Vibration mitigation of high-rise buildings via tuned mass damper subjected to dynamic loads

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Abstract. Vibration mitigation and control problems in structural engineering are complex to deal with due to many reasons such as overall size of the structures (high-rise or low-rise), controlling systems (passive, active, semi-active, hybrid), and unknown input excitations. This study focuses into the vibration mitigation of high-rise buildings via the use of tuned-mass-damper (TMD). To do this end, a 15-storied structure is considered and the investigations are performed by employing MATLAB and SIMULINK. Even though the functionality of TMD is simple as the main controlling parameters are mass ratio, stiffness, and damping of the TMD. However, the tuning process of TMD parameters (e.g. manual tuning) gets complicated when the structures get taller and larger. Therefore, to deal with the aforementioned issues, the sensitivity of the TMD parameters have been performed. And the optimization is carried out by employing an unconstrained multi-variable function using derivative-free method and those (e.g. optimized) parameters are incorporated to perform the final simulations. Herein the performance of the TMD is compared with an uncontrolled system where no damper was used. In a nutshell, the outcome of this study shows that the vibration mitigation of high-rise buildings are possible effectively with optimized (optimal) parameters of the TMD.

Keywords: vibration mitigation and control; tuned mass damper; optimization; dynamic loads; parameters sensitivity.

1. Introduction
Civil structures such as buildings, bridges, and power-plants are prone to extreme dynamic loads (e.g. seismic, and gale loads). The world economy is progressing actively, as a result, humans are in the race of building high-rise buildings as well as skyscrapers. Those structures are not only important for the national economy but also for bridging global economic. Hence all of those structures are substantial to remain in operation even after any unexpected hit by dynamic loads. In order to deal with the aforementioned issue many vibration control technologies have been developed and implemented into real structures [1, 2, 3, 4]. Broadly, all the available vibration mitigation and control technologies can be categorize into (i) passive [4], (ii) active [1, 2], (iii) semi-active [2, 5], (iv) hybrid systems [2]. Among available control systems, the passive control system is the oldest and simplest system to use. Passive controlling systems are in various forms such as base-isolation system, elastomeric bearing [4], tuned mass damper (TMD) [6, 7, 8, 9, 10].

TMDs are widely used in both buildings and bridges for its serviceability and feasibility in comparison to other alternatives. However, the functionality of a TMD device is heavily depends on its parameters tuning process. And this leads to complicated situation especially when the
structures get taller and larger. Primary work of designing and tuning process of TMD was proposed by Den Hartog [6]. Later on, many researchers have been proposed and developed various types of TMDs [7, 8, 9, 11, 12, 13]. Additionally, several works have investigated the possibilities of optimizing of TMDs parameters by adopting Genetic Algorithm [14, 15].

Among many few examples can be given such as John Hancock Tower adopted a TMD on 58-th floot [16]. Further, London Millennium Bridge in UK, Tehran International Tower in Iran, Burj Khalifa in UAE, Taipei 101 in Taiwan, Trump World Tower in USA, and Tokyo Skytree have also used TMD [17] for vibration mitigation. TMDs are tuned to meet the design requirements set by the designer. However, the mass ratio of the TMD to structure play a vital role including the stiffness and damping parameters of the dampers [6, 7, 8, 9, 12, 13, 10].

The tuning process of any TMD parameters often leads to difficult situation and the overall process is quite time consuming. Hence, this study focused into optimization of TMD parameters via the use of search algorithm such as unconstrained derivative-free method. Additionally, parameters sensitivities are also investigated and presented herein. To do this end, a 15-storied structure is considered and the controlled and uncontrolled performances are evaluated.

2. Problem Description

It is mentioned in the previous section that to perform the numerical investigations, a fifteen-storied structure is adopted. And the structure is modeled as lumped-mass system depicted in figure 1. In the aforesaid figure, the lumped-mass model of the structure itself figure 1(c) and structure with TMD figure 1(d) are presented. Note that both of the structures are subjected to same ground motion as shown in the figure using symbol \( \ddot{x}_g \). In order to derive the equation of motion free-body-diagrams (FBDs) are essential for every floor. However, herein sample FBDs of two different floors have shown in figure 1(a-b).

The system (without TMD) depicted in figure 1(c) can be described by the following equation of motion in matrix-vector form:

\[
M \ddot{x}(t) + C \dot{x}(t) + Kx(t) = -\gamma M \ddot{x}_g(t)
\]

where \( M \) represents the mass matrix, \( C \) is the damping matrix, \( K \) indicates the stiffness matrix of the system, \( x, \dot{x} \) and \( \ddot{x} \) are the displacement, velocity and acceleration vectors, \( t \) is the time vector, \( \gamma \) controls the input excitation location and \( \ddot{x}_g \) is the input ground motion.

And the system with TMD depicted in figure 1(d) can be described as:

\[
M \ddot{x}(t) + C \dot{x}(t) + Kx(t) = -\gamma M \ddot{x}_g(t) + \lambda f_{tmd}(t)
\]

where \( \lambda \) controls the TMD location, and \( f_{tmd} \) represents the control force applied by TMD.

Further, both the system with and without TMD brought into state-space system to deal first-order differential equation instead of second-order differential equation. The state-space formulation is described via the following system equation in Eq.(3) and measurement equation Eq.(4).

\[
\dot{Z}(t) = AZ(t) + Bu(t)
\]

where \( \dot{Z} \) is the state vector, \( A \) represents the system matrix, \( B \) represents the input matrix.

\[
y(t) = CZ(t) + Du(t)
\]

where \( y \) is the measured state/output vector, \( C \) means the system output matrix, \( D \) is the feedthrough matrix.
3. Results and Discussions

The numerical investigations are performed by adopting the state-space formulation described in the previous section. The simulations start with a randomly chosen value of TMD stiffness and the value changes until the desire results are achieved. Later, to be concise, the TMD stiffness value has changed in an interval of 500 unit. However, this value was selected after few initial trials. In total, 31 cases were considered and the summary of the changes of the TMD stiffness is presented in Table 1. The last case was not included in the table that case would be C-31 and the value of $k_d$ is 15100. The time-history of the top floor (e.g. 15th) with different values of stiffness of TMD is depicted in figure 2. However, only 18 cases are presented in the previous figure even though the simulations are performed for 31 cases. The results show that the performance may vary due to the choice of the value of stiffness of TMD. However, in order to observe the effect of the TMD’s stiffness only, all other parameters were kept constant in an optimal position. In order to evaluate the efficiencies of the TMD the displacement time-history of 5th, 10th, and 15th floor are depicted in figure 3. The red-dashed line indicates the response of the controlled structure whereas the green solid line represents the uncontrolled response. And it is clearly visible that the vibration of the structure has been mitigated successfully for all of the floors. One-step further, the damping of the TMD has been varied and the performances are evaluated. To attain the goal total 40 cases have been created and simulations are performed. And a set of sample simulations results are shown in figure 4. However, due to the space limitations on 18
### Table 1. Summary of the changes of the TMD stiffness.

| Cases | C − 01 | C − 02 | C − 03 | C − 04 | C − 05 | C − 06 | C − 07 | C − 08 | C − 09 | C − 10 |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| $k_d$ (N/m) | 100 | 600 | 1100 | 1600 | 2100 | 2600 | 3100 | 3600 | 4100 | 4600 |
| Cases | C − 11 | C − 12 | C − 13 | C − 14 | C − 15 | C − 16 | C − 17 | C − 18 | C − 19 | C − 20 |
| $k_d$ (N/m) | 5100 | 5600 | 6100 | 6600 | 7100 | 7600 | 8100 | 8600 | 9100 | 9600 |
| Cases | C − 21 | C − 22 | C − 23 | C − 24 | C − 25 | C − 26 | C − 27 | C − 28 | C − 29 | C − 30 |
| $k_d$ (N/m) | 10100 | 10600 | 11100 | 11600 | 12100 | 12600 | 13100 | 13600 | 14100 | 14600 |

**Figure 2.** The response of 15th floor due to TMD’s stiffness variation.

cases are presented only. The damping coefficient of TMD has started from 30000 N-s/m with the increment of 50000 unit which went up to 1980000 N-s/m. Again the time-history response of 5th, 10th, and 15th floor are presented in figure 5. In the previous figure, the red-dashed line means the dynamical response of the controlled structure whereas the orange solid line shows the response of the uncontrolled structure. Where it is observed that the vibration of the structure has been reduced efficiently for all of the floors.

Finally, the optimization is performed by employing the unconstrained multi-variable scheme via the use of derivative-free method. The norm of the uncontrolled displacements (e.g. 1st, 15th floor) were defined as the targeted fitness−function for the optimization. The formulation detail of the used optimization scheme can be found in [18]. A sample set of results are presented in figure 6. Red-dashed line symbolizes the controlled dynamical response while the black solid line meas the uncontrolled dynamical response. The outcome of the optimization has confirmed
Figure 3. The 5th, 10th and 15th floor’s controlled and uncontrolled response comparison for TMD’s stiffness variation.

Figure 4. The response of 15th floor due to TMD’s stiffness variation.

that the derivative-free optimization can be used to select the optimal set of TMD parameters instead of manual or sub-optimal choice.
Figure 5. The 5\textsuperscript{th}, 10\textsuperscript{th} and 15\textsuperscript{th} floor’s controlled and uncontrolled response comparison for TMD’s damping coefficient variation.

Figure 6. The optimized controlled response of 5\textsuperscript{th}, 10\textsuperscript{th} and 15\textsuperscript{th} floor have compared with uncontrolled response.
4. Conclusions
This study investigates the performance of a TMD used in a high-rise building by applying dynamic excitation. To attain the goal, the parameters of the TMD has been varied to observe the sensitivity and later optimized by employing an unconstrained derivative-free optimization method. The observations can be summarized as: (i) the performance of the TMD heavily relies on the mass-ratio, (ii) the problem description needs to be accurate/precise, (iii) existing models for tuning the parameters of all TMDs may not be suitable due to many reasons such as loading conditions or structure itself, (iv) derivative-free/heuristic optimization algorithms can help to determine the suitable (e.g. optimal) set of TMD parameters. The outcome of this study shows that a TMD with optimized properties will perform better than manual tuning. Because most of the time, TMD parameters may not be optimal when they are manually tuned. Future study will investigate the possibility of identifying optimal parameters for various dynamic loads by employing system identification techniques.

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