by Frahm for vibration reduction in ships, TMDs have subsequently been refined to perfection by researchers such as Den Hartog and Warburton and are extremely efficient at damped vibrations in tall buildings during earthquakes or wind storms [10-12]. Their simplicity, low maintenance cost, and strength make TMDs a favourite in high-rise buildings, such as Boston's John Hancock Tower and Taiwan's Taipei 101. TMDs are not, however, without constraints, as their detuning sensitivity can affect performance if structural frequencies change over time [50-64].

New developments in optimization methods, like genetic algorithms, particle swarm optimization, and machine learning-based algorithms, have transformed structural control systems [65-78]. These methods allow for adaptive systems that can modify themselves dynamically in response to varying loads and environmental factors [16-24]. With the help of sophisticated algorithms and computational power, engineers are able to optimize device placement, locations, and functioning, which saves costs and yields better performance. This research discusses the integration of new optimization methods with TMD systems and how they can break the barriers of conventional methods to enhance the performance and sustainability of high-rise structures against dynamic loads [79-83].

II. LITERATURE REVIEW

Kaveh et al. [1] have studied the "Optimal structural control of tall buildings using tuned mass dampers via chaotic optimization algorithm", in which he has developed advanced optimization techniques by integrating chaotic maps with

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algorithms such as particle swarm optimization (PSO) for optimal structural control of tall buildings. A new chaos-based approach in the PSO paradigm is proposed, resolving the constraints of conventional PSO and improving the performance of several optimization algorithms. The study shows that these methods efficiently optimize seismic control devices like Tuned Mass Dampers (TMDs) and enhance their efficiency in reducing vibrations. The result is a powerful methodology that delivers useful solutions to design control devices in high-rise buildings and is applicable to practical situations.

C. Lee et al. [2] conducted the research on the "Optimal Design Theories and Applications of Tuned Mass Dampers" to develop structural vibration control through enhanced TMD design theories and applications. Beginning with Frahm's original idea and Den Hartog's optimal design theory, the study progressed to encompass random vibration analysis, MTMDs, and numerical optimization techniques. The findings validate the efficacy of the TMD in reducing vibrations under different dynamic loads, with numerical computations that affirm real-world applications in SDOF and MDOF structures. The findings highlight the significance of optimal TMD designs in improving structural safety and performance.

Kaveh et al. [3] conducted the research on the "Emergency management systems after disastrous earthquakes using optimization methods" in which they examined the emergency management (EM) systems and their optimization techniques, presenting a review of current applications and advances. It categorizes the study into Emergency Response Planning, Mass Evacuation, Shelter Location, and Facility Location, noting the evolution of optimization methods within the past four decades. It categorizes the study into Emergency Response Planning, Mass Evacuation, Shelter Location, and Facility Location, noting the evolution of optimization methods within the past four decades. The review calls out critical success factors for effective EM systems and calls for research to fill knowledge gaps, including uncertainties in disaster situations and multi-agent human behaviour, and sets out directions for future research into enhancing emergency response and data handling.

M. S. Hadi and Y. Arfiadi [4] has done a study on the "Optimum Design of Absorber for MDOF Structures" aims to address the complex vibrational behaviour of multi-degree- of-freedom (MDOF) systems through the development of efficient absorber designs. Using optimization techniques, the research seeks to enhance vibration control, comparing existing passive and active control strategies to identify their strengths and limitations. The results focus on bridging gaps in current research, such as adaptability to varying conditions, while proposing innovative methods for practical applications. The outcome establishes a robust foundation for future advancement in absorber design for real-world MDOF structures.

Kaveh et al. [5] have done a study on "Optimum parameters of tuned mass dampers for seismic applications using charged system search" on Tuned Mass Dampers (TMDs) in seismic applications, which aims to enhance structural resilience through advanced optimization techniques and algorithms .Starting from Frahm's original TMD idea and Den Hartog's extension with damping, later research included modern metaheuristic techniques such as Charged System Search (CSS) and hybrid algorithms that blend harmony search to optimize parameters of TMDs against seismic excitations. Results indicate significant improvement in minimizing multi-story building dynamic responses, validating the effectiveness of the techniques. The outcome confirms the feasibility of more advanced hybrid algorithms for seismic-resistant structural performance.

A. Kaveh and S. M. Javedi [6] have studied "Chaos-based firefly algorithms for optimization of cyclically large-size braced steel domes with multiple frequency constraints", here they aim to advance structural optimization by integrating chaotic systems and meta-heuristic algorithms to tackle the challenges of nonlinear, multi-frequency constraint problems. It brings into focus the weakness of conventional methods and the benefits of meta-heuristics, e.g., enhanced search power, but at the risk of pre-mature convergence. Incorporating chaotic systems into algorithms such as the Firefly Algorithm has led to Chaotic Logistic Firefly Algorithm (CLFA) and Chaotic Gaussian Firefly Algorithm (CGFA). The new algorithms, which have been confirmed by numerical examples, show improved efficiency in optimizing truss shape and size, providing realistic solutions to complex structural optimization problems.

Kaveh et al.[7] conducted a work on "Optimal design of large steel skeletal structures using the chaotic firefly optimization algorithm based on the Gaussian map", wherein they sought to promote structural design optimization by investigating metaheuristic methods and combining chaotic maps, with emphasis on large steel skeletal structures.
It highlights the use of genetic algorithms and various metaheuristics, such as Ant Colony Optimization and Particle Swarm Optimizer, as well as the Firefly Algorithm (FA) for mixed-variable problems. The survey also discusses improving FA with chaotic maps, such as logistic and Gaussian maps, to improve optimization performance. This sets the stage for the introduction of the Chaotic Gaussian Firefly Algorithm (CGFA), which demonstrates superior robustness and effectiveness in optimizing large-scale steel structures compared to other heuristic methods.

Julio C. Miranda [8] Did research on the "Discussion of system intrinsic parameters of tuned mass dampers used for seismic response reduction", wherein he examines the intrinsic parameters of Tuned Mass Dampers (TMDs) to minimize

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seismic responses based on core research .It illustrates that TMDs can reduce seismic responses by up to 50 percent and examines various methods, including Miranda's modal energy-based method and new calibration techniques, emphasizing the importance of achieving equal damping ratios. The proposed methods are validated through numerical simulations, which confirm their effectiveness in actual seismic control applications.

Kaveh et al. [9] have conducted a research on "Reliability Analysis via an Optimal Covariance Matrix Adaptation Evolution Strategy: Emphasis on Applications in Civil Engineering", where they have discussed several reliability analysis techniques in civil engineering, placing emphasis on conventional methods such as FORM and SORM, as well as recent methodologies such as Monte Carlo Simulation and evolutionary algorithms. This paper outlines studies by researchers on optimization methods in structural reliability and highlights recent developments like the Cholesky-CMA-ES algorithm, which improves upon the efficiency of classical algorithms. This review highlights the importance of reliability analysis and challenges the current innovations that increase the effectiveness and utility of these methods to find complicated engineering challenges.

Li et al.[10] have done a study of "Optimization and sensitivity of TMD parameters for mitigating bridge maximum vibration response under moving forces" in which they attempt to enhance vibration control in high-speed rail bridges through optimizing Tuned Mass Dampers (TMDs), surmounting limitations of current techniques such as Den Hartog's optimal parameter method. It identifies gaps in sensitivity analysis and the effectiveness of time-domain methods, proposing a frequency-domain approach and the augmented Lagrangian method for better optimization of TMD parameters. This approach is expected to improve TMD application and vibration management in high-speed railway bridges, fill existing research gaps, and improve structural safety and performance.

III. RESULTS

- Case Study 1: Ten-Story Shear Building with Tuned Mass Damper (TMD)

In the initial test case, a ten-story shear building with a Tuned Mass Damper (TMD) is considered for evaluating the applicability of the proposed algorithm. The building is modelled as an idealized dynamic system with ten degrees of freedom, one per floor, where each floor's mass is lumped at the floor level. For the context of this case study, the structural parameters remain unchanged for all scenarios: there are 360 tons, 650×10^3 kN/m stiffness, and 6200 KN·s/m damping coefficient for every floor. This setup is taken as a reference for the study of the dynamic response and control performance of the TMD under different input excitations [8].

Table 1. The maximum displacement of stories subjected to El-Centro (1940) NS for the Ten Storey shear building.

STORY	WITHOUT TMD(m)	WITH TMD				
		GA[4]	LEE[2]	CSS[5]	COA using Circle Map[1]	COA using Chebyshev Map[1]
1	0.031	0.019	0.02	0.018	0.019	0.019
2	0.06	0.037	0.039	0.036	0.037	0.037
3	0.087	0.058	0.057	0.053	0.054	0.053
4	0.112	0.068	0.073	0.068	0.068	0.068
5	0.133	0.082	0.087	0.083	0.082	0.081
6	0.151	0.094	0.099	0.095	0.094	0.093
7	0.166	0.104	0.108	0.106	0.104	0.103
8	0.177	0.113	0.117	0.114	0.113	0.112
9	0.184	0.119	0.123	0.12	0.119	0.118
10	0.188	0.122	0.126	0.123	0.123	0.121
TMD	-	0.358	0.282	0.493	0.349	0.376

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Table 2. The reduction percentage for the maximum value of stories displacement.

Story	GA[4]	Lee[2]	CSS[5]	COA using Circle map[1]	COA using Chebyshev map[1]
1	34.76	34.59	34.59	39.21	35.99
2	34.80	33.96	33.96	39.40	36.32
3	34.94	33.35	33.35	39.56	36.54
4	34.97	32.69	32.69	39.73	36.87
5	35.03	31.96	31.96	39.92	37.14
6	35.03	31.10	31.10	40.02	37.05
7	34.95	30.24	30.24	40.16	36.36
8	35.05	29.84	29.84	40.57	36.17
9	34.73	29.24	29.24	40.50	35.90
10	34.34	28.54	28.54	40.21	35.59

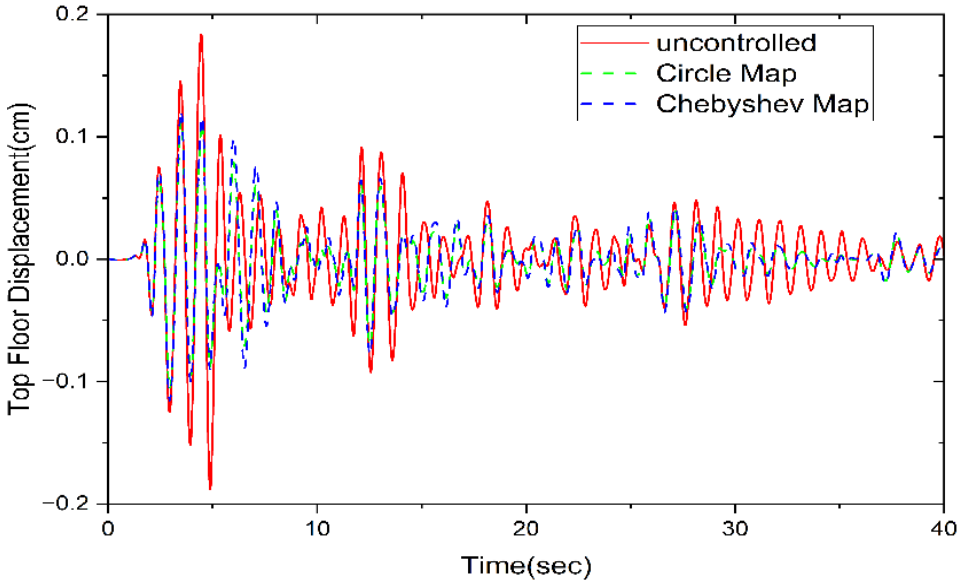

Figure 1. The time history of the Top floor displacement subjected to the El Centro (1940) NS earthquake.

- Case Study 2: Optimal Mass Damper Design for a 76-Storey Concrete Office Tower under Wind Excitations In this case, the benchmark high-rise concrete office tower introduced by Yang et al. [9] is utilized to evaluate the effectiveness of the optimal damper parameters derived using the COA (Chaotic Optimization Algorithm). The structure, a 76-story concrete building, is subjected to wind-induced excitations, making it an ideal candidate for testing vibration control strategies due to its height and slenderness. The total structural mass, which includes substantial mechanical equipment housed within plant rooms, is approximately 153,000 metric tons. With an aspect ratio of 7.3, the tower is classified as wind-sensitive, necessitating careful attention to dynamic response control.

- Key structural and material properties of the tower include:
- Modulus of Elasticity: 40 GPa
- Concrete Compressive Strength: 60 MPa
- Slab Thickness: 12 cm
- Overall Width: 42 meters
- Total Height: 306 meters
- Core Dimensions (Reinforced Concrete Core): 21 m × 21 m
- Spandrel Beam Section: 900 mm × 400 mm
- Structural Damping Ratio: 1%

This model serves as a robust platform for assessing the performance of optimally tuned mass dampers in mitigating wind-induced vibrations in tall concrete structures.

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Table 3. Objective function values of different methods.

	Without TMD		TMD-COA using Circle Map		TMD-COA using Chebyshev Map		ATMD-COA using Circle Map		ATMD-COA using Chebyshev Map	
μ	–		0.01		0.01		0.01		0.01	
α	–		1.01		0.95		0.95		0.90	
ξ	–		0.094		0.096		0.098		0.095	
R	–		–		–		0.90		0.07	
Floor No.	RMS_d	RMS_a	RMS_d	RMS_a	RMS_d	RMS_a	RMS_d	RMS_a	RMS_d	RMS_a
1	0.017	0.059	0.0106	0.0572	0.0107	0.0572	0.0083	0.0570	0.0112	0.0572
30	2.234	1.879	1.3606	0.8955	1.3725	0.9053	1.0645	0.9707	1.4443	0.9781
50	5.412	4.405	3.2811	1.8381	3.3110	1.8685	2.5603	2.0928	3.4901	2.0598
55	6.332	5.145	3.8340	2.1262	3.8694	2.1624	2.9893	2.4168	4.0808	2.3919
60	7.283	5.907	4.4042	2.4085	4.4453	2.4518	3.4309	2.7604	4.6905	2.7167
65	8.261	6.723	4.9897	2.7713	5.0369	2.8202	3.8832	3.1676	5.3175	3.1173
70	9.253	7.536	5.5835	3.1144	5.6369	3.1700	4.3409	3.5360	5.9541	3.5065
75	10.281	8.438	6.1989	3.6141	6.2588	3.6744	4.8146	4.0333	6.6142	4.0387
76	10.512	8.625	6.3368	3.6318	6.3982	3.6929	4.9207	4.0864	6.7621	4.0698
TMD/ATMD	–	–	10.3140	10.3367	12.1100	12.3251	14.4030	14.2024	16.3038	16.3801

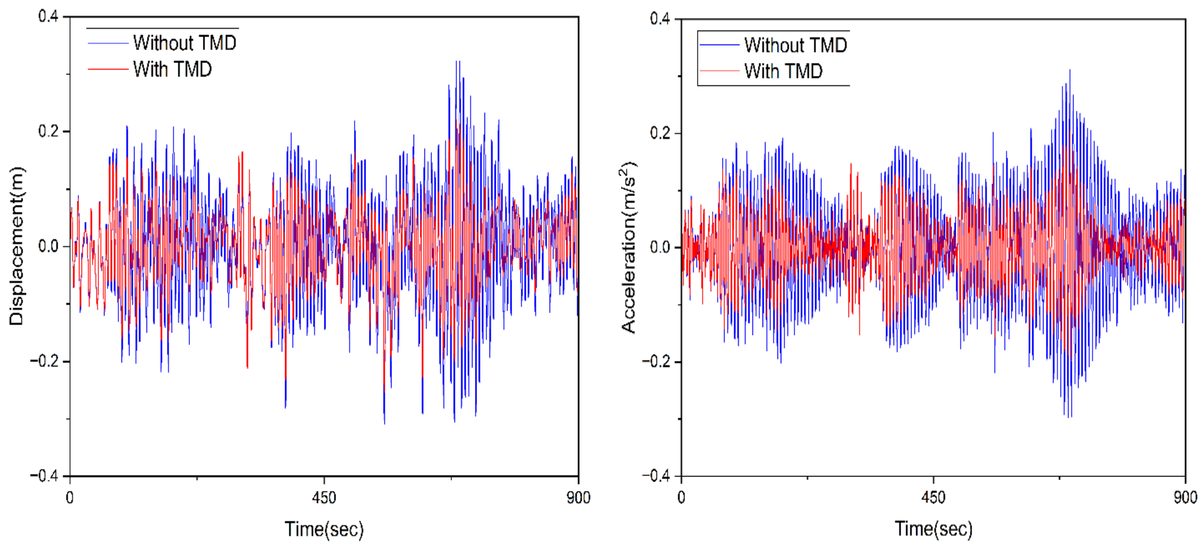

Figure 2. The Time history of the Top floor using COA-Chebyshev map: (a) Displacement; (b) Acceleration

IV. SUMMARY

This paper proposes a new chaos-inspired algorithm, based on Particle Swarm Optimization (PSO), for optimal Tuned Mass Dampers (TMDs) design of high-rise buildings. Chaotic mappings of one dimension, i.e., the Chebyshev and Circle maps, are employed to improve search flexibility and efficiency. The Chebyshev map, with its higher Lyapunov exponent, performs better by providing faster and more effective exploration of the design space. Optimization is the process of initialization, iterative search, and stopping [1-15]. The particle positions are updated based on chaotic velocity

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effects, and a pitch-adjusting rate refines the movements. The simulations were compared with specific hardware and parameters, such as independent runs, iterations, and population size [65-78].

The algorithm was applied to optimize the TMDs for two case studies: a ten-story shear building subjected to seismic forces and a 76-story concrete office tower under wind-induced vibrations. For the ten-story structure, the TMD mass was fixed at 0.3 percent of the building mass [50-64]. The optimization procedure was minimizing structural responses to seismic loading. The maximum displacements were found to decrease significantly, and the Chebyshev map performed better than the Circle map. For the 76-story office building, the emphasis was placed on reducing root mean square (RMS) displacement and acceleration caused by wind loading [16-24]. The results showed significant improvement in vibration control with considerable drift and floor accelerations reductions. In summary, this work justifies the suitability of the new chaotic optimization algorithm to enhance TMD performance [65-78].

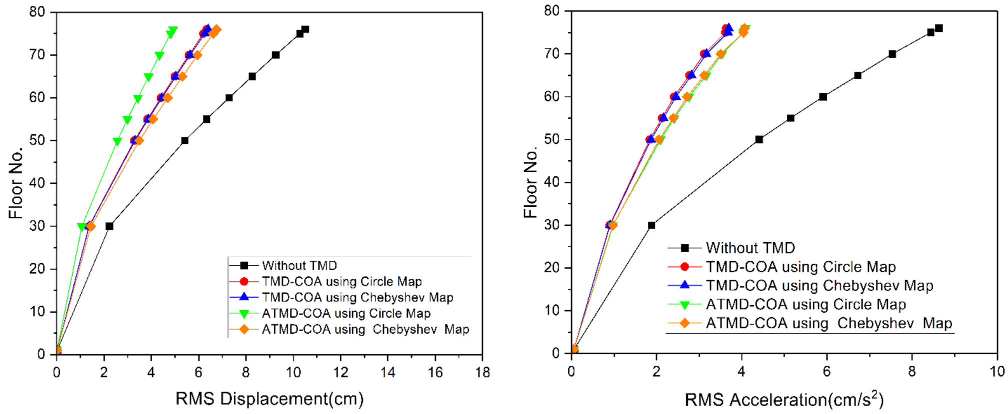

Figure 3. Comparison of RMS Displacement and Acceleration.

The coupling of the chaotic maps, and specifically the Chebyshev map, maximizes the ability to search and provide authentic outcomes. Its ability to survive distortions, combined with the ability to respond well to nonlinear disturbances, translates to a functional system for implementing TMD design for seismic and wind-induced oscillation reduction in tall structures. Its ability to make substantial gains in reducing structure response helps further create safer and more durable constructions and paves the way toward increased innovation in vibration control strategy[25-49].

V. CONCLUSION

This article notes progress in structural control, the importance of the use of mitigation techniques of vibrations, such as passive, active, and hybrid systems, towards improving the toughness of tall structures against external pressures such as seismic forces and winds. Tuned Mass Dampers (TMDs) are known to be effective vibration reduction devices, and the paper introduces a novel Chaotic Optimization Algorithm (COA) method to the optimal performance of such dampers. Under seismic and wind excitations, the algorithm becomes more effective, particularly when utilizing the Chebyshev map, which is superior to the Circle map due to its larger Lyapunov exponent, enabling a superior search for global optimum parameters. Optimized TMDs significantly reduce drift and floor accelerations, improving structural performance under dynamic loads. Conclusively that the COA is robust and fit for practical purposes, the study positions it as a superior resource for designers and engineers to employ in enhancing the resilience and safety of high-rise buildings.

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