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Effectiveness of distributed tuned mass dampers for multi-mode control of chimney under earthquakes

Said Elias [*,1], Vasant Matsagar [2], T.K. Datta [3]

Department of Civil Engineering, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi 110 016, India

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ABSTRACT

Effectiveness of distributed tuned mass dampers (d-TMDs) designed according to the mode shapes for multi-mode control of chimneys as against the TMDs placed arbitrarily (ad-TMDs) and single TMD (STMD) under earthquake ground motions is investigated. The investigation includes geometrically regular and irregular chimneys under un-cracked and cracked conditions. A reinforced concrete (RC) chimney is considered as an assemblage of beam elements, each assumed to have constant diameter over the element length. The coupled differential equations of motion for the chimney and TMDs are derived and solved using Newmark's integration method. Best possible locations of the TMDs are identified based on the mode shapes of the uncontrolled (NC) chimney. A TMD is placed where the mode shape amplitude of the chimney is the largest or larger in a particular mode and is tuned with the corresponding modal frequency. The number of modes to be controlled is decided according to total modal mass participation being ninety percent. In order to achieve the objective of the study, the performance of the d-TMDs used in the present method is compared with the STMD and ad-TMDs cases. A parametric study is conducted to find the most suitable mass ratio and damping ratio for all cases. It is observed that the d-TMDs are more effective than the STMD and ad-TMDs for the same total mass of the TMD/TMDs.

1. Introduction

Reinforced concrete (RC) chimneys are widely used in industries with varied geometries. The height of a chimney influences its ability to transfer flue gases to the external environment via stack effect. The wider area of dissipating the hazardous substances and reduced environmental impact is possible with the taller chimneys, which ranges from 100 to 420 m heights. Chimneys are considered by professionals to be geometrically simplest structures among other choices, when subjected to earthquake ground motion, to perform the same purposes.

Chimneys are damaged or collapsed due to earthquake ground motion all over the world. The examples of the RC chimney collapse at Izmit Tupras Refinery due to the 1999 Kocaeli earthquake can be cited as a case for large financial loss and business interruption. Codes of practice around the world provide conservative guidelines for the seismic design of tall RC chimneys, because earthquake engineers felt that such structures would behave in a brittle manner when subjected to severe earthquake excitation. Later, it was recognized that these structures behave in a ductile manner and in the CICIND code (French for International Committee on Industrial Chimneys) [13] suitable recommendations have been incorporated for the design of the RC chimneys. The newer code provisions resulted in cheaper chimneys which perform better under earthquake excitations. Wilson [54] reported that the RC chimneys possess some ductility when subjected to cyclic loads. Based on the results of the experimental and numerical research concerning the ductility and seismic behavior of the RC chimneys by Wilson [54], a series of code design recommendations were prepared and incorporated in the 2001 CICIND code to encourage reliance on the development of ductility in the RC chimneys and to prevent the formation of brittle failure modes. Wilson [55,56] established, from an experimental program, that the RC chimneys respond in a moderately ductile manner under severe reverse cycle loading through yielding of the reinforcement in tension provided that the sections possess a reasonable curvature capacity. Several researchers such as Vickery and Watkins [52], Maugh and Rumman [35], Rumman [45], Vickery and Clark [51], Watt et al. [53], Kwok and Melbourne [25], Luco [34], and Datta and Jain [14] had proposed different procedures for earthquake and wind response control of chimneys. Murty [38] reported that in tall structures with

* Corresponding author.
E-mail addresses: said.elias@civil.iitd.ac.in (S. Elias), matsagar@civil.iitd.ac.in (V. Matsagar), tkdatta@civil.iitd.ac.in (T.K. Datta).
[1] Ph.D. Research Scholar.
[2] Associate Professor.
[3] Emeritus Professor.

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large height-to-base size ratio, the horizontal movement during ground shaking is large. Chimney, as a structure, can be visualized as a vertical flexible cantilever dominated by higher mode effects. Wilson [56] reported that the behavior of a tall chimney under earthquake excitation is complex, with dominance of higher modes in its response. Due to this complex response, the shear force distribution along the height of the chimney can no longer be treated as triangular or smoothly varying parabolic curve with minimum and maximum shear at the top and bottom, respectively. This odd nature of variation is contrary to most of the code assumptions of the idealized shear distribution. With structures dominated by higher modes, the over-strength factors presently used in the design becomes no longer conservative. Under one such incident, the over-strength factors were increased further to make the design conservative and the additional cost of the structure was assessed. It was found that the structure required an additional amount of US$ 3.2 million [56]. Noting the exorbitant rise in the project cost, it is of interest to analyze reduction in the response and the consequent shear force by using some alternative approaches. Recently, Brownjohn et al. [9] had shown the effectiveness of tuned mass damper (TMD) to control the responses of an old chimney. They installed a TMD on a 183 m high old chimney to improve the damping of the chimney. Later, Longarini and Zucca [33] reported that the TMD improves the seismic response of the chimney in terms of the compressive and tensile stresses, base shear, and top displacement.

In the passive vibration response control, the tuned mass dampers (TMDs) are the popular structural response control devices, which have been extensively researched on. The effective use of the TMDs for vibration response control of structures subjected to earthquake and wind excitations was shown by Kwok and Samali [26], Pinkaew et al. [43], and Parulekar and Reddy [41]. Multiple tuned mass dampers (MTMDs) were confirmed to be more effective than a single tuned mass damper (STMD) in the dynamic response control of structures as reported by several researchers such as Xu and Igusa [59], Yamaguchi and Harnpornchai [60], Abe and Fujino [1], Kareem and Kline [24], Rana and Soong [44], Li [29], Park and Reed [40], Li and Qu [31]; Guo and Chen [18], and Han and Li [19]. Especially, improved structural vibration response control by using the dampers with optimum parameters was demonstrated in the studies conducted by Joshi and Jangid [23], Chang [10], Jangid [22], Chen and Wu [11], Li [30], Ahlawat and Ramaswamy [2], Bakre and Jangid [5], Lee et al. [27], Aydin et al. [4], Ghosh and Basu [17], Hoang et al. [20], Leung and Zhang [28], Lin et al. [32], Bekdas and Nigdeli [7], Patil and Jangid [42], and Bandivadekar and Jangid [6].

Moon [37] had shown that the multiple tuned mass dampers (MTMDs) distributed vertically along the entire structure improved effectiveness of the control of response of the high-rise buildings. Lately, Xiang and Nishitani [58] reported that the MTMDs are effective for multi-mode control of the low-rise buildings with closely spaced frequencies under earthquake ground excitations. Effectiveness of the distributed tuned mass dampers (d-TMDs) to control the across wind vibration of 76-storey benchmark building was studied by Elias and Matsagar [15,16]. However, no study is conducted on the earthquake response control of chimney wherein placement and tuning of the d-TMDs are made in accordance with the modal properties of the chimney.

The objective of the present study is to investigate the effective placement and tuning of the d-TMDs based on the mode shapes and frequencies of the chimney. In this approach, a TMD is placed where the mode shape amplitude of the chimney is the largest or larger in the particular mode and the TMD is tuned to the corresponding modal frequency. Thus, the d-TMDs are placed to suppress the responses of first few selected modes of the chimney, and the approach is called multi-mode control. In order to show the effectiveness of the d-TMDs placed according to the mode shapes, assessment is made with the seismic responses obtained using: (i) d-TMDs placed arbitrarily (ad-TMDs); (ii) single tuned mass damper controlling only the first modal responses ($STMD_1$); and (iii) single tuned mass damper controlling only the second modal responses ($STMD_2$). Further, a detailed parametric study is conducted to identify the parameters which affect the response control subjected to the white noise and number of real earthquakes, for geometrically regular and irregular chimneys under un-cracked and cracked conditions.

2. Theory and modeling

The chimney is modeled as an assemblage of beam elements with sway degrees of freedom considered to be the dynamic degrees of freedom. The theoretical development is based on the assumption that the cross-sectional dimension within the element remains the same, i.e. prismatic beam element. Additional assumptions made for the analytical formulation are: (i) the chimney is considered to remain within the elastic limit under the earthquake excitation in un-cracked condition; (ii) the system is subjected to a single horizontal (uni-directional) component of the earthquake ground motion; and (iii) the effects of soil-structure-interaction (SSI) are not taken into consideration.

2.1. Mathematical modeling of chimney

Fig. 1(a–f) shows the lumped mass model of the chimney, placement of the TMDs, and the degrees of freedom considered in the study. The governing equations of motion for the chimney installed with the STMD at the top and installed with the d-TMDs are obtained by considering the equilibrium of forces at the location of each degree of freedom as follows.

$$[M_s]\{\ddot{x}_s\} + [C_s]\{\dot{x}_s\} + [K_s]\{x_s\} = -[M_s]\{r\}\ddot{x}_g \tag{1}$$

where $[M_s]$, $[C_s]$, and $[K_s]$ are the mass, damping, and stiffness matrices of the chimney, respectively of order $(N+n) \times (N+n)$. Here, N indicates degrees of freedom (DOF) for the chimney and n indicates DOF for the $STMD_1$, $STMD_2$, ad-TMDs, or d-TMDs. Further, $\{x_s\} = \{X_1, X_2, \ldots, X_{N-1}, X_N, x_1, \ldots, x_n\}^T$, $\{\dot{x}_s\}$, and $\{\ddot{x}_s\}$ are the unknown relative nodal displacement, velocity, and acceleration vectors, respectively. The earthquake ground acceleration is represented by $\ddot{x}_g$ and $\{r\}$ is the vector of influence coefficients. The modal frequencies and mode shapes of the chimney without d-TMDs are determined by solving the Eigen value problem. A TMD is placed where the mode shape amplitude of the chimney is the largest/larger in a particular mode and is tuned to the corresponding modal frequency. In addition, the modal masses of the chimney are also computed to make decision for number of modes to be controlled. Only first few modes are controlled, contributing to 90% of the total mass. Not more than one TMD is placed at a location, and the stiffness (k_i) and damping (c_i) parameters of the TMDs ($i = 1 \ldots n$) are calculated based on the modal frequencies. For the d-TMDs, the mass matrix is of order $(N+n) \times (N+n)$ as follows.

$$[M_s] = \begin{bmatrix} [M_N]_{N\times N} & [0]_{N\times n} \\ [0]_{n\times N} & [m_n]_{n\times n} \end{bmatrix} \tag{2}$$

where $[M_N]_{N\times N}$ shows the mass matrix for the chimney and $[m_n]_{n\times n}$ indicates the mass matrix of the TMDs. In Eq. (2), for obtaining mass matrix corresponding to the STMD $n = 1$ is considered. The condensed stiffness matrix $[K_N]_{N\times N}$ is corresponding to the sway degrees of freedom taken as the dynamic DOF. The damping matrix $[C_N]_{N\times N}$ is not explicitly known but is obtained with the help of the Rayleigh's approach using same damping ratio in all modes. The stiffness matrix, $[K_n]_{n\times n}$ and damping matrix, $[C_n]_{n\times n}$ are expressed