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Application of a 245 metric ton Dual-Use Active TMD System

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Abstract

The slender design of a 245 m tall tower structure requires additional structural damping to reduce vortex shedding induced vibrations. Wind tunnel tests indicate that wind speeds can produce critical accelerations at the observation deck on the tower's top level. The resulting displacements not only raise concern regarding the fatigue capacity at the concrete core of the tower, but would also lead to the discomfort of its visitors. To mitigate critical displacements, a state of the art passive Tuned Mass Damper (TMD) system was chosen to be implemented. The primary use of the tower is not only to give visitors access to its observation deck but to also serve as a test facility for equipment susceptible to building sway. To test the equipment under real life conditions the TMD system is required to be either in passive or in active mode, where in the latter it could excite the tower in its fundamental mode of vibration and cause a significant, yet controlled, building sway in any direction. To satisfy these requirements a novel dual purpose active/passive TMD system was developed. This hybrid TMD is capable of even suppressing the occurring vibrations in one direction while, with the aid of active control, synchronously exciting the tower's perpendicular direction. The following paper reports on the design approach of the passive system and describes the control strategy when switched into excitation mode. The initial optimization approach will be presented as well as the in-situ results of vibration tests during a monitoring campaign on the tower. In addition, the safety concept to avoid excessive displacements of the tower will be presented.

Keywords: *Vibration Monitoring; Tall Buildings; Active Control; TMD; Excitation Mode; Optimization*

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1. Introduction

The wind analysis for a 245 m tall and slender tower structure in Germany revealed that resonant excitation of the structure can occur at wind speeds which correspond to ground values (height 10m) in the range of 55 – 60 km/h. It was expected that without additional damping this resonant excitation would cause top deflections of about +/- 750 mm which would not only cause discomfort for the occupants but would also have significant fatigue life implications for the concrete structure of the tower. To reduce the dynamic response to cross wind excitation, a passive Tuned Mass Damper System was implemented. Since the tower shall be used as a test tower for building sway sensitive equipment, the owner was looking for a possibility to artificially excite the tower on calm days, though with displacements that would not cause any fatigue issues. The requested level for the artificial sway motion was in the considered safe range of approximately +/- 200 mm. This request gave the rare opportunity to implement a Hybrid Mass Damper (HMD) or, since the design system deviates from other HMD systems that were introduced in the past, a so called Dual Use TMD. The system shall be presented in the following chapters, including the optimization of the passive system, the design of the actuators' mechanism, control algorithms and the safety concept.

2. Description of the control system

The duality of the control system serves a) the purpose of an reduced energy consumption, while in normal passive operation, to reduce the occurring vibrations b) the purpose of reduced force requirements for the actuators, by using resonance effects in order to excite the main TMD mass for ultimately achieving the actual force demand. So, compared to other control systems (see Fig. 1) the actuators connect the main structure and the TMD mass but are not used to control the TMD mass directly as it would be the case for a typical Active Mass Driver/Damper system. For the implemented Dual Use TMD a reaction mass for the passive operation of 240 tons was chosen. For the excitation operation mode two linear drives – one in each principal direction- are attached to the TMD mass with pivots near the center of gravity of the mass to avoid any torsional artefacts. Each linear drive can provide forces up to 40 kN within a stroke of max. +/- 600 mm (see detail Fig. 2). The linear drives can be detached so that the entire passive mode will not be influenced by the bearings of the actuators for the unlikely event of a bearing failure.

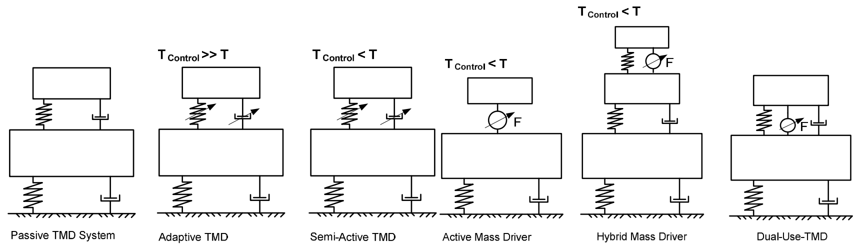

Fig. 1. Types of Control Systems – Dual Use TMD compared to passive, semi-active, active and hybrid systems

The system is instrumented with four uniaxial accelerometers (seismic K-Beam/MEMS; one in each direction) to determine the tower top level and the TMD mass accelerations. The acceleration signals are getting bandpass filtered inside the frequency range of the towers fundamental natural frequencies (0.1 – 0.3 Hz) and integrated to give the tower velocities and deflections. In addition, the integrated displacement values can be compared against the ones of a complimentary Global Navigation Satellite System installed also at the top to compare for signal drifts. An initial correlation tests was performed accordingly. Furthermore, the TMD displacements are monitored directly with string pot transducers and an inductive length measuring system integrated within the linear motors.

3. Optimization of the passive Tuned Mass Damper System

The parameters of the passive TMD system had to be determined considering three different aspects a) to provide sufficient additional structural damping in order to reduce the dynamic response owing to vortex shedding excitation, b) to limit the resulting TMD main mass travel in the passive mode, to an attainable/practical value, for when under gust cross wind excitation and c) to choose the TMD mass according to the energy input that is required for the desired maximum tower deflection in the excitation mode, considering the performance envelope enabled by the provided actuators (i.e. maximum force generated and maximum stroke during operation). To optimize the TMD system a numerical model was used that represented the mass distribution of the tower, and mass moments of inertia as reported in the identified structural properties. The stiffness elements between the floors were also tailored to match the mode shapes and natural frequencies from full-scale observations.

Fig. 2. Left: Pendulum rope supported TMD mass – Right: Linear Motor as actuator

Fig. 3-left shows the mode shapes and natural frequencies of this employed analogous model. Fig. 3-left also compares the mode shapes of the analogous model against these of the detailed model prepared by the structural consultant. In addition, the TMD has been discretely modeled as a pendulum system capturing also its eccentric position at the tower.

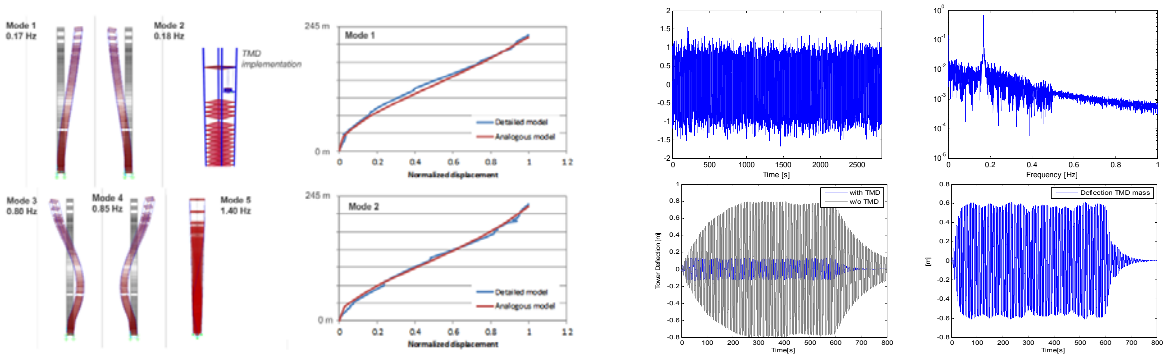

Fig. 3- Left: Relevant modes and calculated natural frequencies for model calibration – mode shape comparison – Right: Above: generated time history for the crosswind loading and resulting FFT spectrum – Below: Tower Displacement with and without optimized TMD and resulting TMD displacement

The load characteristics for the governing input case, i.e. resonant excitation due to vortex shedding, are very alike to that of a single harmonic excitation. Yet, the co-existing gust loading is inherently of stochastic nature and for it, optimization criteria other than the well known Den Hartog criterion apply. In addition, the relative displacements of the TMD mass are bigger for a stochastic than for a harmonic type loading. Since for the numerical determination of the optimum TMD parameters a close to reality loading should be considered, a time history was generated that included both the stochastic gust loading (based on the Davenport Spectrum) and a superimposed resonant, vortex shedding like, component for representing the overall cross wind excitation (see Fig. 3-right). The tower deflection reduction that can be achieved with the optimized passive TMD system as well as the resulting TMD displacements are shown in Fig. 3-right. Based on these results for an estimated inherent structural damping of ξ=0.8 %, it was determined that a TMD mass of 240t was required to keep the displacements within +/- 650 mm while maintaining an optimum TMD damping ratio for the best TMD performance. An increase of the TMD damping could have reduced the travel while the efficacy would still have been sufficient but this would have adversely affected the actuator force requirements. To determine the required forces for the optimum 240 t TMD setup the analogous model has also been used to verify that, with a maximum force of 40 kN from the actuators, tower deflections can be achieved in the range of +/- 200 mm.

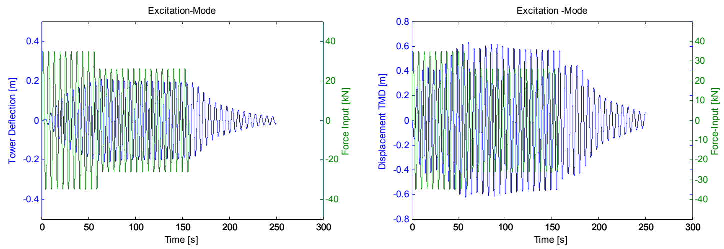

Fig.4. Numerical Time Domain Analysis – Left: Resulting tower deflections from the shown force input/Right: Resulting TMD mass displacements

Fig. 4 shows the results of a time domain numerical simulation on the analogous numerical model; for this the resulting tower top deflections, the TMD mass deflections and the input active forces that cause them are displayed.

4. Control algorithm

The general control loop for the tower is shown in Fig. 5 which illustrates the closed loop control sequence . A detailed design of the control algorithm would require analytical models of the actuators-TMD mass interaction to determine the connection between actuator input to applied action force. These should combine with the analytical model of the main structure that describes the overall building dynamic behavior. Further, compared to standard control algorithms that were applied to other HMD applications as in [2],[3] or theoretically investigated as in [1] the control algorithm for this tower application had to consider synchronous controlled excitation in one main direction and vibration reduction in the perpendicular direction. Since the dynamic response is majorly expected in the fundamental modes, linear feedback control with all its benefits to avoid instabilities could be applied for both these tasks.For the simple control realization practiced, the linear feedback control, that attenuates the towers dynamic response perpendicular to the excitation, drives the relevant actuator through a specified weighted linear sum of seven structural dynamic measurements. These measurements are: TMD and tower top accelerations, TMD and tower top velocities, TMD and tower top displacements, and TMD to tower top relative displacement. It is important to note that the preselected weighting factors are simple, positive or negative scalar gains. The parametrization of the weighting factors is based on the dynamic tests of the tower and are not using any frequency dependent modification. The active actuator feedback is calculated instantaneously (at 50Hz), and it is again a linear combination of the previous dynamic measurements. There is no nonlinear manipulation being used. The control design was also implemented in a time domain numerical simulation (i.e. direct integration) to evidence the performance of the actuator control vibration mitigation. For the excitation mode the same control approach has been used in combination with a displacement offset that represents the excitation of the tower to the desired displacement value. The offset is a sinusoidal function based on the detected fundamental frequency of each direction. The control output to counteract the variation of the top displacement due to other disturbances is then modulated on the sinusoidal offset function and the control value is adapted accordingly.

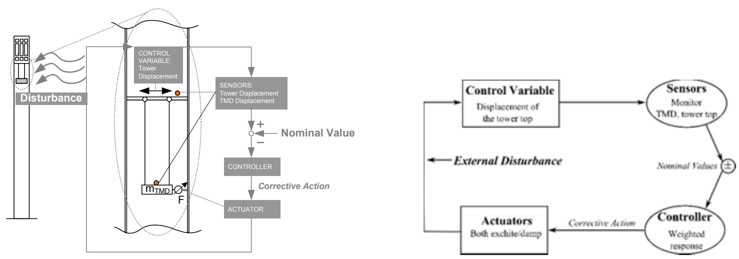

Fig.5 Feedback control loop practice.

5. Safety concept

Considering the force of +/- 40 kN that can be provided by the linear drives that are used as actuators, a safety concept to ensure that the tower displacements do not exceed the fatigue provisions is indispensable. This applies even though the force output is not sufficient to cause top deflections larger than the predetermined +/-200 mm. One approach to enhance the safety of the system was to increase the redundancy of the monitoring sensors which are recording the tower's top deflection. This can be best achieved by implementing an additional independent monitoring system that ideally uses a different measuring principal than the actual control hardware. For the herein presented project, the control hardware used, as quoted, accelerometers and a defined acceleration threshold for signal band-pass filtering within the range of the structure's relevant natural frequencies. The overriding superordinate monitoring system is a Global Navigation Satellite System (GNSS) with an accuracy of +/- 10 mm. The GNNS system requires a reference base station, which is processing the coordinate data to the actual displacement response values. If the tower's top displacement exceeds a predetermined threshold during the artificial excitation mode, which could owe to additional wind or other excitation, a relay will switch the attendance signal to 0V. This will cause aborting the excitation mode. In addition, both monitoring systems are constantly checking the acquired data for faulty sensor signals which will also result in aborting the active excitation mode. The faulty acceleration/string pot signals will be detected by a spectral peak picking criterion – only if peak picking in a relevant range is possible it can be assumed that the sensors provide legitimate signals. While the GNNS system analyzes the change of the coordinate data, if the sampled data do not timely change, a faulty signal is automatically assumed.

6. Vibration tests

Initial vibration tests of the tower were performed at the current stage, where the tower is not yet completed. During these, the fundamental frequencies of the structure were verified to be above the specified theoretical tuning range of the passive TMD system. Thus, the TMD was subsequently adjusted to the highest possible tuning frequency. A main objective of the vibration tests was the determination of the fundamental frequencies of the tower with inactive the TMD system (i.e. blocked) and the sizing of the inherent structural damping. In addition, the dynamic behavior with engaged the passive TMD system was to be determined, particularly with regards to the supplementary damping provision due to the action of the auxiliary vibration mitigation. To identify the fundamental natural frequencies of the tower the Averaged Normalized Power Spectral Density (ANPSD) Method [1] can be used. For this, the recorded time histories have to be separated into segments. These segments have to be transformed into the frequency domain. Fig. 6 left shows the recorded time histories of the horizontal ambient vibrations in the x- and y-principal directions with inactivated the TMD. Fig. 6 right shows the resulting averaged Auto Power Spectra (APS) for a segment length of 120 seconds.

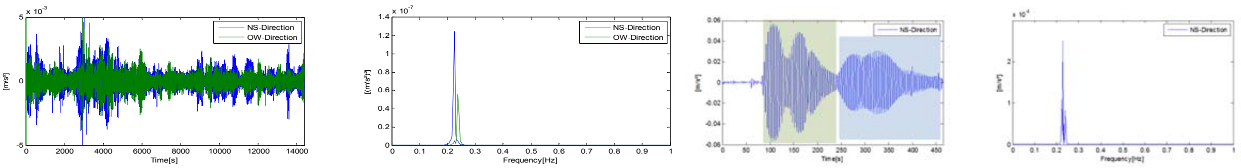

Fig.6. Above-Left: Time History of the measured acceleration at the top of the tower in the two main directions – Above-Right: corresponding APS spectra Below-Left: Time histories of the occurring accelerations at the tower top during the artificial excitation (marked green: sinusoidal excitation / marked blue: controlled excitation mode with suppression in one of the main axis – Below-Right: FFT spectrum

The spectra show that the tower shows considerable dynamic response at two dominant frequencies (0.225 Hz in x-direction and 0.245 Hz in y-direction). Further to the above described Averaged Power Spectrum Method – which assumes that the ambient excitation causes a sufficient dynamic response in the vibration modes of interest to gain stochastic security- the natural frequencies were determined using the commercial signal processing software ARTEMIS which incorporates the Enhanced Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Identification (SSI) methods [1]. Both these identification techniques are widely used for output-only modal parameter identification, particularly in full scale. The former relies on computation and curve fitting of response spectra. Long records are, therefore, required to keep low the error on spectrum estimation and to extract modal parameters in a reliable way. The SSI algorithm, on the other hand, was applied to modal identification case studies of many bridges whereby an output–only approach is the only option. The methods works in the time domain and is based on algebraic manipulations of the state space description of the inherent structural dynamic problem. The system identification process results at different model orders, which are successively compared against them to distinguish the true structural modes from spurious ones within the so called stabilization diagrams. These diagrams are a popular way to select the identified system model, as the true structural modes tend to be stable for increasing model orders, fulfilling certain stabilization criteria that are evaluated in an automated procedure. An increase of the structural damping can be noticed for the case of the TMD addition. The supplementary structural damping is in the range of the theoretical value that can be determined from the analogous model study with the actual detuned TMD setup considered. In addition to the ambient vibration tests with the passive TMD system, preliminary tests with also the excitation mode on were performed, despite the detuned state of the TMD system. Fig. x left shows the time history of the recorded accelerations at the tower top. After an initial sinusoidal excitation the control algorithm for ensuring a steady tower acceleration level was enabled to experimentally determine the correlation between tower deflection and forced displacement of the TMD mass. The time history shown in Fig. x-bottom displays the two test scenarios in the excitation mode and the corresponding FFT spectra indicate the clear response of the tower in its two fundamental frequencies (for the x- and y- direction). The green marked/shadowed time section is a sinusoidal excitation of the mass, with disabled active damping provision perpendicularly, which caused beating dynamic responses in both the main directions. The resulting FFT spectrum displays two peaks enabling identification of the fundamental frequencies in both directions. The blue marked/shadowed time segment is for an excitation, with enabled active damping control perpendicularly, which caused a steadier tower displacement primarily in one direction. The resulting vibration decay, after the excitation mode was switched off, was further used to determine the structural damping; this was determined to be ξ=2.4 %. This result correlates well with the damping ratio determined through using the SSI algorithm.

7. Conclusions and outlook

A Dual Use TMD has been installed at a 245 m tall test tower with the objective to purposely excite it to a controlled dynamic response in its fundamental frequencies. The objective of this excitation is to achieve a predefined building sway in the two principal directions of the tower. Based on numerical calculations it was found that a 240 t TMD mass was necessary in order to achieve the required supplementary damping for the passive mode and to generate the required control force to achieve a tower top displacement of +/- 200 mm for the active mode. To create a steady displacement level for the excitation mode and to suppress the displacements caused by wind and the forced vibration component in the perpendicular direction, a control algorithm was developed and tested through numerical simulations. After the actual installation of the passive pendulum type TMD system, for which prefabricated concrete slabs were used as reaction mass, the actuators were commissioned and initial tests have been performed. The tests revealed that the inherent damping of the tower was higher than anticipated but all relevant modes could be determined clearly. The active excitation mode of the building was verified to be functional and could be tested, although not to its full extent -the building is not entirely completed yet- in order to derive all operation parameters, Due to the premature state of the building, the passive TMD could not be adapted to the experimentally observed fundamental frequencies. As soon as the TMD system has been adapted, further tests of the building will be performed that will also include tests regarding the efficacy of different active control options and the integrity of the safety concept.

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