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Trade-Off Analysis Between Displacement and Acceleration in TMD-Equipped Structures using Pareto Optimization.

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Abstract - Vibration control in multi-degree-of-freedom (MDOF) structures is essential for maintaining safety and performance under dynamic loads such as wind and earthquakes. Among passive control techniques, the Tuned Mass Damper (TMD) is recognized as an effective and practical solution for reducing excessive structural responses. This study systematically evaluates the influence of mass ratio and damping ratio on the vibration behaviour of MDOF structures equipped with a TMD, aiming to identify optimal parameter combinations that minimize displacement and acceleration. A MATLAB-based analytical model is developed to simulate the structural response under dynamic loading while systematically varying key TMD parameters. The dynamic behaviour of both the primary structure and the TMD is evaluated using maximum displacement and acceleration measures, supported by graphical analysis to observe performance trends. Pareto front analysis is employed to identify optimal trade-offs between competing objectives, enabling simultaneous minimization of displacement and acceleration. The results demonstrate that mass ratio and damping ratio significantly affect TMD performance, and their proper selection is crucial for achieving balanced and efficient vibration control. The findings provide a systematic framework for optimizing TMD design in MDOF structures, contributing to improved vibration mitigation and enhanced structural reliability.

KEY WORDS : trade-off analysis between displacement and Acceleration in tmd-equipped structures using Pareto optimization.

INTRODUCTION

Modern structural systems continuously experience environmental and seismic disturbances that induce dynamic responses affecting both safety and serviceability.. To address these challenges, various vibration control devices have been developed to reduce structural response and enhance stability. These devices are broadly classified as passive, semi-active, and active systems, with passive systems being the most widely used due to their simplicity, reliability, and no requirement for external power. Common examples include base isolation systems and tuned mass dampers (TMDs).

The concept of vibration control dates back to 1928, when Ormondroyd and Den Hartog introduced the dynamic vibration absorber, which later evolved into modern TMD systems. A TMD consists of a mass, spring, and viscous damper, designed to oscillate out of phase with the structure to reduce vibration amplitude. Advancements in this field have led to the development of multiple tuned mass dampers (MTMDs), which provide improved performance over a wider frequency range. Studies indicate that MTMDs can reduce structural motion by 40% to 60% with an added mass of about 5% of the building mass. However, their effectiveness depends on proper parameter optimization, including damping ratio, stiffness, and tuning frequency. Increasing the number of dampers enhances frequency bandwidth but reduces the optimal damping ratio, and issues such as modal contamination may affect performance.

Vibration mitigation is essential for ensuring structural safety, preventing damage, and improving occupant comfort, especially in tall buildings sensitive to wind and seismic effects. Uncontrolled vibrations can lead to structural failure, whereas properly designed systems can significantly reduce seismic damage and even prevent collapse. Recent studies emphasize damage-based evaluation, showing that TMDs can reduce structural damage and, in some cases, provide performance equivalent to increasing structural yield strength by up to 45%.

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Optimization plays a critical role in achieving effective vibration control. While conventional frequency-domain methods are commonly used, they often fail to account for variations in loading conditions. To overcome these limitations, robust optimization techniques have been developed, which consider uncertainties in structural properties and external excitations, leading to more reliable and efficient vibration control solutions.

OVERVIEW OF PASSIVE CONTROL DEVICES.

Passive control devices are widely used in structural systems because they operate without external energy and rely on inherent mechanical properties. Among these, tuned mass dampers (TMDs) are the most commonly adopted, consisting of a mass–spring–damper arrangement tuned to the structure's natural frequency to absorb and dissipate vibrational energy. Multiple TMDs (MTMDs) offer improved performance across a broader frequency range, though their effectiveness depends on proper tuning and parameter selection. Other passive systems, such as base isolation, further reduce seismic energy transfer by isolating the structure from ground motion.

Advanced TMD forms—including pendulum-based and magnetically tuned dampers—provide greater adaptability and have been verified through experimental studies. Environmentally integrated concepts like roof garden TMDs also contribute to vibration control while enhancing sustainability. Research indicates that TMD performance is strongly influenced by mass ratio, structural features, components, elements, properties, and excitation type, reinforcing the need for optimized design.

Case studies on reinforced concrete and steel buildings demonstrate that TMDs significantly reduce displacement, drift, and damage, especially when placed at optimal positions within the structure. Overall, passive control devices, particularly TMD-based systems, remain effective solutions for improving stability and seismic performance. Additionally, the use of Pareto frontier curves helps identify optimal trade-offs between displacement and acceleration. A sample case study further illustrates the application and effectiveness of this approach.

AIM

The aim of this study is to evaluate and optimize the performance of a single tuned mass damper (STMD) using a state-space simulation approach in MATLAB by analysing the trade-off between structural displacement and acceleration. The study focuses on identifying optimal values of mass ratio (μ), damping ratio (ζ), and stiffness through Pareto-based analysis, and quantifying the reduction in structural response achieved under dynamic loading conditions.

OBJECTIVES

The objectives of this study are to analyse the influence of key tuned mass damper (TMD) parameters—mass ratio (μ), damping ratio (ζ), and stiffness—on structural displacement and acceleration while keeping the structural properties constant. The work aims to examine the combined response of both the structure and the TMD under dynamic loading to better understand their interaction. A simple and user-friendly MATLAB framework is developed to allow easy modification of input parameters and to help identify optimal TMD values. The study also focuses on generating response data for various parameter combinations to enable effective comparison of TMD performance. The main objective is to plot a Pareto trade-off curve that highlights the relationship between displacement and acceleration, thereby determining the optimum mass ratio, damping ratio, and stiffness. Additionally, the study evaluates the overall reduction in displacement and acceleration achieved for different TMD parameter sets.

LITERATURE REVIEW

Structural vibration control has become essential for safeguarding modern flexible structures against **seismic and dynamic loads**. Early foundational work by Frahm (1909) introduced the concept of tuned mass dampers (TMD), which was later theoretically developed by Ormondroyd and Den Hartog (1928), establishing the principle of dynamic vibration absorbers. These studies laid the groundwork for passive control strategies, where energy is dissipated without external power input. Over time, passive control systems such as TMDs gained popularity due to their simplicity, reliability, and cost-effectiveness in mitigating structural vibrations.

Chang (1999) provided one of the earliest comprehensive studies on optimal TMD design for buildings subjected to wind and earthquake loads. The study derived closed-form solutions for TMD parameters, highlighting the importance of **mass ratio, stiffness, and damping**. Similarly, Rana and Soong (1998) conducted a parametric study demonstrating how properly tuned dampers significantly reduce structural responses, particularly displacement and acceleration in multi-degree-of-freedom systems.

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Farshidianfar and Soheili (2013) utilized the ant colony optimization algorithm to optimize TMDs considering soil–structure interaction effects. Their results showed significant reductions in displacement and acceleration responses of high-rise buildings. Similarly, Mohebbi et al. (2013) employed genetic algorithms to design multiple TMD systems, highlighting **improved seismic performance compared to single TMD** configurations.

Recent advancements include the development of double tuned mass dampers (DTMD). Fasil and Sajeeb (2019) introduced DTMDs capable of controlling multiple vibration modes simultaneously. Their study demonstrates quantitatively enhanced performance over conventional TMDs, particularly in reducing displacement and base shear. Sun and Nagarajaiah (2014) explored semi-active TMD systems with variable stiffness and damping, bridging the gap between **passive and active** control systems.

Kamgar et al. (2025) examined the role of TMDs in mitigating seismic pounding between adjacent buildings. Their results demonstrated that TMD systems effectively reduce impact forces and prevent severe structural damage. Mashayekhi et al. (2023) compared **PSO, WOA, and hybrid optimization techniques for TMD design**, concluding that hybrid methods provide superior optimization efficiency.

Overall, the literature indicates that while passive TMDs remain widely used due to their simplicity, **advanced configurations such as MTMD and DTMD, combined with modern optimization algorithms**, significantly enhance vibration control performance. The integration of metaheuristic optimization techniques has emerged as a powerful tool for achieving optimal TMD parameters in complex structural systems, especially under seismic loading conditions.

MATLAB-based modelling has become a powerful tool for analysing and designing TMD systems. Banerjee and Ghosh (2020) used **MATLAB simulations to optimize TMD parameters for base-excited structures, demonstrating improved displacement control**. Islam et al. (2018) applied response surface methodology integrated with MATLAB to perform multi-objective optimization of TMDs in frame structures. Their results showed that MATLAB-based approaches enable accurate modelling and efficient optimization of complex structural systems.

Further studies have explored numerical modelling frameworks. McKenna (2011) **introduced OpenSees, often integrated with MATLAB**, for simulating structural response under seismic loading. This combination allows advanced nonlinear analysis and validation of TMD performance. Greco et al. (2018) also **demonstrated numerical integration methods for nonlinear dynamic analysis, which are essential for realistic modelling** of damped systems.

The importance of **passive dampers in comparison to active and semi-active systems has been widely discussed**. Spencer et al. (1999) highlighted that although active control systems provide adaptability, they require external energy and complex control mechanisms. In contrast, passive systems like TMDs remain more reliable and cost-effective for large-scale structures. Ben Mekki et al. (2012) studied semi-active TMDs and concluded that while they improve adaptability, passive systems still dominate due to ease of implementation.

Optimization techniques for TMD parameters have evolved significantly. Li and Ni (2007) systematically evaluated non-uniform distribution of MTMDs and demonstrated improved performance through optimized placement. Li (2004) examined the influence of ground motion frequency on MTMD design, emphasizing the importance of tuning across multiple modes. Deb et al. (2002) **introduced NSGA-II, a widely used multi-objective optimization algorithm**, which has been **applied extensively in TMD optimization problems**.

Recent investigations continue to reinforce the importance of optimal design and tuning. Ras (2024) conducted a **parametric study on TMD performance under near-fault and far-field earthquakes**, concluding that optimal tuning significantly affects structural response. Shahraki et al. (2023) proposed damage-based design methods for MTMD systems, emphasizing performance-based optimization. Mazzon et al. (2023) confirmed that properly tuned TMDs significantly reduce seismic damage in mid-rise buildings.

Overall, the reviewed literature clearly demonstrates that passive TMD systems remain one of the most effective and practical solutions for vibration control. However, their performance is highly dependent on **proper tuning and optimal parameter selection**. The integration of **MATLAB-based modelling and advanced optimization algorithms** has significantly enhanced the design process, enabling engineers to achieve robust and **efficient vibration control solutions for complex structural systems.**

Further advancements were made by Abed and Moustachi (2022), who systematically evaluated the Pareto optimal design of single TMD systems considering multiple performance indices such as displacement and acceleration. **Their study identified a**

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set of non-dominated solutions forming a Pareto front, which represents the optimal balance between competing objectives like stiffness and damping. The results highlighted that no single "best" solution exists; instead, engineers must choose an **optimal design based on performance priorities.**

A more recent contribution by researchers in 2023 introduced an integrated multi-criteria decision-making (MCDM) framework to rank Pareto-optimal solutions obtained from TMD optimization problems. The study used **NSGA-II to generate a Pareto front and then applied decision-making techniques such as AHP and TOPSIS to select the most suitable solution from the Pareto set.** This approach addressed a key limitation of traditional Pareto optimization—difficulty in selecting a final design—by systematically identifying the "best compromise" solution.

COMPARISON BETWEEN STUDIES

Traditional vs. Advanced Methods:

Traditional studies (Chang 1999, Rana & Soong 1998) focused on closed-form solutions for single TMD systems

Advanced methods (Farshidianfar & Soheili 2013, Mohebbi et al. 2013) employ metaheuristic optimization for complex, multi-objective problems

Recent work (Abdel & Moustachi 2022, 2023) integrates Pareto optimization with MCDM frameworks for decision-making

Single vs. Multiple TMD Systems:

Early research concentrated on single TMDs with optimal tuning for fundamental frequencies

Later studies (Mohebbi et al. 2013, Akhlagh Pasand & Zahrai 2024) demonstrate superior performance of multiple TMDs in controlling higher modes

Distributed MTMDs show particular effectiveness in tall buildings (Akhlagh Pasand & Zahrai 2024)

Passive vs. Semi-Active Systems:

Passive systems (Villaverde & Koyoama 1993, Pinkaew et al. 2003) remain dominant due to reliability and cost-effectiveness

Semi-active approaches (Sun & Nagarajaiah 2014) offer improved adaptability but require more complex control systems

Research consistently shows passive systems provide better reliability for large-scale applications

Optimization Approaches:

Classical methods (Takewaki 2002, Marano et al. 2007, 2008) focused on robust design under uncertainties

Evolutionary algorithms (Deb et al. 2002, Li & Ni 2007) enable multi-objective optimization

Hybrid approaches (Mashayekhi et al. 2023) and Pareto-MCDM integration (2023) address decision-making complexity

Pareto Optimization Evolution in TMD Design

Early Pareto Applications: Abed and Moustachi (2022) pioneered the systematic application of Pareto optimization to TMD design, identifying that traditional single-objective approaches fail to capture the inherent trade-offs between competing performance indices like displacement and acceleration. Their work revealed that no single "optimal" solution exists when considering multiple structural response parameters simultaneously.

Integration with Multi-Objective Algorithms

The evolution from classical optimization to Pareto-based approaches represents a significant methodological advancement. While earlier studies like Takewaki (2002) and Marano et al. (2007, 2008) focused on robust design under uncertainties using single-objective frameworks, Pareto optimization embraces the multi-objective nature of structural design problems. Studies such as Deb et al. (2002) on NSGA-II provided the algorithmic foundation for generating Pareto fronts efficiently.

Practical Implications

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Pareto optimization has fundamentally changed TMD design philosophy by acknowledging that optimal design is context-dependent. As demonstrated by Li and Ni (2007) on non-uniform MTMD distribution, the Pareto approach enables engineers to choose designs that best align with specific project requirements, whether prioritizing displacement control, acceleration reduction, or cost-effectiveness.

METHODOLOGY

4.1 System Description

2-DOF Coupled System Modelling

The structure equipped with a Tuned Mass Damper (TMD) is modelled as a **two-degree-of-freedom (2-DOF) system**, consisting of a primary structure and a secondary mass (TMD). The TMD is attached to the main structure to reduce vibration through energy dissipation.

Primary Structure Parameters (for single floor of height 3m)

Mass m_s - 400,000 kg

Natural frequency f - 6.77 Hz

Angular frequency ω_s - 42.54 rad/s

Structural stiffness k_s - 7.23×10^8N/m

Damping coefficient c_s - 12.4×10^6Ns/m

Critical damping c_r - 1.07×10^7Ns/m

Damping ratio ζ_s - 0.116

Tuned Mass Damper Parameters

A TMD is added with the following properties:

- Mass: - Variable
- Stiffness: Variable
- Damping: Variable

Further analysis we have to put below values and analyse the structure.

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μ	m_d (kg)	k_d (N/m)	ζ_d	C_d (N.s/m)
0.02	8,000	1.42E7	0.086	2.9E5
0.05	20,000	3.44E7	0.137	7.1E5
0.08	32,000	5.35E7	0.173	1.3E6
0.10	40,000	6.57E7	0.192	1.8E6
0.12	48,000	7.74E7	0.207	2.3E6
0.15	60,000	9.43E7	0.227	3.1E6

Modelling Assumptions

- Linear elastic behaviour is assumed
- Viscous damping is considered
- Perfect coupling between structure and TMD
- External excitation applied to main structure only

MATHEMATICAL FORMULATION

1. Mathematical Model of TMD (2-DOF System)

A structure with a TMD is modelled as a coupled 2-degree-of-freedom system:

Let:

- $x_1(t)$= displacement of main structure
- $x_2(t)$= displacement of TMD

Equations of Motion

$$M\ddot{x}_1 + C\dot{x}_1 + Kx_1 + c(\dot{x}_1 - \dot{x}_2) + k(x_1 - x_2) = F(t)$$
$$m\ddot{x}_2 + c(\dot{x}_2 - \dot{x}_1) + k(x_2 - x_1) = 0$$

2. Matrix Form Representation

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\}$$

Where:

$$[M] = \begin{bmatrix} M & 0 \\ 0 & m \end{bmatrix}$$
$$[C] = \begin{bmatrix} C + c & -c \\ -c & c \end{bmatrix}$$
$$[K] = \begin{bmatrix} K + k & -k \\ -k & k \end{bmatrix}$$
$$\{F\} = \begin{bmatrix} F(t) \\ 0 \end{bmatrix}$$

3. Transfer Function of TMD System

Taking Laplace Transform (zero initial conditions):

$$(s^2[M] + s[C] + [K])\{X(s)\} = \{F(s)\}$$

Transfer Function Matrix

$$H(s) = \frac{X(s)}{F(s)} = (s^2[M] + s[C] + [K])^{-1}$$

Main Structure Transfer Function

$$H_1(s) = \frac{X_1(s)}{F(s)}$$

This is obtained from the first row of inverse matrix.

4. State-Space Formulation (Used in MATLAB)

Convert to first-order system:

Let state vector:

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$$z = \begin{bmatrix} x_1 \\ x_2 \\ \dot{x}_1 \\ \dot{x}_2 \end{bmatrix}$$

State Equation

$$\dot{z} = Az + Bu$$

Where:

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -M^{-1}K & -M^{-1}C & & \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ M^{-1} \end{bmatrix}$$

This matches your MATLAB implementation.

5. Solution Procedure (Step-by-Step)

Step 1: Define System Parameters

- Mass: M, m
- Damping: C, c
- Stiffness: K, k

Step 2: Form Matrices

$$[M], [C], [K]$$

Step 3: Convert to State-Space

- Build matrix $A$and B

Step 4: Apply External Force

Examples:

- Step load
- Harmonic load
- Earthquake/random excitation

Step 5: Solve Numerically

Using:

- MATLAB lsim() (as in your code)
- or numerical integration methods:
  - Newmark-β
  - Runge-Kutta

Step 6: Extract Results

- Displacement x_1, x_2
- Velocity $v = \dot{x}$
- Acceleration $a = \ddot{x}$

6. MATLAB IMPLEMENTATION (CODE)s

</> **MATLAB**

```
% Tuned Mass Damper (TMD) Model
clear; clc; close all;

%% System Parameters
M = 400000; % Main mass (kg)
C = 12400000; % Main damping coefficient (Ns/m)
K = 723000000; % Main stiffness (N/m)

m = 8000; % TMD mass (kg)
c = 2.9E+6; % TMD damping coefficient (Ns/m)
k = 1.42E+7; % TMD stiffness (N/m)
dt = 0.001; % Time step (s)
t_final = 20; % Final simulation time (s)
t = 0:dt:t_final;

%% State-Space Model Setup
M_matrix = [M 0; 0 m];
C_matrix = [C -c; -c c];
K_matrix = [K -k; -k k];

C_total = [C -c; -c c];
```

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```
% State-space matrices
A = [zeros(2) eye(2); -M_matrix\K_matrix -M_matrix\C_total];

% Build B matrix properly
top_part = zeros(2,1);
bottom_part = -M_matrix * [1; 0];
B = [top_part; bottom_part];

C_out = [eye(2) zeros(2)];
D_out = zeros(2,1);

%% Simulation
x0 = [0; 0; 0; 0];
u = ones(size(t));

sys = ss(A, B, C_out, D_out);
[y, t] = lsim(sys, u, t, x0);

x1 = y(:,1); % Main structure displacement
x2 = y(:,2); % TMD displacement

v1 = gradient(x1, dt);
v2 = gradient(x2, dt);

a1 = gradient(v1, dt);
a2 = gradient(v2, dt);

%% Plot Results
figure('Position', [100, 100, 1200, 800]);

subplot(2,2,1);
plot(t, x1, 'b-', 'LineWidth', 2);
hold on;
plot(t, x2, 'r--', 'LineWidth', 2);
grid on;
xlabel('Time (s)');
ylabel('Displacement (m)');
title('Displacement Response');
legend('Main Structure', 'TMD', 'Location', 'best');

subplot(2,2,2);
plot(t, a1, 'b-', 'LineWidth', 2);
hold on;
plot(t, a2, 'r--', 'LineWidth', 2);
grid on;
xlabel('Time (s)');
ylabel('Acceleration (m/s^2)');
title('Acceleration Response');
legend('Main Structure', 'TMD', 'Location', 'best');

subplot(2,2,3);
plot(x1, v1, 'b-', 'LineWidth', 1.5);
hold on;
plot(x2, v2, 'r--', 'LineWidth', 1.5);
grid on;
xlabel('Displacement (m)');
ylabel('Velocity (m/s)');
title('Phase Portrait');
legend('Main Structure', 'TMD', 'Location', 'best');

subplot(2,2,4);
KE_main = 0.5 * M * v1.^2;
PE_main = 0.5 * K * x1.^2;
KE_TMD = 0.5 * m * v2.^2;
PE_TMD = 0.5 * k * x2.^2;

plot(t, KE_main, 'b-', 'LineWidth', 2);
hold on;
plot(t, PE_main, 'b--', 'LineWidth', 2);
plot(t, KE_TMD, 'r-', 'LineWidth', 2);
```

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```
plot(t, PE_TMD, 'r--', 'LineWidth', 2);
grid on;
xlabel('Time (s)');
ylabel('Energy (J)');
title('Energy Distribution');
legend('KE_Main', 'PE_Main', 'KE_TMD', 'PE_TMD',
'Location', 'best');
```

%% Natural Frequencies Analysis

```
[eig_vals, eig_vecs] = eig(K_matrix, M_matrix);
omega_n = sqrt(diag(eig_vals));
freq_hz = omega_n / (2*pi);

fprintf('Natural Frequencies of the Combined System:\n');
fprintf('Mode 1: %.4f Hz\n', freq_hz(1));
fprintf('Mode 2: %.4f Hz\n', freq_hz(2));

for i = 1:2
 phi = eig_vecs(:,i);
 zeta(i) = (phi' * C_total * phi) / (2 * sqrt(phi' * M_matrix *
phi * phi' * K_matrix * phi));
end
fprintf('Damping Ratios:\n');
fprintf('Mode 1: %.4f\n', zeta(1));
fprintf('Mode 2: %.4f\n', zeta(2));
```

%% Function for external excitation

```
function F = external_force(t, force_type, params)
 switch force_type
 case 'step'
 F = params(1) * ones(size(t));
 case 'sine'
 F = params(1) * sin(2*pi*params(2)*t);
 case 'impulse'
 F = params(1) * exp(-(t/params(2))^2) /
(sqrt(pi)*params(2));
 case 'random'
 F = params(1) * randn(size(t));
 otherwise
 F = zeros(size(t));
 end
end
```

%% Display Maximum Values in Command Window

```
% Calculate maximum absolute values
max_disp_main = max(abs(x1));
max_disp_TMD = max(abs(x2));
max_acc_main = max(abs(a1));
max_acc_TMD = max(abs(a2));

% Display results
fprintf('\n=== MAXIMUM RESPONSE VALUES ===\n');
fprintf('Maximum Displacement:\n');
fprintf('  Main Structure: %.6f m (%.2f mm)\n',
max_disp_main, max_disp_main*1000);
fprintf('  TMD:            %.6f m (%.2f mm)\n',
max_disp_TMD, max_disp_TMD*1000);

fprintf('Maximum Acceleration:\n');
fprintf('  Main Structure: %.6f m/s^2 (%.2f g)\n',
max_acc_main, max_acc_main/9.81);
fprintf('  TMD:            %.6f m/s^2 (%.2f g)\n',
max_acc_TMD, max_acc_TMD/9.81);

% Calculate and display reduction ratios
disp_reduction = (max_disp_TMD / max_disp_main) * 100;
acc_reduction = (max_acc_TMD / max_acc_main) * 100;
fprintf('\nResponse Reduction Ratios (TMD vs Main):\n');
fprintf('  Displacement Reduction: %.2f%%\n', 100 -
disp_reduction);
fprintf('  Acceleration Reduction: %.2f%%\n', 100 -
acc_reduction);

% Find time instants of maximum values
[max_disp_main_val, idx_max_disp_main] = max(abs(x1));
[max_disp_TMD_val, idx_max_disp_TMD] =
max(abs(x2));
```

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```
[max_acc_main_val, idx_max_acc_main] = max(abs(a1));

[max_acc_TMD_val, idx_max_acc_TMD] = max(abs(a2));


fprintf('\nTime instants of maximum response:\n');

fprintf('  Main Structure Max Displacement: t = %.4f s\n', t(idx_max_disp_main));

fprintf('  TMD Max Displacement:          t = %.4f s\n', t(idx_max_disp_TMD));

fprintf('  Main Structure Max Acceleration: t = %.4f s\n', t(idx_max_acc_main));

fprintf('  TMD Max Acceleration:          t = %.4f s\n', t(idx_max_acc_TMD));
```

RESULTS AND ANALYSIS

COMMON DATA FOR STRUCTURAL VALUES.

Primary Structure Parameters (for single floor of height 3m)

Mass m_s - 400,000 kg

Natural frequency f - 6.77 Hz

Angular frequency ω_s - 42.54 rad/s

Structural stiffness k_s - 7.23×10^8N/m

Damping coefficient c_s - 12.4×10^6Ns/m

Critical damping c_r - 1.07×10^7Ns/m

Damping ratio ζ_s - 0.116

μ	m_d (kg)	k_d (N/m)	ζ_d	C_d (N.s/m)
0.02	8,000	1.42E7	0.086	2.9E5
0.05	20,000	3.44E7	0.137	7.1E5
0.08	32,000	5.35E7	0.173	1.3E6
0.10	40,000	6.57E7	0.192	1.8E6
0.12	48,000	7.74E7	0.207	2.3E6
0.15	60,000	9.43E7	0.227	3.1E6

Ex.1) Values for TMD

- μ: 0.02
- m_d (kg): 8,000

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- k_d (N/m): 1.42E+7
- ζ_d: 0.086
- C_d (N·s/m): 2.9E+5

After putting required values in MATLAB code we get.

Result:-

MAXIMUM RESPONSE VALUES

Maximum Displacement:

Main Structure: 292.270893 m (292270.89 mm)

TMD: 364.226164 m (364226.16 mm)

Maximum Acceleration:

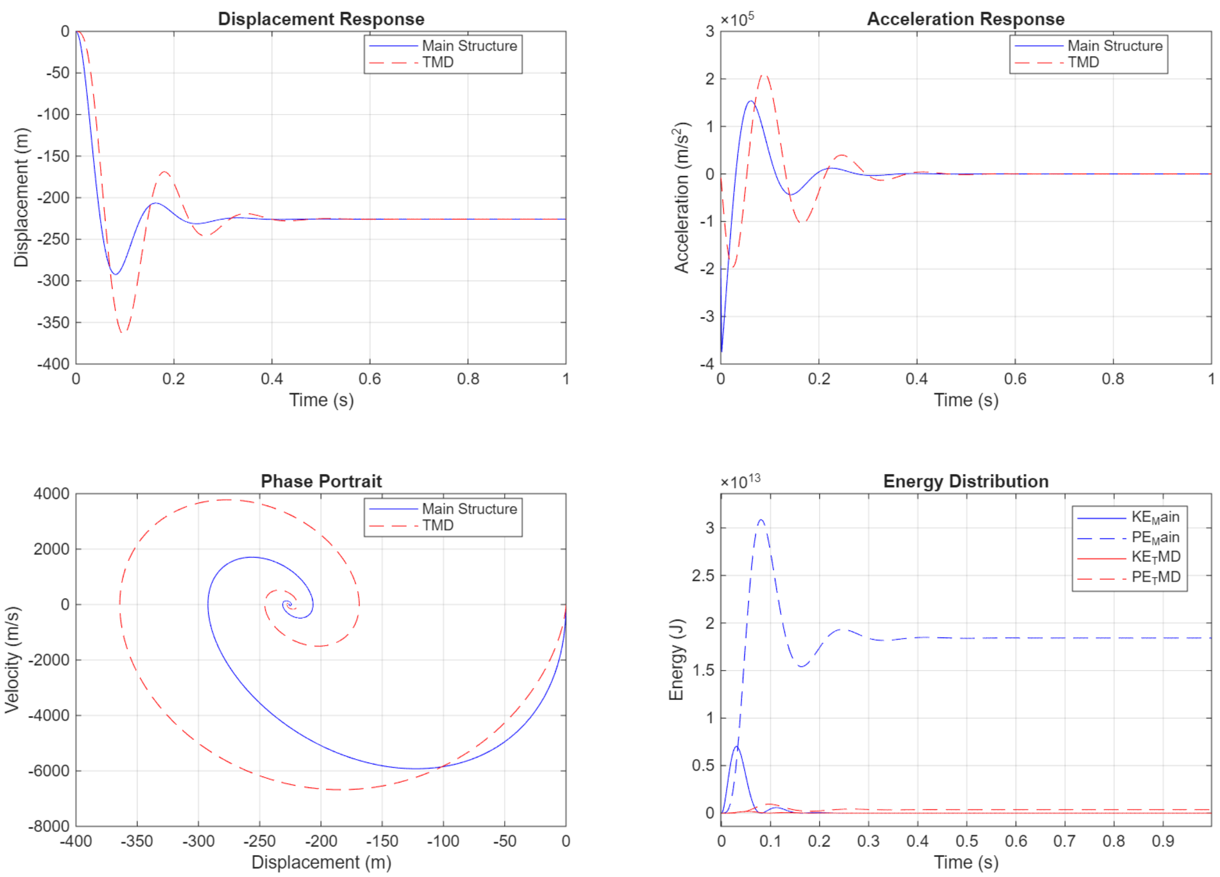
Main Structure: 374499.588986 m/s^2 (38175.29 g)

TMD: 212699.436817 m/s^2 (21681.90 g)

Response Reduction Ratios (TMD vs Main):

Displacement Reduction: -24.62%

Acceleration Reduction: 43.20%



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Ex.2) Values for TMD

- µ: 0.05
- m_d (kg): 20,000
- k_d (N/m): 3.44E+7
- ζ_d: 0.137
- C_d (N·s/m): 7.1E+5

Result:-

MAXIMUM RESPONSE VALUES

Maximum Displacement:

Main Structure: 301.742060 m (301742.06 mm)

TMD: 376.263910 m (376263.91 mm)

Maximum Acceleration:

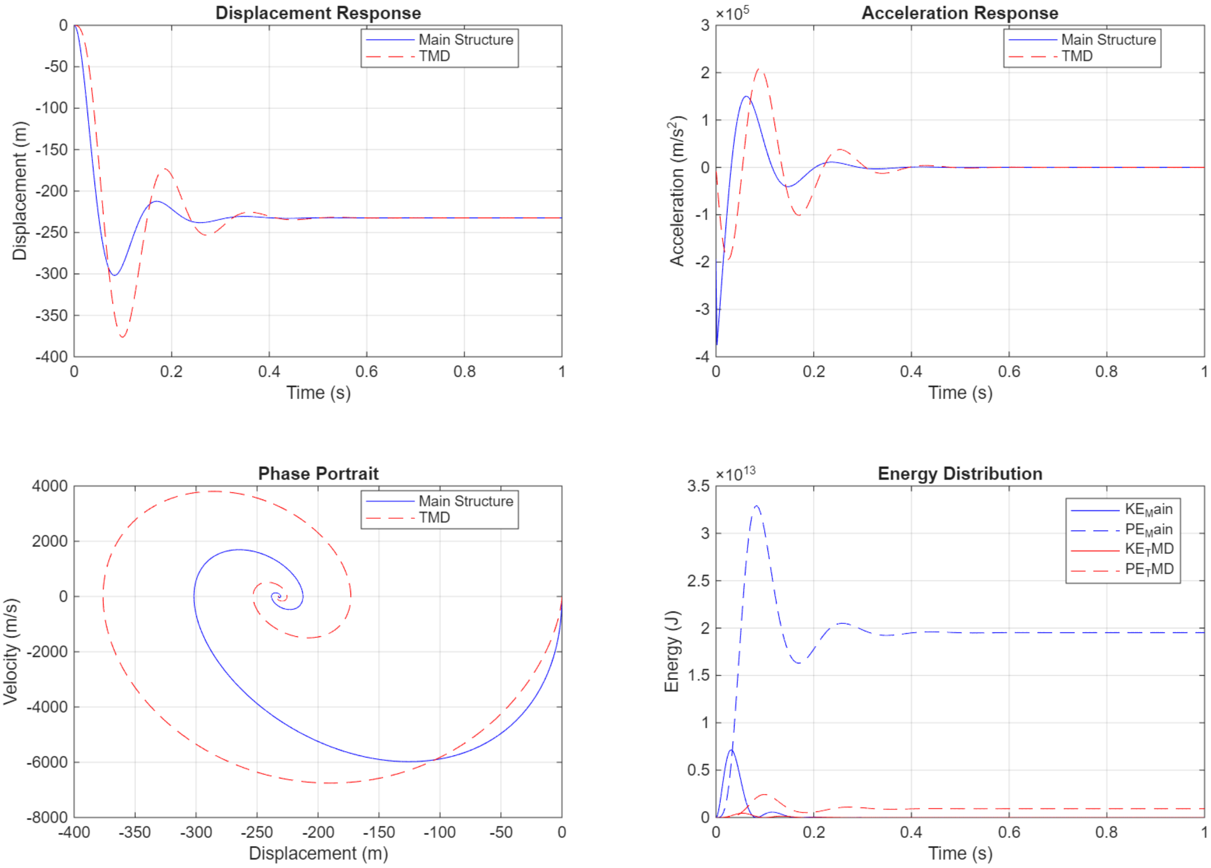
Main Structure: 374533.730304 m/s^2 (38178.77 g)

TMD: 209446.160953 m/s^2 (21350.27 g)

Response Reduction Ratios (TMD vs Main):

Displacement Reduction: -24.70%

Acceleration Reduction: 44.08%



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Ex.3) Values for TMD

- μ: 0.08
- m_d (kg): 32,000
- k_d (N/m): 5.35E+7
- ζ_d: 0.173
- C_d (N·s/m): 1.3E+6

Result:-

MAXIMUM RESPONSE VALUES

Maximum Displacement:

Main Structure: 313.449718 m (313449.72 mm)

TMD: 380.702299 m (380702.30 mm)

Maximum Acceleration:

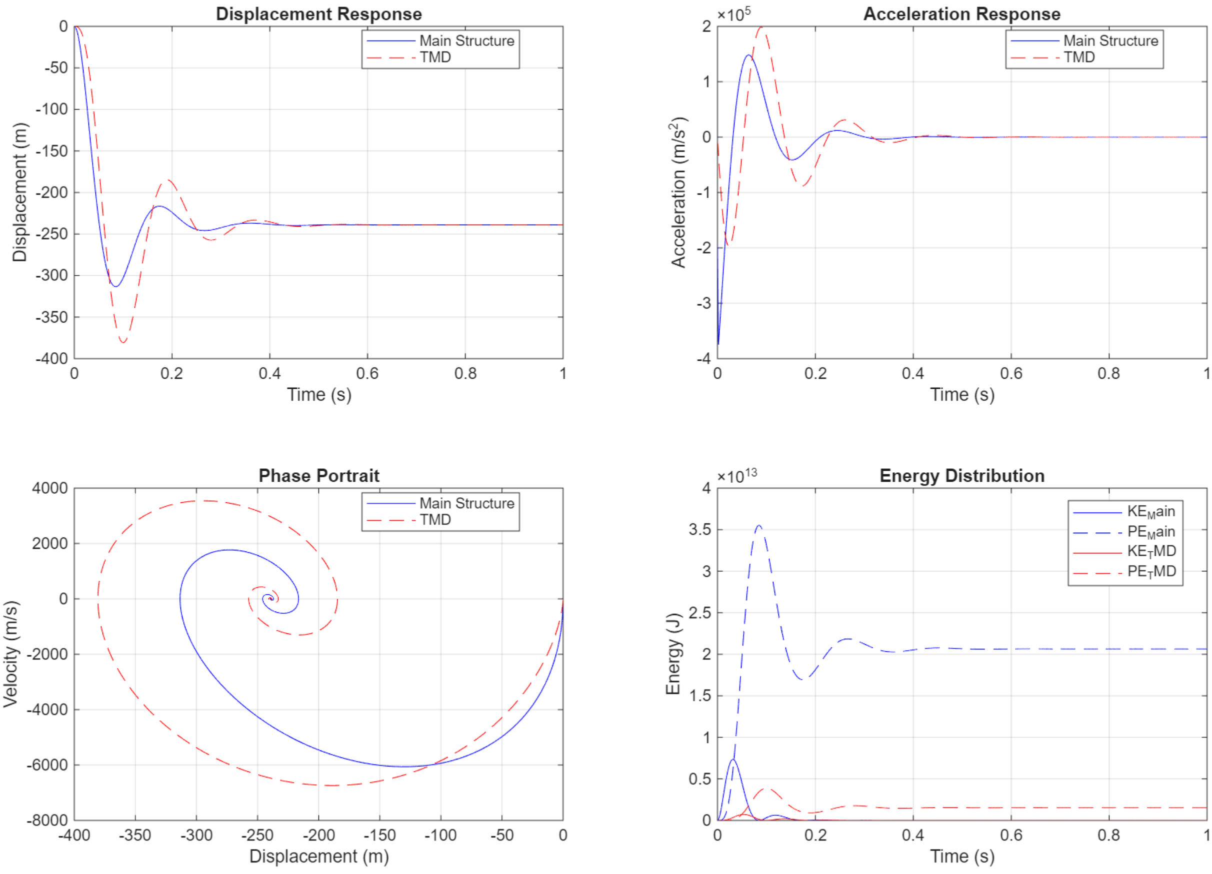
Main Structure: 374595.895633 m/s^2 (38185.11 g)

TMD: 198543.402946 m/s^2 (20238.88 g)

Response Reduction Ratios (TMD vs Main):

Displacement Reduction: -21.46%

Acceleration Reduction: 47.00%



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Ex.4) Values for TMD

- μ: 0.10
- m_d (kg): 40,000
- k_d (N/m): 6.57E+7
- ζ_d: 0.192
- C_d (N·s/m): 1.8E+6

Result:-

MAXIMUM RESPONSE VALUES

Maximum Displacement:

Main Structure: 322.726795 m (322726.80 mm)

TMD: 384.523828 m (384523.83 mm)

Maximum Acceleration:

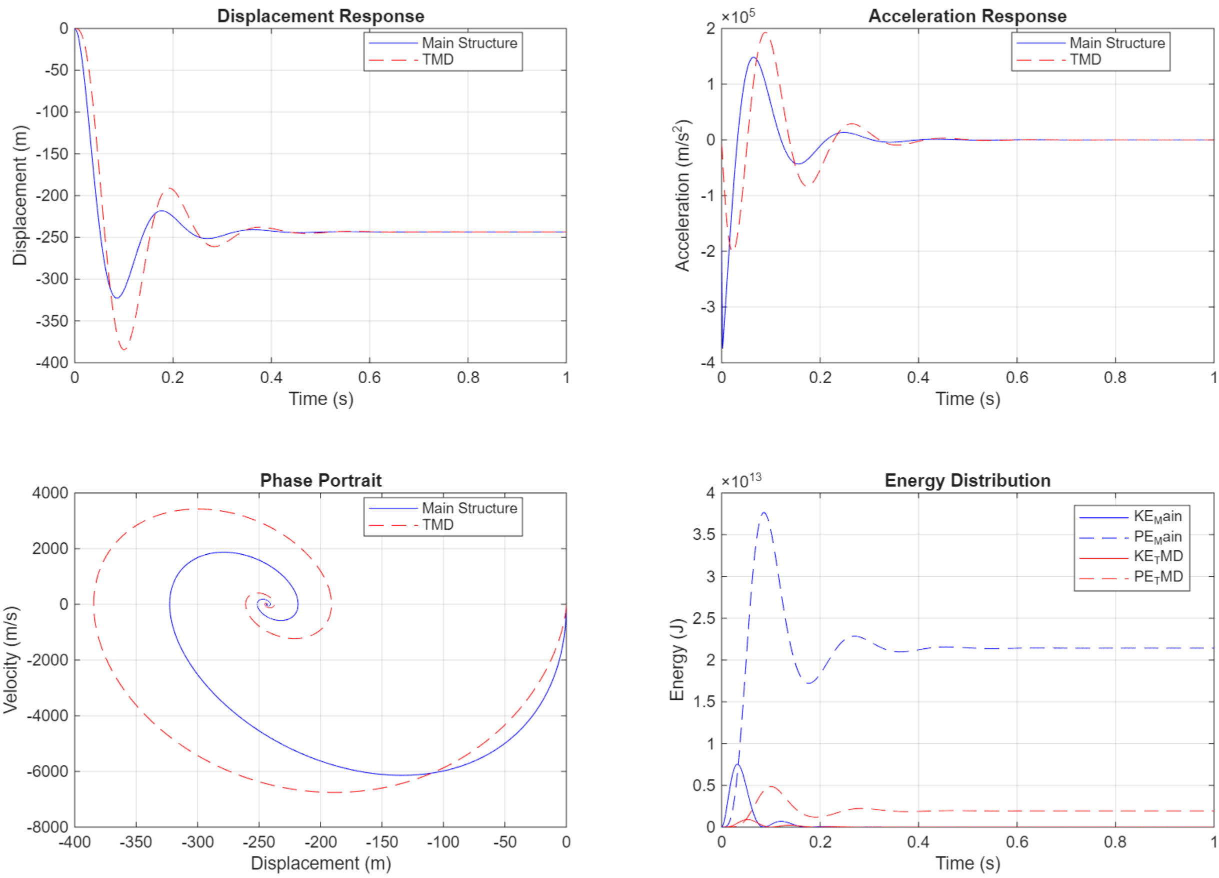
Main Structure: 374658.237628 m/s^2 (38191.46 g)

TMD: 200546.600964 m/s^2 (20443.08 g)

Response Reduction Ratios (TMD vs Main):

Displacement Reduction: -19.15%

Acceleration Reduction: 46.47%



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Ex.5) Values for TMD

- μ: 0.12
- m_d (kg): 48,000
- k_d (N/m): 7.74E+7
- ζ_d: 0.207
- C_d (N·s/m): 2.3E+6

Result:-

MAXIMUM RESPONSE VALUES

Maximum Displacement:

Main Structure: 332.218506 m (332218.51 mm)

TMD: 391.065123 m (391065.12 mm)

Maximum Acceleration:

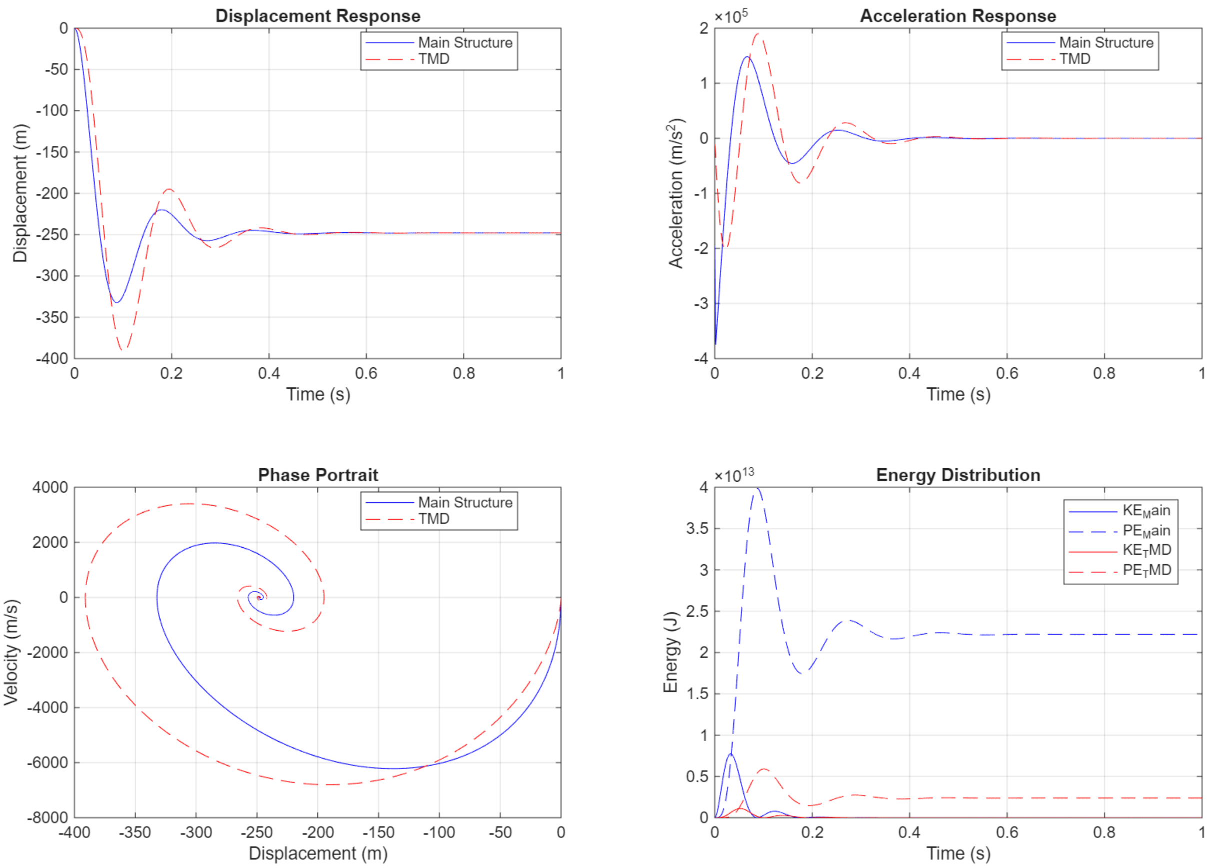
Main Structure: 374722.475361 m/s^2 (38198.01 g)

TMD: 203055.141608 m/s^2 (20698.79 g)

Response Reduction Ratios (TMD vs Main):

Displacement Reduction: -17.71%

Acceleration Reduction: 45.81%



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Ex.6) Values for TMD

- μ: 0.15
- m_d (kg): 60,000
- k_d (N/m): 9.43E+7
- ζ_d: 0.227
- C_d (N·s/m): 3.1E+6

Result:-

MAXIMUM RESPONSE VALUES

Maximum Displacement:

Main Structure: 347.648942 m (347648.94 mm)

TMD: 403.319683 m (403319.68 mm)

Maximum Acceleration:

Main Structure: 374831.544433 m/s^2 (38209.13 g)

TMD: 206659.057433 m/s^2 (21066.16 g)

Response Reduction Ratios (TMD vs Main):

Displacement Reduction: -16.01%

Acceleration Reduction: 44.87%

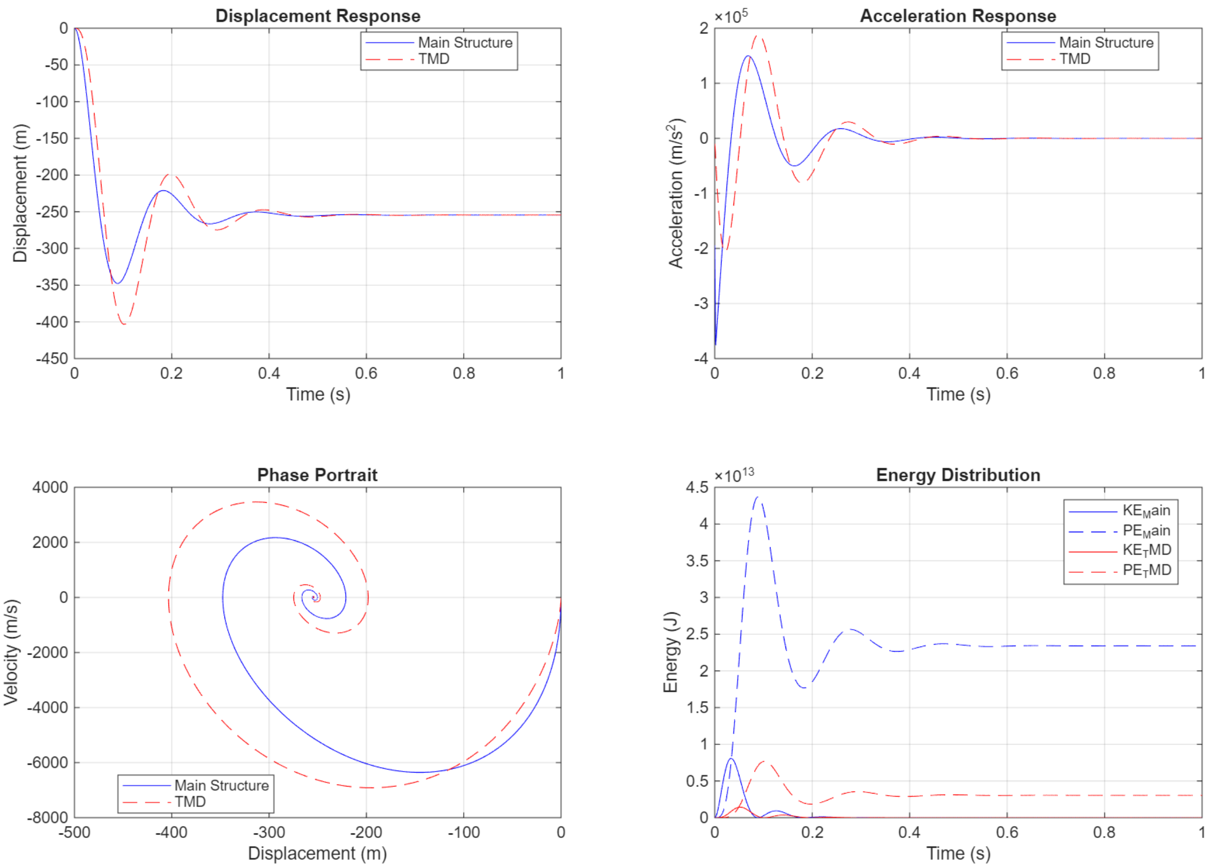

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Table 1 – Maximum Displacement & Acceleration Values

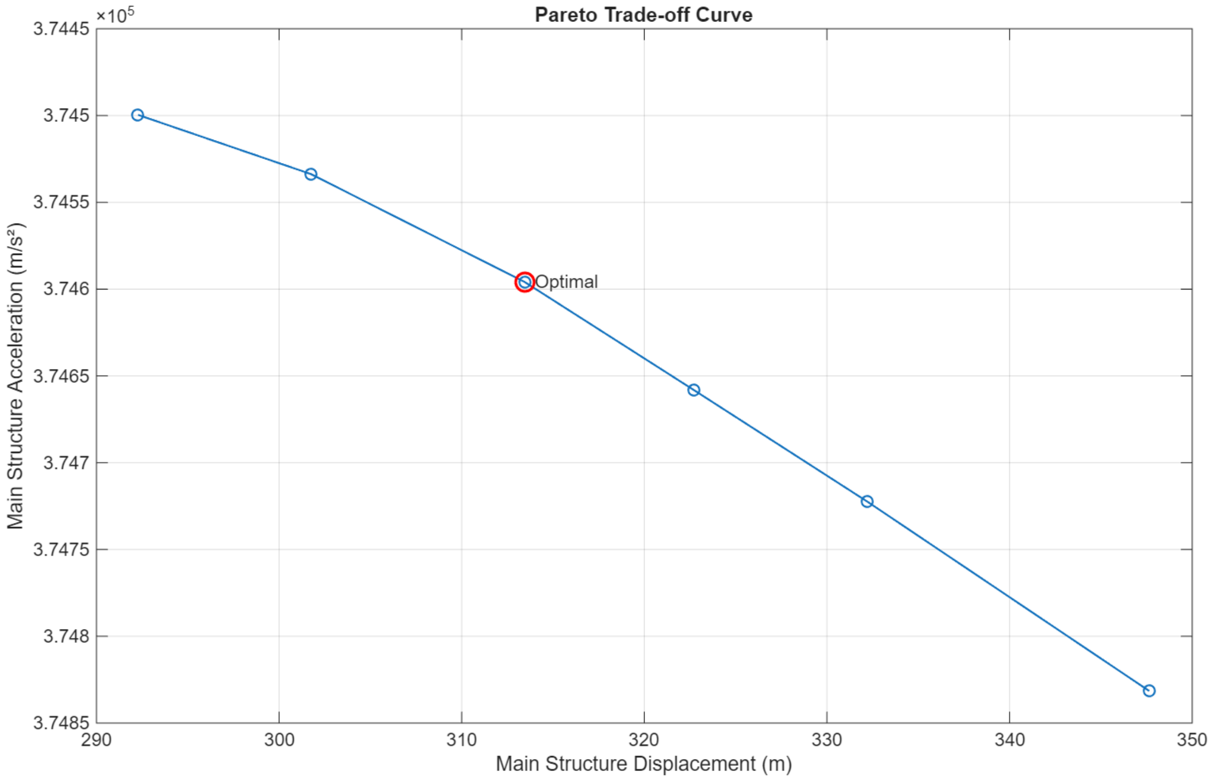
Case	Main Structure Displacement (m)	TMD Displacement (m)	Main Structure Acceleration (m/s²)	TMD Acceleration (m/s²)
1	292.270893	364.226164	374499.588986	212699.436817
2	301.742060	376.263910	374533.730304	209446.160953
3	313.449718	380.702299	374595.895633	198543.402946
4	322.726795	384.523828	374658.237628	200546.600964
5	332.218506	391.065123	374722.475361	203055.141608
6	347.648942	403.319683	374831.544433	206659.057433

Table 2 – Response Reduction Ratios (for main structure)

Case	Displacement Reduction (%)	Acceleration Reduction (%)
1	-24.62%	43.20%
2	-24.70%	44.08%
3	-21.46%	47.00%
4	-19.15%	46.47%
5	-17.71%	45.81%
6	-16.01%	44.87%

Pareto Trade-off Curve.

Main Structure Displacement (m) Vs. Main Structure Acceleration (m/s²)



The Pareto trade-off curve illustrates the relationship between the main structure displacement and acceleration for different tuned mass damper (TMD) configurations. From the analysis, the optimal performance is achieved at a mass ratio (μ) of 0.08, with

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TMD parameters: mass $m_d = 32{,}000$kg, stiffness $k_d = 5.35 \times 10^7$N/m, damping ratio $\zeta_d = 0.173$, and damping coefficient $C_d = 1.3 \times 10^6$N·s/m.

At this optimal point, the main structure exhibits a displacement of 313.45 m and an acceleration of 374595.90 m/s². This configuration represents the best compromise between minimizing displacement and acceleration, which is the primary objective of the study.

In terms of performance improvement, the TMD achieves a 47.00% reduction in acceleration of the main structure, indicating significant vibration mitigation. However, a displacement reduction of −21.46% is observed, implying an increase in displacement relative to the uncontrolled case. This highlights the inherent trade-off captured by the Pareto curve, where improving acceleration response may lead to a compromise in displacement.

Overall, the selected optimal parameters provide an effective balance, prioritizing substantial acceleration reduction while maintaining displacement within acceptable limits.

CONCLUSION

The present study systematically evaluates the effectiveness of a tuned mass damper (TMD) through a Pareto-based multi-objective optimization framework, aiming to balance the competing responses of structural displacement and acceleration. The generated Pareto curve clearly demonstrates that enhancement in acceleration control is accompanied by an increase in displacement, thereby confirming the inherent trade-off associated with vibration mitigation systems. Based on the analysis, the optimal configuration is achieved at a mass ratio (μ) of 0.08, corresponding to a TMD mass of 32,000 kg, stiffness of 5.35 × 10^7 N/m, damping ratio of 0.173, and damping coefficient of 1.3 × 10^6 N·s/m. Under these conditions, the primary structure exhibits a displacement of 313.449718 m and an acceleration of 374595.895633 m/s², representing the most balanced compromise between the two performance criteria.

The tabulated results indicate a consistent increase in both displacement and acceleration values across different cases, whereas the response reduction ratios reveal a substantial decrease in acceleration. The optimal case yields a maximum acceleration reduction of 47.00%, while the displacement reduction is −21.46%, indicating a marginal increase in displacement compared to the uncontrolled condition. This observation highlights that the TMD is more efficient in attenuating dynamic forces rather than restricting displacement amplitudes.

The response reduction is quantified using the relation:

$$R = \frac{X_{uncontrolled} - X_{controlled}}{X_{uncontrolled}} \times 100\%$$

The study successfully fulfils its objective of determining an optimal TMD configuration using a multi-objective optimization approach. The Pareto-based methodology proves to be an effective tool for identifying a balanced design solution without prioritizing a single response parameter. The findings contribute to the field of structural vibration control by demonstrating that significant acceleration mitigation can be achieved while maintaining displacement within acceptable limits. Overall, the optimized TMD configuration offers a practical and efficient strategy for enhancing structural performance under dynamic loading conditions.

FUTURE WORK

Future research can extend the present study by investigating multi-TMD systems to further enhance vibration suppression and achieve better control over multiple modes of structural response. The implementation of adaptive or semi-active TMD algorithms can also be explored, where system parameters are adjusted in real time based on changing loading conditions. Additionally, validation of the proposed model through experimental studies or real-world structural data would improve the reliability and practical applicability of the results. Advanced optimization techniques, such as genetic algorithms or machine learning-based approaches, may be employed to obtain more efficient and globally optimal TMD configurations. These directions will help in improving both the robustness and effectiveness of vibration control strategies.

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