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Inerter-Based Vibration Control Systems for Seismically Resilient Structures-A Review

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Abstract: The development of advanced vibration control systems has grown due to the rising susceptibility of civil infrastructure to dynamic excitations, particularly seismic occurrences. The Tuned Mass Damper (TMD), one of these, has shown promise but is constrained by its reliance on significant additional mass. The development and improvement of TMDs by including the inerter—a mechanical device that generates force proportional to relative acceleration—is examined in this paper. With lower mass requirements, the resultant systems, referred to as Tuned Mass Damper Inerters (TMDIs) or Tuned Mass Inerter Dampers (TMIDs), provide notable enhancements in vibration mitigation. Key studies on a range of TMDI structures and applications, such as fluid inerters, clutching mechanisms, negative stiffness elements, and hybrid active-passive control frameworks, are methodically reviewed in this study. Additionally included are optimization methods like surrogate modelling and genetic algorithms. According to the review, TMIDs achieve improved damping performance, installation flexibility, and decreased structural reaction, which is a significant development in structural control, particularly for seismic applications.

Keywords: Tuned Mass Damper (TMD), Tuned Mass Damper Inerter (TMDI), Structural Vibration Control, Inerter-Based Dampers, Seismic Response Mitigation, Passive Control Systems, Surrogate Optimization, Fluid Inerter, Equal model Damping (EMD).

I. INTRODUCTION

Structural systems are increasingly subjected to dynamic forces, especially seismic activities, which can lead to serious damage or even catastrophic failures if not properly mitigated [1-5]. Conventional approaches to improve seismic resilience, such as enhancing stiffness or strength, often result in uneconomical or impractical designs [5-10]. Consequently, passive vibration control devices have become more popular due to their effectiveness, simplicity, and minimal maintenance needs [11-15]. Among these devices, the Tuned Mass Damper (TMD) is commonly utilized to diminish structural responses by transferring energy from the main structure to a supplementary mass that is aligned with the dominant frequency of the structure [41- 45].

Although conventional tuned mass dampers (TMDs) are effective, they face limitations such as the requirement for considerable mass and restricted frequency bandwidth [25-30]. To address these issues, the concept of the inerter—a mechanical element that generates a force proportional to the relative acceleration between its ends—has been applied to structural engineering [1-5]. First introduced for use in automotive suspensions by Malcolm C. Smith in 2002, the inerter allows for a notable enhancement of the dynamic mass effect without the need to physically increase the device's mass [6-11].

When combined with conventional Tuned Mass Dampers (TMDs), the resultant system is referred to as a Tuned Mass-Inerter Damper (TMID) [9-14]. This cutting-edge arrangement provides improved vibration control by amplifying the inertia of the tuned mass system thanks to the contribution of the inerter [65-71]. Unlike traditional TMDs, the TMID can attain comparable or even better performance with lower mass ratios, making it especially appealing for high-rise structures and retrofitting situations where the addition of heavy masses is unfeasible [50-55].

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The implementation of TMIDs in seismic vibration control has shown promising results in both theoretical and experimental research [19-24]. TMIDs can offer better damping and wider frequency coverage by utilising the inerter's special acceleration-dependent force mechanism, which will lessen structural responses during intense ground motions [45-49]. Their passive design provides dependability in the event of failures in systems or power outages, which is crucial during earthquakes [30-35].

II. LITERATURE REVIEW

Miriam et al.,[1] present a study on the Nonlinear Mechanical Model of a Fluid Inerter. This paper explores the advancements in vibration control technologies, focusing on fluid inerter. It highlights the growing vulnerability of slender structures to vibrations caused by natural disasters and human activities, emphasizing the need for effective vibration control systems. Passive systems like Tuned Mass Dampers (TMDs) are commonly used but have limitations due to their reliance on mass. Inerters, which enhance the mass effect without adding physical weight, offer a promising solution, especially in large civil structures. Fluid inerters are particularly easier to design require lower maintenance and provide significant importance with minimal mass. The paper presents a comprehensive nonlinear mechanical model that accounts for factors like fluid compressibility and air entrapment, improving performance predictions. Experimental validation of this model shows strong alignment with real-world results. The authors suggest future research should focus on scaling effects, long-term stability, and integrating these models into broader passive control frameworks to enhance simulation accuracy.

Salah et al.,[2] present a study on the "Optimum Double Mass Tuned Damper Inerter for Control of Structure Subjected to Ground Motions" reviews the development and enhancement of Tuned Mass Dampers (TMDs) through the integration of inerters. TMDs, introduced in 1909, effectively reduce vibrations in structures, but their performance is often limited by the need for large masses, which can be costly and space-consuming. The incorporation of inerters, which produce a force proportional to acceleration without adding significant mass, offers a promising solution to this problem. Tuned Mass Damper Inerters (TMDIs) combine traditional TMDs with inerters to enhance vibration control, improving seismic response and reducing the required mass. Optimization studies, including the use of genetic algorithms, have demonstrated that TMDIs can significantly improve peak displacement, acceleration, and base shear. The paper also explores various configurations of TMDIs, such as grounded versus ungrounded systems, and suggests that grounding the inerter generally leads to better performance. Furthermore, the use of multi-TMD configurations, with several TMDs arranged in parallel or series, is being investigated to enhance vibration control in large structures. This literature survey underscores the evolution of TMD technology and ongoing research aimed at optimizing these systems for seismic applications.

Yuehao et al.,[3] present a study on the "Physical Realizations of Inerter and Inerter-Based Vibration Control" reviews the development and applications of the inerter, a two-terminal dynamic element introduced in 2002. It highlights the inerter's significant advancement in filling a gap in mechanical systems, akin to the function of a capacitor in electrical systems. Over the past two decades, the use of inerters has expanded across various applications, including vehicle suspension, building and bridge vibration control, landing gear buffers, and energy harvesting. The paper discusses several physical realizations of the inerter, such as rack-and-pinion, hydraulic, and electromechanical systems, each tailored to specific mechanical needs. Inerter-based vibration control systems are categorized into three main methods, demonstrating their broad applicability across multiple engineering fields. The paper also outlines the normative derivation processes used to understand the dynamics of these systems and concludes by identifying future research opportunities in innovation and applications of inerter-based vibration control. This survey provides an extensive overview of the inerter's evolution, its diverse uses, and ongoing potential in vibration control technologies.

Qigang et al.,[4] present a study on the "Optimal design for a novel inerter-based clutching tuned mass damper system" explores advancements in vibration control systems, particularly focusing on the evolution of Tuned Mass Dampers (TMDs) and their enhancements through inerters. Traditional TMDs, while effective in controlling vibrations, face challenges in achieving optimal damping levels due to complex damping elements. Alternative systems, such as impact dampers and Pounding Tuned Mass Dampers (PTMDs), offer simpler designs but also introduce new complications in performance evaluation. Introducing inerter-based devices like the Rotational Inertia Double Tuned Mass Damper (RIDTMD) and the Tuned Inerter Damper (TID) has significantly improved vibration suppression. The novel Clutching Inerter Damper (CID) replaces traditional damping elements in TMDs by converting translational kinetic energy into rotational energy, enhancing design flexibility. The paper discusses the performance evaluation of the Clutching Tuned Mass Damper (CTMD) system, which involves equivalent linearization to optimize design parameters. Future research is suggested to explore dynamic testing of the CTMD system to improve its performance further and address challenges

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inherent in traditional TMD designs. This survey highlights the promising potential of the CID and CTMD in advancing vibration control technologies.

Djerouni et al.,[5] present a study on the "Optimal Seismic Response Using a Passive Tuned Mass Damper Inerter (TMDI)" reviews the development and application of inerters, particularly focusing on the Tuned Mass Damper Inerter (TMDI). The concept of the inerter, introduced in 2002 for automotive applications, generates forces proportional to relative acceleration and has since been adapted for structural vibration control. The TMDI combines the traditional Tuned Mass Damper (TMD) with an inerter, improving performance while reducing the required mass, making it more efficient for mitigating vibrations, especially in base-isolated structures. The TMDI offers installation flexibility, as it can be placed on any floor of a building, unlike conventional TMDs that are usually positioned at the top or bottom. The paper highlights that TMDIs significantly enhance vibration suppression, especially for seismic activity, and presents them as a promising solution in the ongoing challenge of developing effective vibration suppression systems in civil engineering.

Salah et al.,[6] present a study on the "A Tuned Mass Damper Inerter Control Device for Base Isolated Structures" examines advancements in seismic vibration control, focusing on the integration of tuned mass dampers (TMDs) with inerters. TMDs, widely used for mitigating structural vibrations, rely on mass, which can increase load and space requirements. The introduction of the inerter, a device that amplifies mass through rotational inertia, enhances the performance of TMDs, leading to the development of Tuned Mass Damper Inerters (TMDI). The paper also highlights base isolation (BI) systems, which reduce seismic responses by shifting a structure's frequency, but often require additional systems like TMDIs to handle large deformations. Through dynamic analysis of an eight-story structure, the study demonstrates that TMDIs significantly improve performance over conventional TMDs, particularly in reducing bearing displacement and top floor acceleration during seismic events. The paper underscores the potential of combining TMDIs with base isolation to optimize seismic resilience without complex optimization algorithms.

Sijie et al.,[7] present a study on the "A Unified Method for Parameter Optimization and Dynamic Characteristics Analysis of Tuned Mass Damper Inerter" reviews the evolution of vibration control technologies, focusing on the enhancement of traditional Tuned Mass Dampers (TMDs) through the integration of inerters. TMDs, effective in mitigating vibrations, rely heavily on added mass, which can pose design challenges, especially in large structures like long-span bridges. The introduction of inerters, which amplify mass and offer negative stiffness effects, has expanded the capabilities of vibration control systems. The paper highlights the development of Tuned Mass Damper Inerters (TMDIs), combining TMDs with inerters to reduce mass requirements and improve performance, particularly in low-frequency applications. Additionally, the study proposes a unified design approach for TMDIs, linking them to traditional TMDs through a complex effective mass concept, enhancing understanding of their dynamic characteristics. This work paves the way for further research on optimizing TMDIs for improved vibration suppression in engineering applications.

Yuji et al.,[8] present a study on the Optimal design and performance analysis of a tuned negative-stiffness inerter mass damper for vibration control systems: This study explores the design, optimization, and performance evaluation of a Tuned Negative Inerter Mass Damper (TNIMD) for vibration control in structures. It emphasizes the combination of inerters with negative stiffness elements to enhance energy dissipation and reduce vibration responses without compromising system stability. The TNIMD integrates mass, damping, stiffness, and inertance elements, and its performance is optimized using $\mathbf{H}_\infty$ and $\mathbf{H}_2$ techniques, including genetic algorithms. Stability analysis is performed using the Routh-Hurwitz criterion, while sensitivity analysis (via Sobol’s method) identifies key parameters like stiffness and inertance that significantly impact performance. TNIMDs show superior vibration isolation under harmonic, random, and seismic excitations compared to conventional dampers. Results highlight the effectiveness of optimal parameter tuning, particularly for seismic applications, and encourage further research for analytical solutions under seismic loads.

Mohammad et al.,[9] present a study on the proposes an active inerter-based tuned mass damper (ATMDI) for seismic vibration control, where a fuzzy logic controller (FLC) is optimized via a genetic algorithm (GA). Its key innovation is using GA not only to select the best passive TMDI configuration but also to tune twelve FLC parameters—including membership functions, inference rules, and input/output gains—to maximize vibration mitigation with minimal added mass. First, various passive TMDI layouts are evaluated on a three-story shear-frame model under seismic excitation. GA identifies the PTMDI-II configuration—installed between the top two floors with its inerter linked to the penultimate floor—as the most practical, achieving a 56% reduction in peak top-story displacement and a 44% drop in RMS displacement compared to the uncontrolled case. Building on this, the same layout is equipped with an actuator governed by the GA-optimized FLC (ATMDI-II). Under the El Centro ground motion, ATMDI-II (with just a 2% added mass ratio) reduces peak top-story displacement and acceleration by 72% each, and RMS responses by 72% and 65%, respectively outperforming an equivalent active TMD without inerter despite its higher 3% mass ratio.

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Overall, the study demonstrates that integrating an inerter with a GA-tuned FLC yields a high-performance, feasible control device that significantly attenuates seismic-induced motion in multi-story buildings, suggesting strong potential for future applications in high-rise and wind-excited structures.

Hao-ding et al.,[10] this study presents a novel DNS-TLID (Damping Net and Sloped-bottom Tuned Liquid Inerter Damper), developed to address the limitations of traditional Tuned Liquid Dampers (TLDs), such as large water requirements and low damping efficiency. The DNS-TLID combines a rack-and-pinion inerter, a damping net, and a sloped-bottom liquid tank to enhance damping capacity and achieve lightweight vibration control. The paper proposes a mechanical model for the DNS-TLID-SDOF system, derives the damping ratio calculation formula, and introduces a method to estimate the equivalent liquid motion velocity. Shaking table tests on a single-story steel frame validate the proposed model and confirm the superior damping performance of DNS-TLID compared to traditional TLDs, DNS-TLDs, and TLIDs. The DNS-TLID achieves better vibration control with reduced liquid mass, indicating significant potential for practical engineering applications where lightweight and efficient damping is essential.

III. RESULT

- Single Degree of Freedom (SDOF) System

equation of motion for mass m_1 in the Laplace domain can be written as,

$$m_1 s^2 X_1 + k(X_1 - R) = F_{1,0}$$

equation of motion for the inertance b_d in the Laplace domain can be written as,

$$b_d s^2 (Y - R) = k_d (X_1 - Y) + c_d s (X_1 - Y)$$

$$\therefore Y = \frac{b_d s^2 R + (k_d + c_d s) X_1}{b_d s^2 + k_d + c_d s}$$

where, $F_{1,0} = (k_d + c_d s)(Y - X_1)$

After Solving equations to find X_1, the equation of X_1 as,

$$\therefore X_1 = \frac{(k + T_d) R}{m_1 s^2 + k + T_d}$$

$$where,\ T_d = \frac{b_d s^2 (k_d + c_d s)}{b_d s^2 + k_d + c_d s}$$

Remove all the complex terms from the above equation, we can perform the following operation

$$\therefore \frac{X_1}{R} = \sqrt{\frac{(k k_d - k b_d \omega^2 - b_d k_d \omega^2)^2 + {c_d}^2 \omega^2 (k - b_d \omega^2)^2}{\left((k - m_1 \omega^2)(k_d - b_d \omega^2) - b_d k_d \omega^2\right)^2 + {c_d}^2 \omega^2 (k - m_1 \omega^2 - b_d \omega^2)^2}}$$

- SDOF system is defined by the following parameters,

m_1 = 1000 kg, k = 5000 kN/m, c_d = 2500 Ns/m

After performing the surrogate optimization for the above-mentioned parameters, the damper properties are, k_d = 602.17 kN/m and b_d = 138.03 kg

- SDOF system is defined by the parameters (m, k, c_d) and then surrogate optimization are performed.

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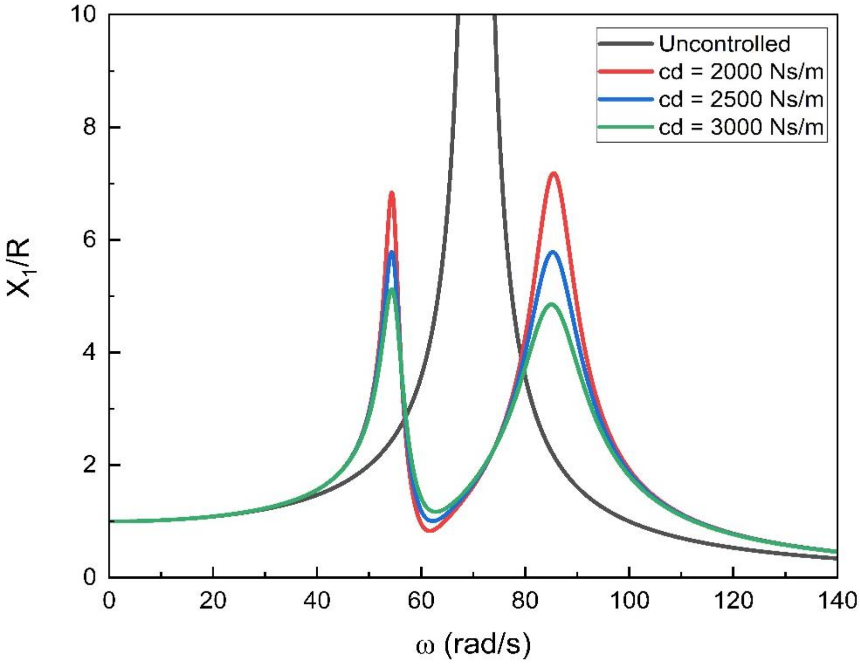

Figure 1 Results of Optimization of SDOF system

- Equation of motion for a single degree of freedom

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}g$$

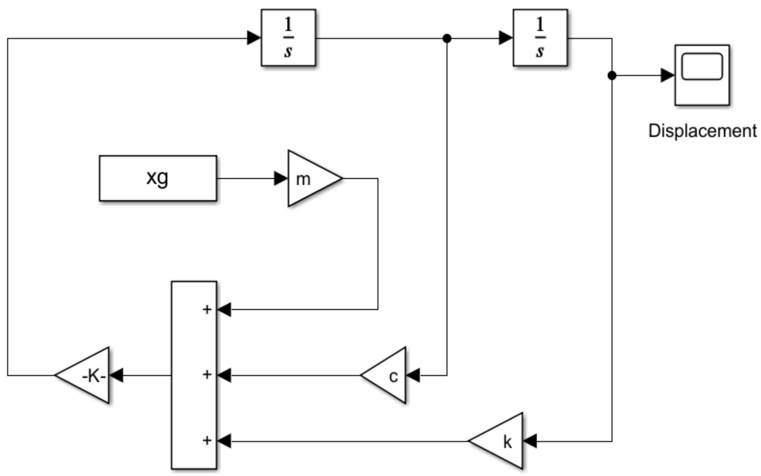

Figure 2 Simulink Model of SDOF System

- Multiple Degree of Freedom (MDOF) System

Surrogate optimizations are performed on the objective function made from the transfer function same as the SDOF system from above equation.

m = 1000 kg for each floor, k = 5000 kN/m for each floor and c_d = 2500 Ns/m.

After performing the optimization, damper parameter values are k_d = 538.58 kN/m and b_d = 536 kg.

- MDOF system is defined by the parameters (m, k, c_d) and then surrogate optimization are performed
- Equation of motion for a 2 degree of freedom

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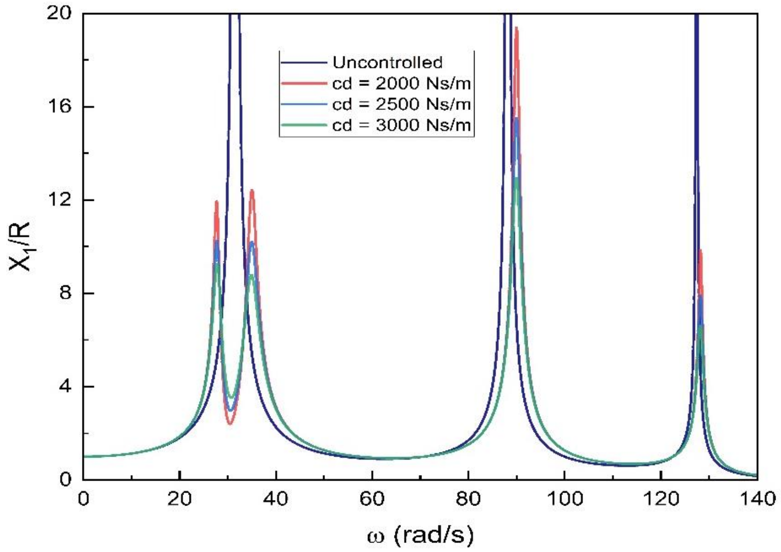

Figure 3 Result of Optimization of MDOF system

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 = -\ddot{x}_g m_1$$

$$m_1\ddot{x}_1 + (c_1 + c_2)\dot{x}_1 + (k_1 + k_2)x_1 - c_2\dot{x}_2 + k_2x_2 = -\ddot{x}_g m_1$$

$$m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) = 0$$

- SDOF system with inherent Structural damping

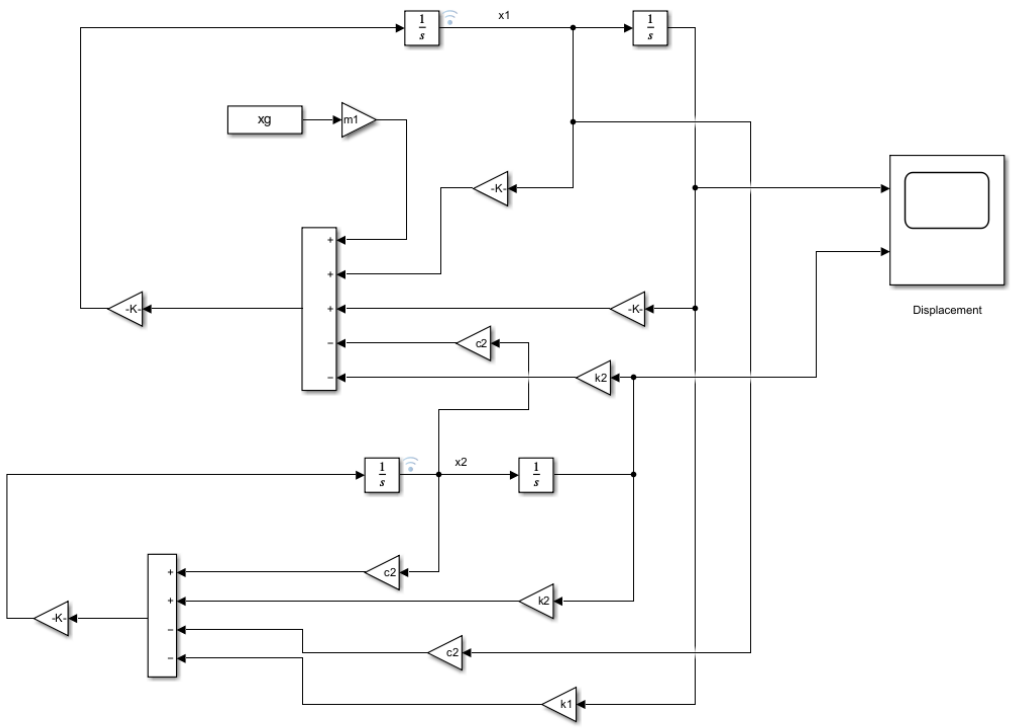

Figure 4 Simulink Model of SDOF System

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Table 1 SDOF system with the effect of inherent damping ratio

Sr no.	System	ξ	Damper Parameters			Peak of the Transfer function
			k_d (kN/m)	b_d (kg)	c_d (kNs/m)	
1	With Inherent Damping	0%	499.71	122.62	2.5	4.29
2	With Inherent Damping	3%	496.44	115.38	2.5	3.56
3	With Inherent Damping	5%	490.18	114.92	2.5	3.24

Table 3 Peak response and optimal parameters for various mass ratio

R1				
μ	EMD	γ^{opt}	ξ^{opt}	H_x
0.01	0.1	0.985	0.149	6.857
0.02	0.12	0.974	0.189	5.862
0.03	0.136	0.963	0.219	5.33
0.04	0.149	0.952	0.244	4.984
0.05	0.161	0.942	0.266	4.735

Table 2 Peak response and optimal parameters for various mass ratio

R2				
μ	EMD	γ^{opt}	ξ^{opt}	H_x
0.01	0.1	0.995	0.149	7.043
0.02	0.121	0.987	0.189	6.146
0.03	0.137	0.979	0.219	5.654
0.04	0.15	0.971	0.244	5.326
0.05	0.162	0.963	0.266	5.086

Table 5 Peak response and optimal parameters for various mass ratio

R3				
μ	EMD	γ^{opt}	ξ^{opt}	H_x
0.01	0.05	0.985	0.05	6.912
0.02	0.071	0.974	0.091	6.074
0.03	0.087	0.963	0.122	5.584
0.04	0.101	0.952	0.148	5.247
0.05	0.113	0.942	0.17	4.997

Table 4 Peak response and optimal parameters for various mass ratio

R4				
μ	EMD	γ^{opt}	ξ^{opt}	H_x
0.01	0.05	0.995	0.05	7.235
0.02	0.071	0.987	0.091	6.446
0.03	0.087	0.979	0.122	5.973
0.04	0.101	0.971	0.148	5.643
0.05	0.113	0.963	0.17	5.394

- From table 3-5 represent results comparing the performance of a tuned mass damper (TMD) under different configurations labeled R1, R2, R3, R4 and U/C (Uncontrolled**)**.

IV. SUMMARY

This review paper presents the development and improvement of Tuned Mass Dampers (TMDs) by including inerters—mechanical devices that generate a force proportionate to relative acceleration—is thoroughly covered in this review study [1-10]. Inerters were first used in the automobile industry but have since been modified for use in civil engineering applications to enhance vibration control, particularly when seismic loads are present [40-45]. Despite their effectiveness in lowering structural vibrations, traditional TMDs are constrained by their reliance on high mass ratios [10-12]. The Tuned Mass Damper Inerter (TMDI) or Tuned Mass Inerter Damper (TMID) concept has been developed as a solution to these limitations [13-15]. These systems are ideal for retrofitting tall structures and improving earthquake resistance because they increase inertial effects without adding physical bulk [45-49].

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A range of TMDI setups and advancements are covered in the paper's literature review, including:
• Fluid inerters: a simpler design that requires less maintenance and effectively simulates bulk [30-35].
• Clutching Mechanisms: Convert translational motion to rotational motion to enhance energy dissipation [79-83].
• Elements of Negative Stiffness: Improve energy absorption while preserving system stability [70-75].
• Hybrid Systems: Mix active control systems like genetic algorithms (GA) and fuzzy logic controllers (FLC) with passive [71-75].
• DNS-TLID Systems: Effective lightweight damping achieved by integrating liquid-based dampers with inerters [16-20].

To attain the best damper designs for both SDOF and MDOF systems, the review emphasises optimisation techniques such surrogate modelling and GA-based parameter adjustment [65-71]. Multiple studies' performance analysis consistently shows that TMDIs outperform traditional TMDs in reducing base shear, acceleration, and structural displacement [72-78].
The study also includes optimization study results that demonstrate that, even at low mass ratios, TID (Tuned Inerter Damper) devices considerably lessen the displacement of the top story caused by the mass magnification effect [11-15]. These findings support the notion that the TMDI approach holds promise for addressing contemporary structural vibration control issues [45-49].

V. CONCLUSION

The substantial improvements in vibration control made possible by the incorporation of inerters into traditional Tuned Mass Dampers have been emphasised in this review. For tall or modified structures, the Tuned Mass Damper Inerter (TMDI) systems are more viable since they increase the inertial force without requiring enormous physical masses. Numerous studies have shown that TMDIs offer greater seismic response reduction, particularly when optimised or equipped with extra features like fluid damping, clutch mechanisms, or active control systems. The reviewed literature confirms TMDIs can dramatically lower displacement, acceleration, and base shear under seismic stress, according to the reviewed research. Additionally, the application of surrogate optimisation techniques allows for accurate damper parameter setting, guaranteeing efficacy across a range of structural configurations. The significance of TMIDs as a dependable and effective structural vibration control solution will be further cemented by ongoing research in this field, particularly into long-term performance, practical implementation, and interaction with base-isolation systems.

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