ASPS Conference Proceedings 1: 991-997 (2022)

Proceedings of

12th Structural Engineering Convention-An International Event (SEC 2022)

Available at https://asps-journals.com/index.php/acp

# Tall Building Installed With Bio-Inspired TMD With Inerter

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**Paper ID - 060530**

**Abstract**

This paper explores the combined effect of inerter and bio-inspired tuned mass damper (BTMD) on enhancing the performance the wind excited benchmark building. Initially, the performance of the building installed with BTMD on the top floor, under across wind loads is evaluated. In addition to this, an inerter is attached to the BTMD (BTMDI) and the performance of the benchmark building is studied. A mechanical device called an inerter has two terminals and generates an equal and opposing force proportionate to the relative acceleration between the terminals. One terminal of the inerter is linked to the BTMD and the other terminal is connected to the 76$^{th}$ floor of the structure in order to improve the performance of the structure. The response quantities of the building installed with BMTDI are studied, and compared with those installed with TMD and BTMD. Comparative study of various performance criteria of the building installed with BMTDI, BMTD and TMD is also carried out. Optimum values of parameters such as, damping ratio, frequency ratio and mass ratio of BTMDI are found by numerical search technique. The performance of the 76$^{th}$ - storey benchmark tower installed with BMTDI is enhanced considerably as compared to that with BMTD.

*Keywords*: Tuned mass damper, Wind excited benchmark building, Bio-inspired Tuned mass damper, Inerter

## 1. Introduction

The development in construction technologies, urbanization and development in construction materials has resulted in construction of tall and slender multi-storeyed buildings. However, these slender buildings are prone to excessive vibrations due to dynamic loads such as wind and earthquake loads. These undesirable vibrations can be controlled either by energy dissipation or by providing stiffer structural components [1].

Many control devices like viscous dampers, friction dampers, tuned mass dampers etc. have been designed and implemented in structures to reduce vibrations [2, 5]. The Tuned mass damper (TMD) theory was initially applied by Frahm (1909) to minimize the rolling movement of ships. TMD is actually a system that comprises of a spring, a mass and a viscous damper this is attached to the vibrating host structure to reduce the structure's response, when the structure is subjected to the dynamic loads such as wind and earthquake [8]. The damper's frequency is adjusted to a certain structural frequency, so when that frequency is stimulated, the damper resonates out of phase with the motion of the structure and releases energy [10]. It is well-known that, performance of TMD mainly depends on tuning and on the inertial property, the larger the attached mass is, more is the vibration suppression [14]. From the past few years, TMD with heavy attached mass has been installed on tall structures in order to alleviate vibration and to avoid discomfort to the occupants [6, 7]. Despite being frequently utilised because of the fairly simple and well-established design processes, the TMD has a "detuning" issue that could considerably impair its efficacy in terms of vibration suppression [3]. TMD mass offers better performance but practically heavy mass handling, transportation and installation on the top floor of tall structures is difficult and crucial. To address the issues, in the present study the newly developed device "inerter" is considered. The inerter is actually a new kind of mechanical device and suspension component that was developed by Malcolm Smith [12] at University of Cambridge. The inerter converts the linear motion of a flywheel to the rotational motion and can provide large effective inertia mass (mass amplification) using small physical mass. The resisting force generated by inerter is expressed as,

$$f = b\left(\ddot{x}_1 - \ddot{x}_2\right) \tag{1}$$

where, '$b$' is the proportionality constant (inertance), $x_1$ and $x_2$ are the inerter terminals coordinates for displacement and a dot over $x_1$ and $x_2$ indicates differentiation in relation to time t.

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Proceedings of the 12th Structural Engineering Convention (SEC 2022), NCDMM, MNIT Jaipur, India| 19-22 December, 2022



Published online: December 19, 2022
doi:10.38208/acp.v1.611

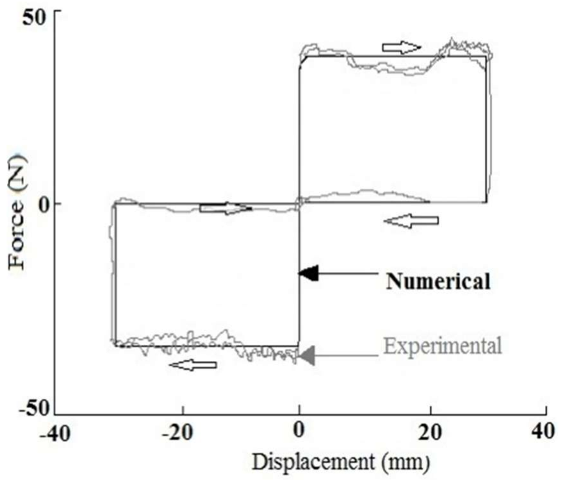


Fig. 1: The force-displacement connection of the hidden length mechanism and sacrificial bond observed in abalone shell (Kwon et al.[8])

Many researchers have implemented the inerter in the conventional TMD arrangement and found that there is better reduction in the response quantities [9, 11 and 13]. Giarlias and Petrini [4] have studied the performance of tuned mass damper inerter (TMDI) mounting it atop a 74-story steel frame structure. One inerter terminal was linked to the attached mass in the study, while another terminal was connected to the penultimate floors. From the study, it was found that inerter terminal which spans more floors in linking the attached mass have showed better results.

Some researchers were motivated by the sacrificial bond and hidden length mechanism identified in the shells and bones of abalones. According to the researchers, such mechanisms promote energy dissipation and make the component molecules more stiff [8, 15]. Based on the concepts of sacrificial bond and hidden length mechanism, Kwon et al. [8] have developed a bio-inspired actuator. The force-displacement connection of the hidden length mechanism and sacrificial bond observed in abalone shell and bone is shown in Fig. 1.

The performance of the wind-excited benchmark building is assessed in the current study, installed with BTMD and BTMDI. Initially, the BTMD is installed on the 76-storey benchmark tower. The response quantities of the building are found. Further, the performance of the building is studied by installing the BMTD attached with inerter. This is done to get the same performance of the building with BTMD, but with the reduced physical mass. The building installed with TMD is also studied for comparison. A parametric study is also carried out to optimize the parameters such as damping ratio, frequency ratio and mass ratio of BTMDI

## 2. Model of the benchmark tower installed with BTMDI

To evaluate the performance of Bio-inspired tuned mass damper attached with inerter for reducing the wind induced vibrations, a 76-storey benchmark tower is considered for the study. The benchmark structure is an office tower that has been proposed for Melbourne, Australia. It is a 76-storey building, 306 m high [11]. With a height to width ratio of 306/42=7.3, the structure is slender. It is hence wind-sensitive. The construction is to be made of Reinforced Cement Concrete (RCC) comprising of concrete frame and concrete core. The building has an estimated mass density of 300 kg/m$^3$. Except for the first floor, which is 10 metres high, floors 38 to 40 and 74 to 76, which are 4.5 metres high and for the remaining storey's the typical height is 3.9 metres. The University of Sydney conducted wind tunnel experiments on the 76-story structure model.

***Performance Criteria***

Building response quantities resulting from cross-winds and along-winds may be calculated separately because the coupled lateral-torsional motion is ignored and across-wind and along-wind loads are uncorrelated. Based on the wind tunnel data, structure response quantities due to a cross-wind loads are much higher compared to those caused by long-wind loads [14]. Therefore, only the controller design adopting across-wind loading (such as ATMD) is taken into account.

The peak response quantities may be retrieved from the response time histories, and the temporal RMS values can be calculated. The primary goal of putting control systems on the tall structure is to lower the absolute acceleration to lessen the discomfort of the occupants. The frequency dependency of a person's sense of acceleration, however, is not taken into account. The performance criteria for a non-dimensional version is given in the basic paper. Consequently, a set of 12 performance criteria are provided to make direct comparison and evaluation of the capabilities of numerous defensive devices and algorithms more convenient [14]. Since the response quantities of the wind-excited benchmark tower are normalised by the corresponding response quantities of the uncontrolled building, the performance criteria $J_1$ to $J_4$ are established to evaluate reduction in the RMS response quantities of the wind-excited benchmark structure; $J_7$ to $J_{10}$ are mainly based upon peak responses that are calculated using the normalised peak response quantities of uncontrolled structure. Only eight of the 12 criteria i.e, $J_1$ to $J_4$ and $J_7$ to $J_{10}$ are included in this study since the remaining four i.e, $J_5$, $J_6$, $J_{11}$, and $J_{12}$ represent the actuator's performance [14].

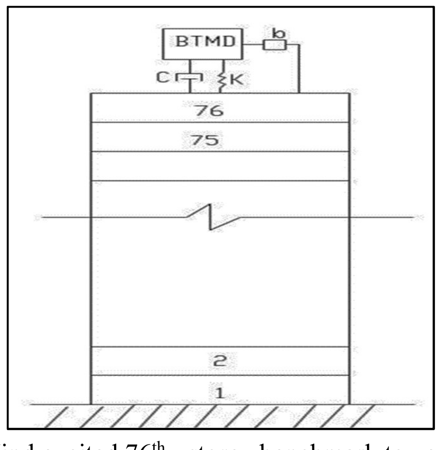


Fig. 2: Wind excited 76$^{th}$ - storey benchmark tower installed with BTMDI (Yang et al. [14]).

## 3. Principal equations of motion

The BTMDI is installed on the top storey of the benchmark tower. The characteristics of the BTMDI are mass ($m_{BTMDI}$), stiffness ($k_{BTMDI}$), damping constant ($c_{BTMDI}$) and inertance (b).

The natural frequency of BTMDI is given by,

$$\omega_{BTMDI} = \sqrt{\left(\frac{k_{BTMDI}}{m_{BTMDI}+b}\right)} \quad (2)$$

The damping ratio of BTMDI is expressed as,

$$\zeta_{BTMDI} = \frac{c_{BTMDI}}{2\left(m_{BTMDI}+b\right)\omega_{BTMDI}} \quad (3)$$

The frequency ratio is expressed as,

$$\upsilon_{BTMDI} = \frac{\omega_{BTMDI}}{\omega} \quad (4)$$

The mass ratio is given by,

$$\mu = \frac{m_{BTMDI}}{m} \quad (5)$$

And the inertance ratio is given by,

$$\beta = \frac{b}{m} \quad (6)$$

where, $k_{BTMDI}$ is linear spring of stiffness of BTMDI, m is the mass of structure, $m_{BTMDI}$ is the mass of attached BTMDI, b is the inertance and $c_{BTMDI}$ is damping coefficient of BTMDI.

To evaluate the performance of BTMDI for reducing the wind induced vibrations, a 76-storey benchmark tower is considered for the study. For the wind excited benchmark tower along with BTMDI, the principal equations of motion can be written as,

$$M_d\ddot{x} + c_d\dot{x} + k_d x = F_d - F \quad (7)$$

$$M_d = \begin{bmatrix} m & 0 \\ 0 & \left(m_{BTMDI}+b\right) \end{bmatrix}$$

where; M being the mass matrix , k the stiffness matrix, and C is the damping matrix. For the building's finite element model, each of the order (7676) is created and submitted for analysis [14]. The mass matrix of the structure installed with BTMDI ($M_d$) is constructed by adding the mass of BTMD and inertance (which is generated by the inerter) diagonally to the mass matrix. Similarly, the set of motion equations are expressed in matrix form to create the stiffness matrix ($K_d$) and damping matrix ($C_d$) for the structure connected with BTMDI. x being the displacement vector of order (m+1) where, m is the DOF of the structure, $\dot{x}$ and $\ddot{x}$ are the differentiation in relation to time t i.e, velocity and acceleration respectively. 'F' is the wind load vector and '$F_d$' is control force applied by the bioinspired actuator. Based on the numerical bio-inspired actuator operation, a damping function is given by Kwon et al. [8] and the corresponding parameters are considered for the study.

$$F\left(x_d, v_d\right) = \begin{cases} F_{\max}\left(\frac{2}{1+e^{-k_{steep}\cdot x_d}} - 1\right) & If\ x_d \cdot v_d > 0 \\ 0 & If\ x_d \cdot v_d < 0 \end{cases} \quad (8)$$

where, $F_{max}$ is the control force for saturation value; tuned mass displacement and velocity with respect to the main mass are given by $x_d$ and $v_d$, respectivelyand $k_{steep}$ is $200 \times F_{max}$

## 4. Numerical study

The building's finite element model (FEM) is used to create the mass matrix and stiffness matrix, both of which are of the order of (76x76). Using Rayleigh's method, the building's damping matrix is created. For the first five modes, it is assumed that the damping ratio is $\zeta = 1\%$. The building's first five natural frequencies are determined to be 0.16, 0.7651, 1.9921, 3.7899 and 6.3945 Hz.

The comparative study of the performance of the wind excited benchmark tower installed with BTMDI as compared to that installed with BTMD is carried out. The peak acceleration and peak displacement quantities of the selected floors of the tower installed with different type of TMDs considered for the study are presented in the Fig. 3 and Fig. 4, respectively. The mass of BTMD is 500 tonnes. The same mass is maintained in BTMD, but with an inertance of 500 tonnes, which results in BTMDI. The reduction in the response quantities is achieved by bio-inspired actuator which applies the unique force in two opposite directions and energy is dissipated in these directions, when the building is displacing away from the position of equilibrium. Further, the enhancement in the structural performance is due to the attached inerter to the BTMD. Because of the mechanism of inerter, inertance (apparent mass) is generated. This inertance enhances the attached mass, thereby increasing the effective mass. As a result, the structure's response quantities are further reduced.

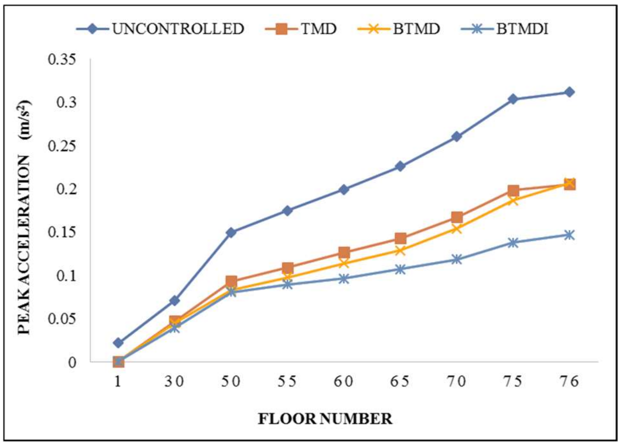


Fig. 3: Comparison of peak acceleration of 76-storey benchmark tower with different controllers

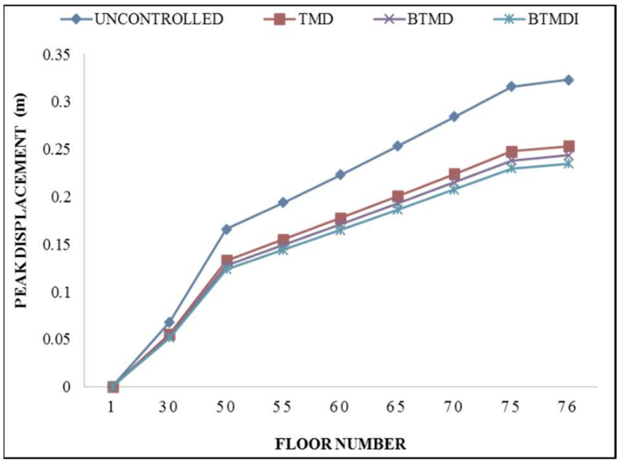


Fig. 4: Comparison of peak displacement of 76-storey benchmark tower with different controllers

From Fig. 3 and Fig. 4, it is observed that the effect of inerter is better against acceleration than displacement. The effectiveness of inerter mainly depends on the number of gears, radius of the gear and radius of the flywheel. When inerter is attached to BTMD, there is a large reduction in the response quantities when compared with the conventional ones.

An attempt is made to reduce the attached mass of BTMDI and the response quantities are reduced by varying the inertance co-efficient 'b'. Initially, the performance of the building installed with BTMD having a mass of 500 tonnes is studied. Then the mass of BTMD is reduced to 250 tonnes and inerter is coupled to BTMD. This resulted in bio-inspired tuned mass damper with inerter (BTMDI). The inertance is varied from 100 tonnes to 400 tonnes with an increment of 100 tonnes. The variation of peak acceleration quantities of the selected floors of the benchmark building are presented in Fig. 5. From the Fig. 5, it has been noted that the performance of the building improves with inertance. It is also observed that with the attached mass of 250 tonnes along with inertance of 400 tonnes, the performance, same as the BMTD having mass of 500 tonnes is achieved. Thus, large reduction in physical mass can be achieved with the attachment of inertance and ease of installation can be achieved.

Yang et al. [14] define a set of 12 performance criteria. $J_1$ to $J_4$ are depending on peak responses estimated by normalising the peak response quantities by the equivalent peak response quantities of uncontrolled tower. $J_7$ to $J_{10}$ are based on the reduction in RMS response quantities of the wind excited benchmark structure [14]. The performance criteria $J_1$ to $J_4$ and $J_7$ to $J_{10}$ are studied by installing BMTD and BMTDI separately on the wind excited benchmark structure. This is being done in order to conduct a performance comparison study between BMTD and BMTDI. Later on, a parametric study is also carried out to obtain optimum design parameters i.e, damping ratio, frequency ratio and mass ratio of BTMDI. Initially, the effect of variation of damping ratio on performance criteria for different mass ratios are studied. Subsequently, the effect of variation of frequency ratio on performance criteria are studied. The mass ratio of BTMDI are differed as 0.33%, 0.5%, 0.66%, 0.82%, 1.00%, 1.16% and 1.33% to find the optimum parameters of BTMDI

. The damping ratio is been differed from 0.01 to 0.1 with an increase of 0.01 and the frequency ratio is been differed from 0.1 to 1.00 with an increase of 0.1. After that, $J_1$ performance need is lowered. The variation of the criteria $J_2$, $J_3$, and $J_4$ is known using the optimal values obtained by minimising $J_1$. Each performance criterion is afterwards reduced to determine the settings that are most optimal.

Performance criteria ($J_1$ to $J_4$) variations with damping ratio of BTMDI for different mass ratios is presented in the Fig. 6 to Fig. 9. In the Figures μ represents the mass ratio and β is the inertance ratio. It can be seen from the Figures, that as there is increase in the mass ratio there is reduction in all the

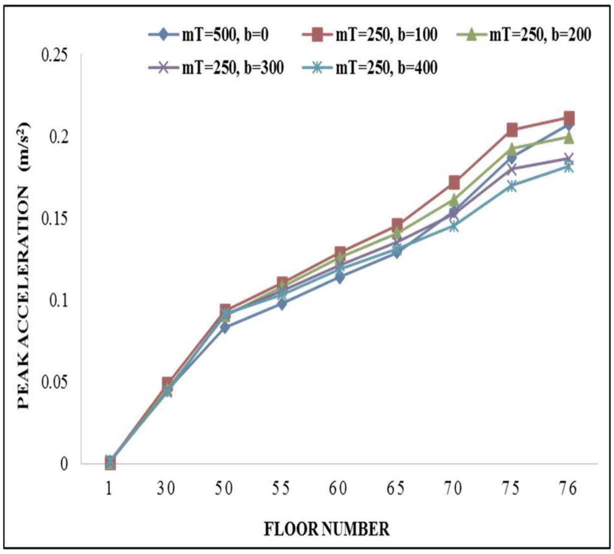


Fig. 5: Variation of peak acceleration of selected floors with inertance coefficient and mass of BTMD.

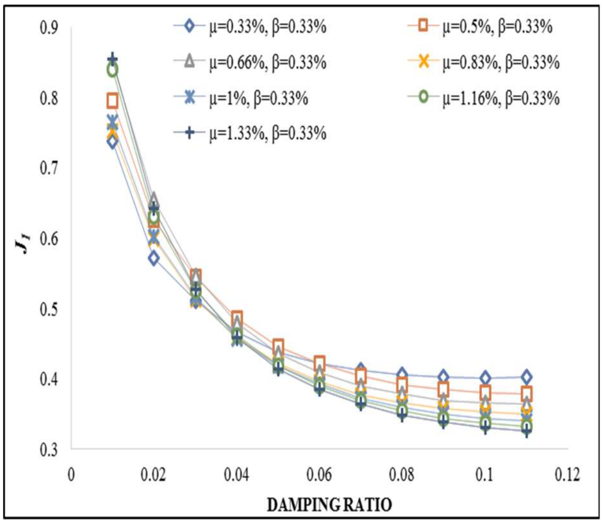


Fig. 6: Performance criteria ($J_1$) variation with damping ratio of BTMDI for different mass ratios

performance criteria. Figures 10 to 13 show the performance criteria ($J_1$ to $J_4$) variations with frequency ratio of BTMDI for various mass ratios. The figures show that the tuning frequency ratio's ideal value, which reduces performance requirements is close to 1, also there is reduction in the performance criteria with increase in the mass ratios. The optimal parameters so determined by altering the mass ratio, damping ratio, and frequency ratio are shown in Table 1.

Table 1: Variations of optimum parameters of BTMDI (b=500 t) with the mass ratio for the minimization of the performance criteria

| **Mass of BTMD** (Ton) | | **PERFORMANCE CRITERIA** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $J_1$ | $J_2$ | $J_3$ | $J_4$ | $J_7$ | $J_8$ | $J_9$ | $J_{10}$ |
| 500 (μ=0.33%) | $f_{opt}$ | 0.97 | 0.97 | 0.95 | 0.95 | 0.95 | 0.96 | 0.91 | 0.91 |
| | $\zeta_{opt}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | $J_{opt}$ | 0.389 | 0.3833 | 0.5512 | 0.5532 | 0.422 | 0.4456 | 0.6292 | 0.6375 |
| 750 (μ=0.5%) | $f_{opt}$ | 0.96 | 0.97 | 0.95 | 0.95 | 0.97 | 0.97 | 0.92 | 0.92 |
| | $\zeta_{opt}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | $J_{opt}$ | 0.3699 | 0.3644 | 0.5391 | 0.5412 | 0.423 | 0.4385 | 0.6037 | 0.6089 |
| 1000 (μ=0.66%) | $f_{opt}$ | 0.97 | 0.96 | 0.94 | 0.94 | 0.91 | 0.97 | 0.93 | 0.93 |
| | $\zeta_{opt}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | $J_{opt}$ | 0.35721 | 0.3514 | 0.5329 | 0.5351 | 0.4134 | 0.44 | 0.5997 | 0.6026 |
| 1250 (μ=0.82%) | $f_{opt}$ | 0.97 | 0.96 | 0.95 | 0.95 | 0.9 | 0.92 | 0.94 | 0.94 |
| | $\zeta_{opt}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | $J_{opt}$ | 0.3491 | 0.3435 | 0.5287 | 0.5309 | 0.3959 | 0.4218 | 0.6035 | 0.6068 |
| 1500 (μ=1%) | $f_{opt}$ | 0.97 | 0.96 | 0.94 | 0.95 | 0.9 | 0.91 | 0.91 | 0.91 |
| | $\zeta_{opt}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | $J_{opt}$ | 0.3412 | 0.3354 | 0.5256 | 0.5278 | 0.3817 | 0.4039 | 0.5977 | 0.5992 |
| 1750 (μ=1.16%) | $f_{opt}$ | 0.97 | 0.98 | 0.94 | 0.95 | 0.9 | 0.9 | 0.9 | 0.9 |
| | $\zeta_{opt}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | $J_{opt}$ | 0.3354 | 0.3294 | 0.5232 | 0.5253 | 0.3689 | 0.3915 | 0.5905 | 0.5993 |
| 2000 (μ=1.32%) | $f_{opt}$ | 0.97 | 0.98 | 0.94 | 0.94 | 0.91 | 0.9 | 0.9 | 0.9 |
| | $\zeta_{opt}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | $J_{opt}$ | 0.3301 | 0.3239 | 0.5213 | 0.5235 | 0.3753 | 0.3883 | 0.602 | 0.6106 |

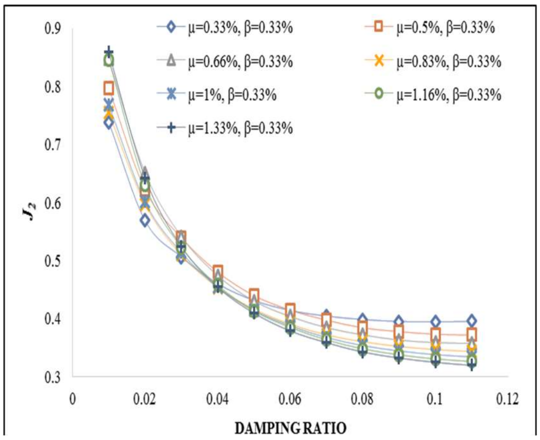


Fig. 7: Performance criteria ($J_2$) variation with damping ratio of BTMDI for different mass ratios

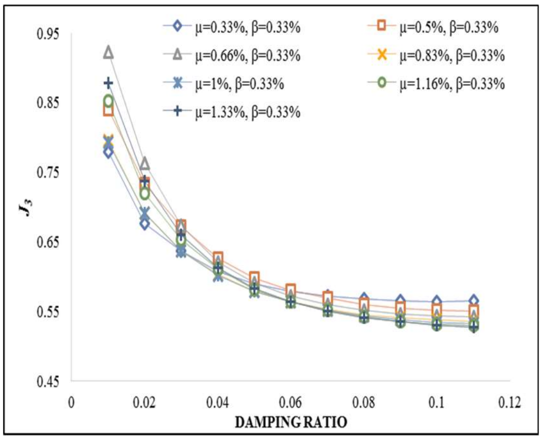


Fig. 8: Performance criteria ($J_3$) variation with damping ratio of BTMDI for different mass ratios

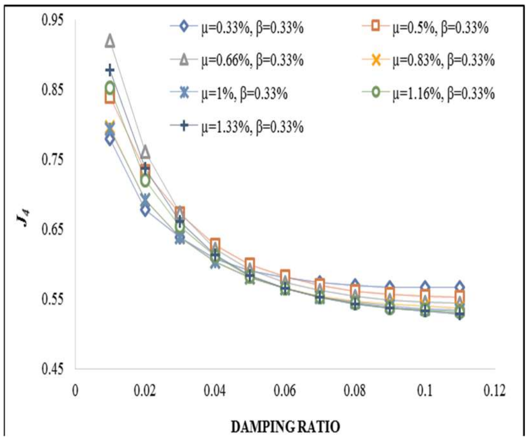


Fig. 9: Performance criteria ($J_4$) variation with damping ratio of BTMDI for different mass ratios

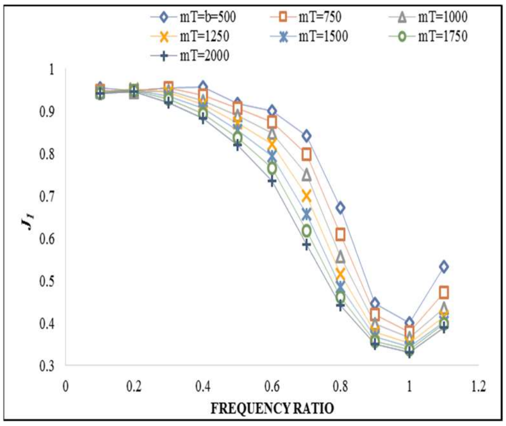


Fig. 10: Performance criteria ($J_1$) variation with frequency ratio of BTMDI for different mass ratios

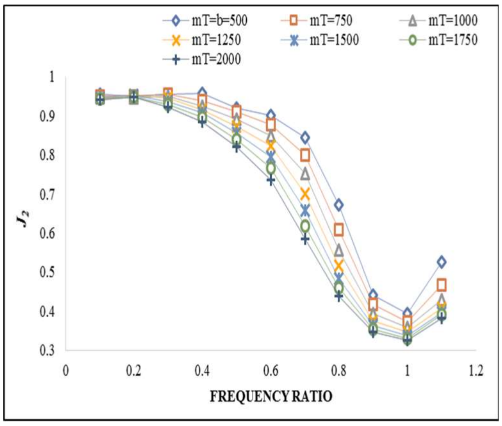


Fig. 11: Performance criteria ($J_2$) variation with frequency ratio of BTMDI for different mass ratios

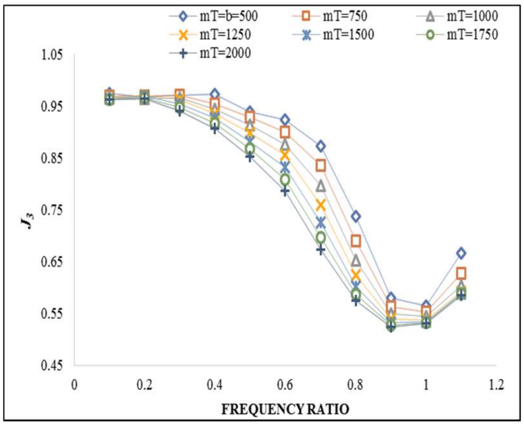


Fig. 12: Performance criteria ($J_3$) variation with frequency ratio of BTMDI for different mass ratios

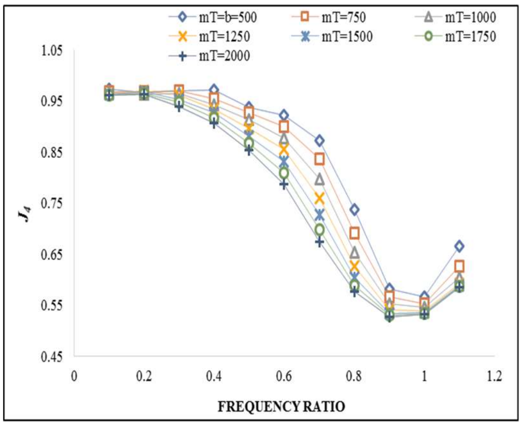


Fig. 13: Performance criteria ($J_4$) variation with frequency ratio of BTMDI for different mass ratios

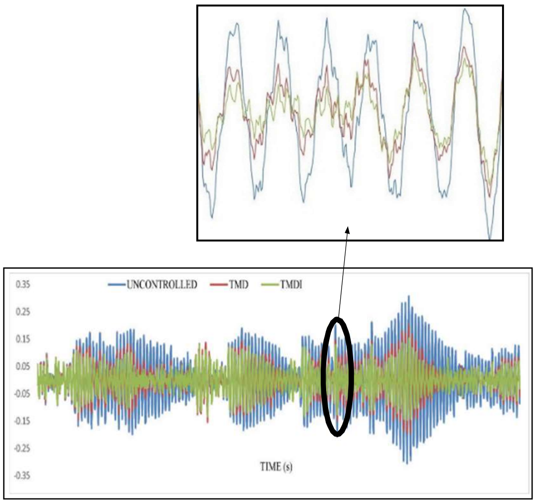


Fig. 14: Comparison of 76th floor acceleration in the uncontrolled case and the controlled case using TMD and BTMDI

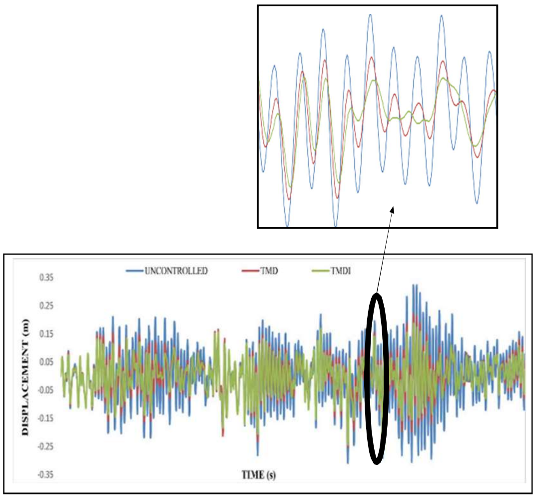


Fig. 15: Comparison of 76th floor displacement in the uncontrolled case and the controlled case using TMD and BTMDI

For 900 s, the response quantities of the benchmark tower equipped with various controllers are examined. Figures 14 and 15 show, respectively, the acceleration and displacement values with time for the 76th floor. It is evident from the Figure that, the BTMDI outperforms as compared to TMD.

## 5. Conclusions

Comparative study of the wind excited benchmark building installed with BTMD and BTMDI is carried out under the deterministic across wind load. The parametric study of BTMDI is carried out. The Optimum parameters of BTMDI are obtained for the minimization of several performance criteria of the building by numerical search technique. It is examined how design factors like mass ratio, damping ratio, and tuning frequency ratio affect the final output. The following conclusions are taken from the patterns of the numerical results of the current study,

- From the comparative study, it can be concluded that there is a large reduction in the response quantities of the structure attached with BTMDI as compared to conventional TMD and BTMD.

- When BTMDI is employed, there is 52.807 % reduction in the peak acceleration and 27.21 % reduction in the peak displacement compared to the uncontrolled structure.
- Performance of BTMDI is higher in displacement when compared to acceleration.
- From the parametric study, it is found that there is reduction in the performance criteria with the increase in the damping ratio.
- The optimum value of tuning frequency ratio lies between 0.9 to 1.

## Disclosures

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