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Original Research Article

Kinematically excited parametric vibration of a tall building model with a TMD—Part 2: Experimental analyses

K. Majcher, Z. Wójcicki, J. Grosel, W. Pakos, W. Sawicki*

Wrocław University of Technology, 27 Wybrzeże Wyspiańskiego St, 50-370 Wrocław, Poland

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ABSTRACT

This paper constitutes the second part of the article *Kinematically excited parametric vibration of a tall building model with a TMD. Part 1: numerical analyses* (ACME, in press) by K. Majcher and Z. Wójcicki, which presents the results of theoretical research. This paper presents the experimental verification of those results. The experimental studies were carried out with the use of an especially designed physical model of a tall building, which rested on an earthquake simulator – a shaking table – created for this project. The simulator was used to generate several types of kinematic excitations: harmonic ones, superpositions of harmonic ones and, finally, ones generated on the basis of real seismograms. Vibrations were kinematically excited in the horizontal and vertical directions independently and simultaneously.

The vertical component of the earthquake causes the pendulum suspension point to vibrate, thus exciting the pendulum parametrically. The theoretical study indicated a significant influence of this parametric excitation (parametric resonance) on the effectiveness of the Pendulum Tuned Mass Damper (PTMD). Therefore, the experimental analyses were especially focused on the parametric effects' impact on:

- the PTMD's ability to reduce the building's vibration, and
- the possibility of parametric resonance of the building due to parametric resonance of the PTMD.

1. Introduction

The design of civil engineering structures under seismic load is part of the branch of science known as earthquake engineering. It is a branch especially cultivated in countries that are positioned in the vicinity of boundaries of tectonic plates, where earthquakes are a significant problem. These countries include Japan, the USA, China, Taiwan, India, Chile, Mexico, Russia, Turkey, Italy and many others. Therefore, many of the authors of the literature of seismic engineering come from these countries. Among the most important positions in the literature of the subject are: Taranath [1], Hori [2], Chen and Lui [3], Takewaki [4], Cheng and others [5].

*Corresponding author. Tel.: +48 713202934.
E-mail address: krzysztof.majcher@pwr.wroc.pl (K. Majcher).

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During an earthquake, vibrating motions of the ground occur that constitute the kinematic excitation of the structures and buildings. The intensity and character of these vibrations differ. Each earthquake has its own characteristic spectrum of excitation frequency. However, their common trait is that the greatest excitation usually occurs in the range of low or very low values of the frequency.

It is usually the horizontal component of the kinematic excitation that is the most dangerous to civil engineering structures. Therefore, scientists dealing with seismic engineering focus their attention on this dominant problem [6–9]. This is the result of, above others, the fact that buildings are designed to withstand mainly the vertical loads, as the main part of forces, i.e. dead load and imposed load, and the weight of the building's equipment, act in the vertical direction. Therefore, the buildings' structures are usually weaker and less stiff in the horizontal direction. The eigenfrequencies connected to the eigenforms with dominant horizontal displacements are usually lower than the ones with dominant vertical displacements. The taller the buildings, the lesser their horizontal stiffnesses – and as a result the values of their eigenfrequencies are even lower. The greatest resonant amplification of vibration occurs when the earthquake-induced kinematic excitation frequency is equal to the building's main eigenfrequency. Therefore, tall buildings whose main eigenfrequencies are usually low are especially vulnerable to earthquakes.

This second part of the paper describes experimental studies performed with the use of a physical laboratory model of a tall building. The model was described in detail. A dimensional analysis was also presented, which was used to appropriately determine the ratio of dynamic parameters of the model to the dynamic parameters of a hypothetic real building. The experiment equipment was also described in detail – a shaking table designed and built by the authors especially for this experiment. The experimental study also used Brüel & Kjær's PULSE system, which was equipped with 32 mini-accelerometers THETASHEAR 4507 and a modal hammer with a set of impact tips with differing hardness, used to measure the force of vibration excitation. The results of the studies were used to verify the concordance of the two models: the experimental and the numerical, and to validate and attune the numerical FEM model created in the COSMOS/M software on the one hand. On the other hand, the results were used to confirm the thesis posed in the paper.

For the modal analysis of the model, Brüel & Kjær's PULSE system software for Modal Analysis was used. The modal analysis algorithms include Experimental (Classical) Modal Analysis (EMA), as well as Operational (Exploitational) Modal Analysis (OMA) also known as the Output-Only Modal Analysis. In the OMA, it is not necessary to especially excite vibration in the structure. The vibration caused by exploitation, or e.g. by the natural movement of the air around the structure, are sufficient. The OMA package contains 6 algorithms which were used in the analysis:

- FDD (Frequency Domain Decomposition)
- EFDD (Enhanced Frequency Domain Decomposition)
- CFDD (Curve-Fit Frequency Domain Decomposition)
- SSI-UPC (Stochastic Subspace Identification-Unweighted Principle Components)
- SSI-PC (Stochastic Subspace Identification-Principle Components)
- SSI-CVA (Stochastic Subspace Identification-Canonical Variate Analysis)

Some of the algorithms made it possible to determine not only the modal frequencies and modal forms, but also the modal damping coefficient values.

2. Aim of the paper

The main aim of the two parts of this paper was to prove the thesis that, in the case of a Pendulum Tuned Mass Damper (PTMD) installed in a tall building, it is necessary to take into account the vertical component of the seismic excitation alongside the horizontal one.

The aim of this part of the paper is to finally verify the results obtained through theoretical analyses performed with the use of the numerical FEM model, which were presented in the first part of the paper [10]. The verification was performed with the use of results obtained through detailed experimental studies performed on a physical model of a tall building with a PTMD installed.

3. Experiment equipment

3.1. *Measuring equipment*

Brüel & Kjær's system PULSE was used for the measurements and analysis of the vibration. The system's measuring properties are as follows:

- Input channels with a frequency range 0–25.6 kHz.
- The system and its acquisition modules are Dyn-X, i.e. they contain two 24-bite measurement cards; due to this, the system channels have:
  - a dynamics of 160 dB (80 dB for each card), and
  - perfect linearity and phase matching.

The well-developed diagnostics of the input channels allows for a practically unattended acquisition of signals; most importantly, it does not require regulating the input ranges. All of this, together with TEDS technology and the extensive diagnostics of the input chain condition, makes the data acquisition practically unattended, mostly because there is no need to control the input range settings.

The study used TEDS miniature accelerometers THETA-SHEAR type 4507 with frequency range 0.4 Hz–6 kHz, sensitivity 100 mV/ms^{-2}, mass 4.8 g input range do 700 m/s^2, noise level 1.50 mm/s^2. A modal hammer type 8206 was also used.

The PULSE system's software makes it possible to record the measured signals, in parallel to the real time analysis or separately for further post processing, as well, as different kinds of structural analysis. The modal analysis package deserves special attention. The package incorporates all