International Journal of High-Rise Buildings
June 2019, Vol 8, No 2, 117-123
https://doi.org/10.21022/IJHRB.2019.8.2.117

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Reduced-mass Adaptive TMD for Tall Buildings Damping

Felix Weber[1†], Peter Huber[2], Simon Spensberger[2], Johann Distl[3] and Christian Braun[2]

[1]*Maurer Switzerland GmbH, Neptunstrasse 25, 8032 Zurich, Switzerland*
[2]*Maurer SE, Frankfurter Ring 193, 80807 Munich, Germany*
[3]*Maurer Engineering GmbH, Frankfurter Ring 193, 80807 Munich, Germany*

Abstract

Tall buildings are prone to wind-induced vibrations due to their slenderness whereby peak structural accelerations may be higher than the recommended maximum value. The common countermeasure is the installation of a tuned mass damper (TMD) near the highest occupied floor. Due to the extremely large modal mass of tall buildings and because of the narrow to broad band type of wind excitation the TMD mass may become inacceptable large – in extreme cases up to 2000 metric tons. It is therefore a need to develop more efficient TMD concepts which provide the same damping to the building but with reduced mass. The adaptive TMD concept described in this paper represents a solution to this problem. Frequency and damping of the adaptive TMD are controlled in real-time by semi-active oil dampers according to the actual structural acceleration. The resulting enhanced TMD efficiency allows reducing its mass by up to 20% compared to the classical passive TMD. The adaptive TMD system is fully fail-safe thanks to a smart valve system of the semi-active oil dampers. In contrast to active TMD solutions the adaptive TMD is unconditionally stable and its power consumption on the order of 1 kW is negligible small as controllable oil dampers are semi-active devices. The adaptive TMD with reduced mass, stable behavior and lowest power consumption is therefore a preferable and cost saving damping tool for tall buildings.

Keywords: Adaptive, Control, Damping, Semi-active, TMD, Vibration

1. Introduction

Tall buildings are susceptible to wind-induced vibration because of their slenderness. The most economic and therefore most often applied countermeasure is to install a pendulum type tuned mass damper (TMD) near the top floor to reduce structural vibrations of commonly the fundamental bending mode (Den Hartog, 1934, Soong and Dargush, 1997, Asami and Nishihara, 2003) besides other methods such as the incorporation of distributed hydraulic and smart dampers or steel hysteretic dampers (Aly, 2016, Ali et al., 2019). The key parameter of the TMD to provide sufficient supplemental damping to the structure is its pendulum mass relative to the effective modal mass of the building which is denoted as mass ratio. To reduce peak structural accelerations to the acceptable values for residential and office buildings for the 1-year return period wind according to the Standard ISO 10137:2007 the mass ratio is often between 1% and 3% which may lead to pendulum masses up to 2000 metric tons. Such big TMD masses are not preferable both from the economic and safety point of view. It is therefore a need to develop more efficient TMD concepts to generate the same structural vibration mitigation as classical TMDs but with reduced TMD mass. A further TMD requirement is to consume less space for TMD installation to augment the economic benefit of the building. Finally, impacts of the pendulum mass during extreme wind events and earthquakes must be avoided to ensure structural safety. Considering these requirements TMD concepts with adaptive behavior are needed to reduce pendulum mass and installation height and to avoid impacts of the TMD mass on the building (Pinkaew and Fujino, 2001, Aly, 2014, Rezaee and Aly, 2018). Within the large variety of adaptive TMDs active TMDs do not seem to be the appropriate solution due to their increased relative motion, energy consumption, stability issues and not existing fail-safe behavior (Kim et al., 2011). One promising solution is therefore the concept of semi-active TMDs where the passive oil dampers of the classical TMD are replaced by real-time controlled oil dampers which are semi-active devices and as such do not require great power (~1 kW) and cannot lead to unstable TMD behavior (Kang et al., 2011, Zemp et al., 2011, Weber, 2014, Weber et al., 2016 (a, b), Weber et al., 2017, Weber et al., 2018). The key principle of these semi-active TMDs is that semi-active oil dampers allow emulating a superimposed dynamic stiffness force by the modulation of their damping force during each half vibration cycle whereby frequency and damping of semi-active TMDs can be controlled in real-time (Weber and Maślanka, 2014). In the past, the semi-active TMD were mainly developed for enhanced vibration mitigation. However,

†Corresponding author: Felix Weber
Tel: +41-44-520-8069
E-mail: F.Weber@maurer.eu

for tall building damping the space demand of the TMD system and the costs related to the extremely large pendulum masses are the crucial issues. Therefore, this paper presents a novel semi-active TMD concept which aims at producing the same building damping but with reduced pendulum mass compared to the classical passive TMD. The proposed semi-active TMD concept is enriched with an adaptive nonlinear relative motion control approach to keep the relative motion within specified limits for great wind loads with long return periods and a fail-safe mechanism within the controlled oil dampers makes the presented semi-active TMD highly reliable.

2. Narrow to Broad Band Wind Excitation

Since 2014, the Danube City (DC) Tower in Vienna, Austria, is equipped with an adaptive TMD based on two semi-active dampers that are controlled by two independent real-time controllers including the monitoring code to obtain redundancy (Fig. 1). The monitoring system is programmed to observe the TMD relative motion amplitude, the semi-active oil damper forces, relevant control states and the top acceleration of the DC Tower in case that the top structural acceleration is greater than the trigger level of 5 milli-g. The triggered data acquisition during a winter storm in December 2016 is shown in Fig. 2 (left). The according spectrum depicted in Fig. 2 (right) reveals that the DC Tower mainly responded at its fundamental sway mode with eigenfrequency of 0,19 Hz. This real measurement demonstrates that TMDs must be able to mitigate narrow to broad band type structural responses.

3. MAURER Adaptive TMD

The enhanced vibration mitigation efficiency of the adaptive TMD of MAURER is based on the real-time controlled oil damper whose semi-active force is controlled by the electromagnetic bypass valve no. 1 (Figs. 3(a), 3(b)). The electromagnetic valve is controlled in real-time to track the desired semi-active control force

$$f_{desired\text{-}semi\text{-}active}=\begin{cases} f_{desired\text{-}active} & (\dot{x}_{TMD}\cdot f_{desired\text{-}active})\geq 0 \\ 0 & (\dot{x}_{TMD}\cdot f_{desired\text{-}active})<0 \end{cases} \quad (1)$$

where $\dot{x}_{TMD}$ is the relative pendulum velocity and $f_{desired\text{-}active}$ the desired active control force which is composed of one component compensating for the structural acceleration $\ddot{x}_{structure}$ and one damping component controlling the pendulum relative motion $\dot{x}_{TMD}$

$$f_{desired\text{-}active}=k_1\cdot\ddot{x}_{structure}+k_2\cdot x_{TMD}^{\alpha} \quad (2)$$

Nonlinear ($\alpha\geq 2$) viscous damping is generated by the control law (2) in order to disproportionally increase the TMD damping force at great relative TMD motion amplitudes in order to avoid impact of the pendulum mass on the structure. Notice that controllable dampers do not only allow generating quadratic but also cubic (α=3) or higher order viscous damping. The feedback gains k_1 and k_2 are model-based designed to obtain the best compromise between structural acceleration reduction and pendulum motion control. Successful force tracking control tests as shown in Fig. 4 confirming that the semi-active oil damper technology is capable to control damping and frequency of the adaptive TMD in real-time without the disadvantageous of active systems such as huge power demand and stability issues.

4. Smart Fail Safe Mechanism

The valve no. 1 controlling the actual oil damper force is accompanied by the bypass valve no. 2 to make the adaptive TMD fully fail-safe (Figs. 3(b), 3(c)). Under current feed valve no. 1 is controlled to generate the semi-active oil damper force while valve no. 2 is closed at 0.8 A. During power break down valve no. 1 is closed



Figure 1. (a) Danube City Tower (Vienna, Austria), (b) two semi-active oil dampers connected to pendulum mass, and (c) two independent real-time controllers with monitoring system.

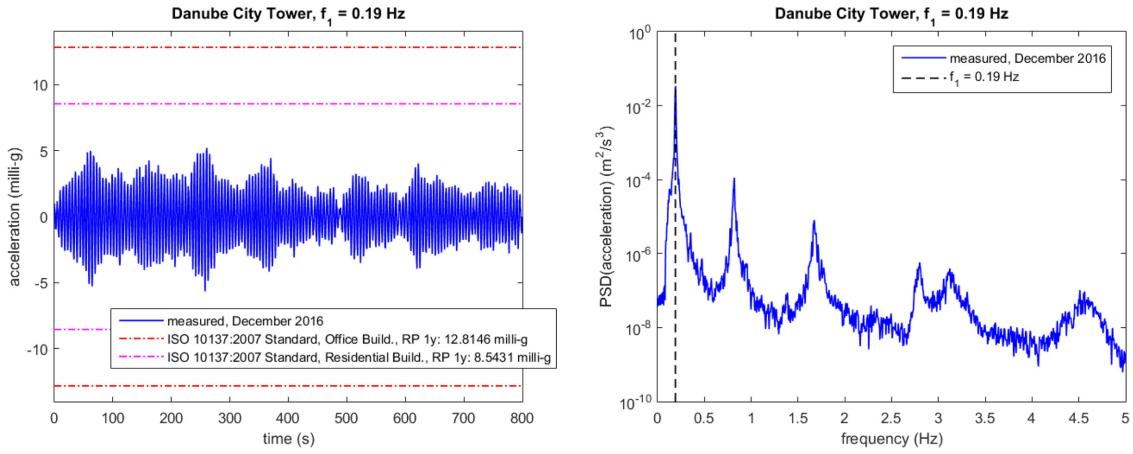


Figure 2. Measured top acceleration of the DC Tower (left) and the corresponding spectrum (right).

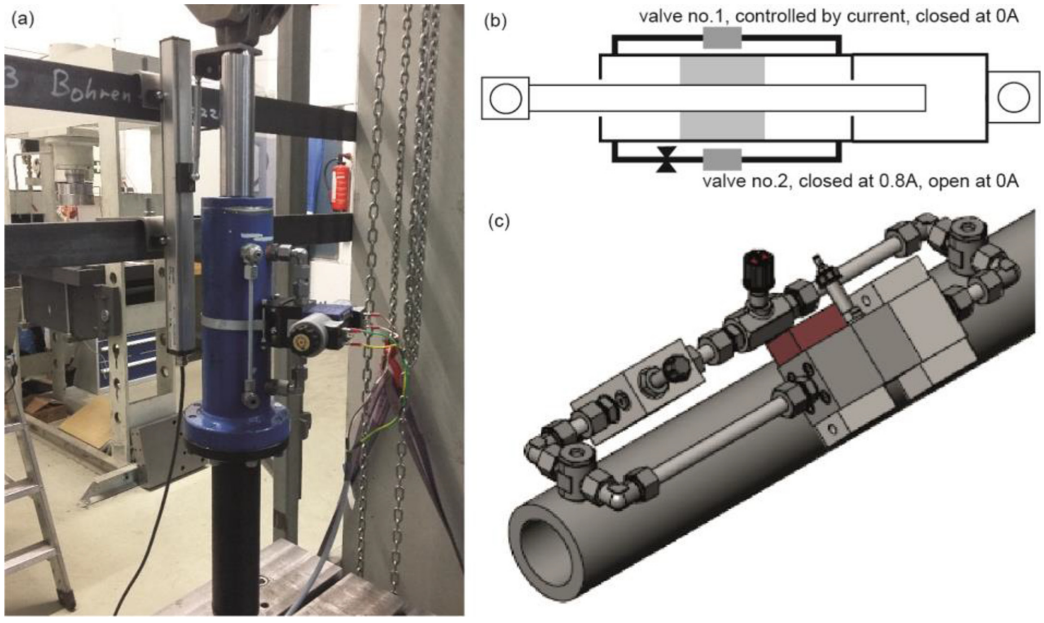


Figure 3. (a) Prototype semi-active oil damper, (b) schematic of entire semi-active oil damper with smart fail-safe valve system and (c) smart fail-safe valve system.

(at 0 A) and valve no. 2 open (at 0 A). Then, the damping of the TMD is equal to that of the passive TMD whereby the adaptive TMD behaves as a passive TMD.

5. Improved Performance at 90% TMD Mass

The performance of the adaptive TMD with 90% of pendulum mass is computed by dynamic simulation of the entire TMD system and building structure excited by wind in the time domain. The results in terms of structural acceleration and TMD relative motion are compared to those obtained from the passive TMD with 100% of pendulum mass and quadratic viscous damping optimized for the 1-year return period (1y-RP) wind (Fig. 5). From the structural acceleration time history for the 1y-RP wind the according peak value is determined as follows

$$peak\ value = mean(\ddot{x}_{structure}) \pm g_p \cdot \sqrt{mean(\ddot{x}^2_{structure})} \quad (3)$$

$$g_p = \sqrt{2 \cdot \ln(f_1 T_{\max})} + \frac{0.577}{\sqrt{2 \cdot \ln(f_1 T_{\max})}} \quad (4)$$

where g_p denotes the peak factor and $T_{\max}$ the duration of simulation. The peak value is compared with the value recommended by the Standard ISO 10137:2007 for 1y-RP wind

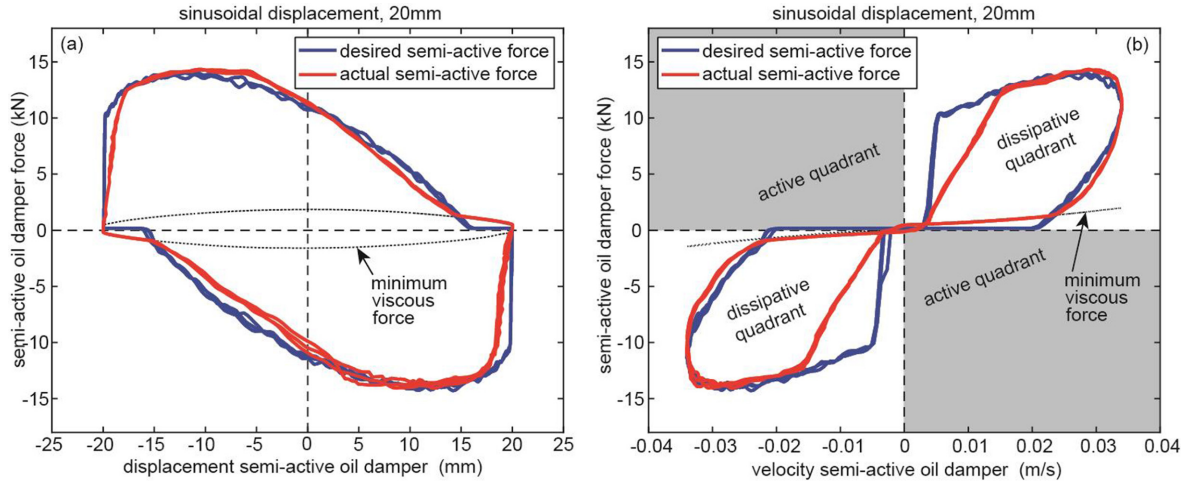


Figure 4. (a) Force displacement and (b) force velocity diagram of semi-active oil damper shown for the case to control the TMD frequency by controlled negative dynamic stiffness.

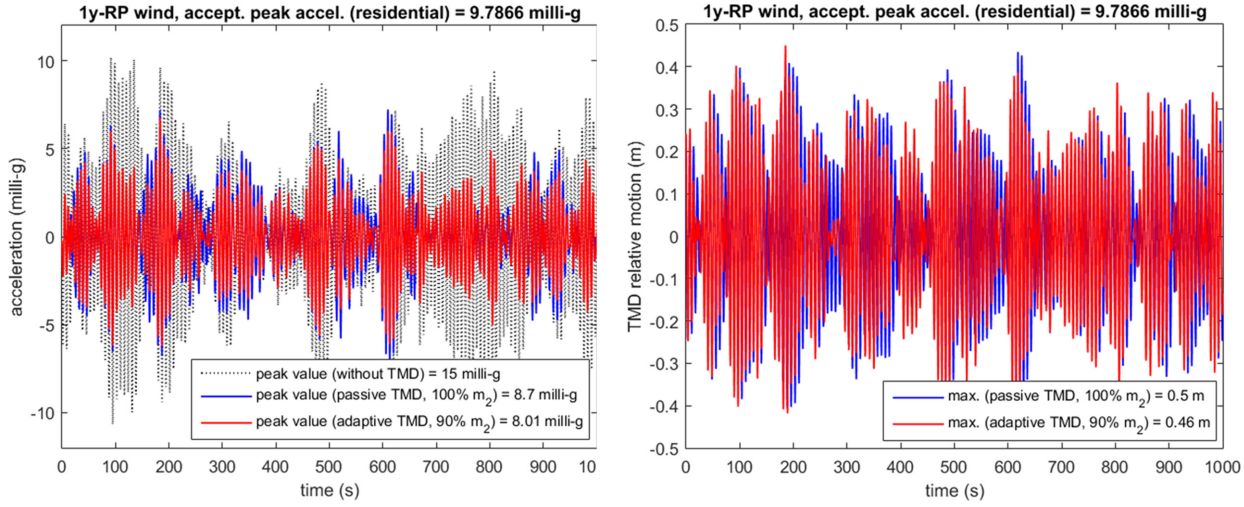


Figure 5. Structural acceleration (left) and TMD relative motion (right) for 1y-RP wind.

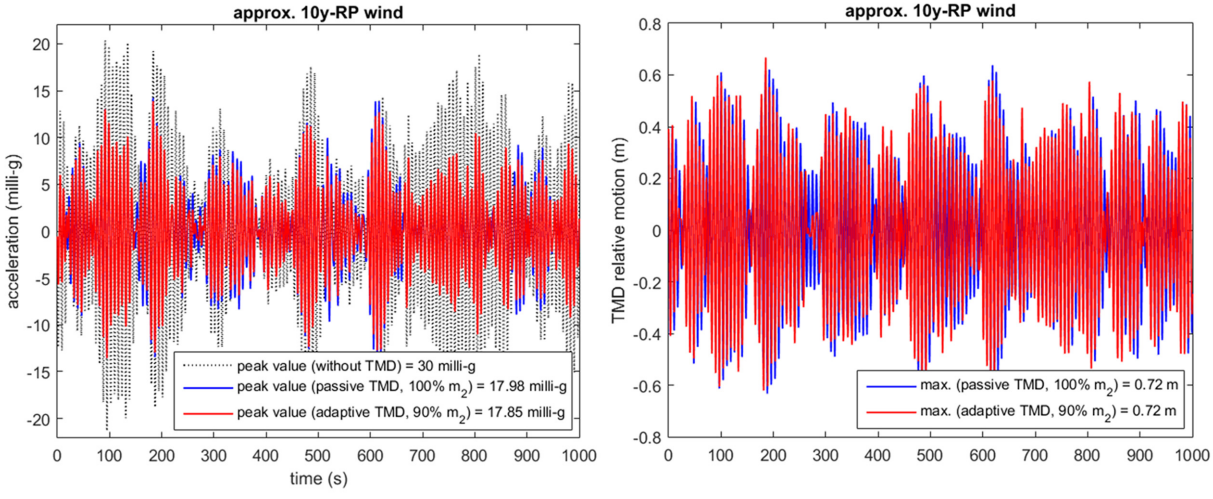


Figure 6. Structural acceleration (left) and TMD relative motion (right) for 10y-RP wind.

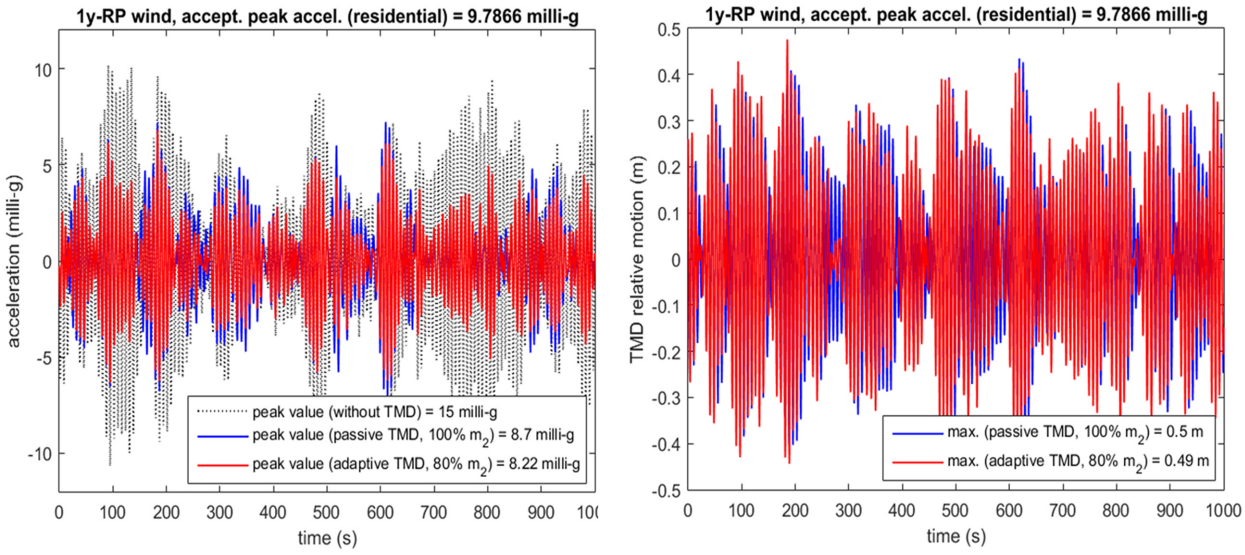


Figure 7. Structural acceleration (left) and TMD relative motion (right) for 1y-RP wind.

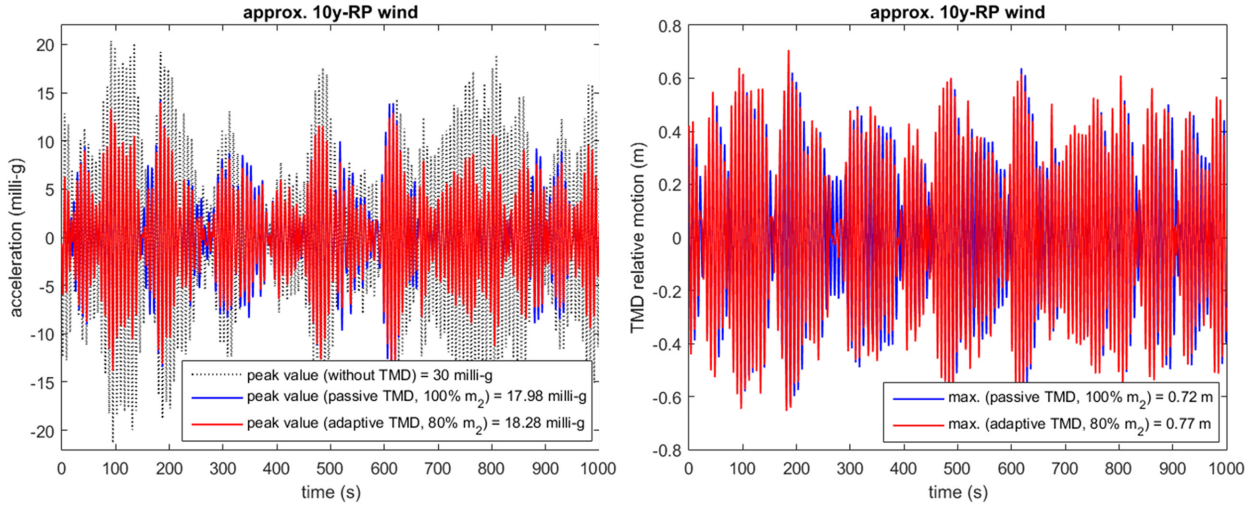


Figure 8. Structural acceleration (left) and TMD relative motion (right) for 10y-RP wind.

$$acceptable\ peak\ value = const. \cdot f_1^{-0,445} \quad (milli-g) \qquad (5)$$

where *const.* = 4,08 for residential buildings. The simulations are also made for the 10y-RP wind to assess the adaptive TMD also for stronger winds (Fig. 6). The simulations both for the 1y-RP and 10y-RP winds demonstrate that the adaptive TMD with 90% mass further reduces structural accelerations, which augments the safety margin relative to the ISO 10137:2007 criterion, and additionally reduces the TMD relative motion which minimizes the required installation space of the adaptive TMD.

6. Performance at 80% TMD Mass

The analogue case study is performed by dynamic simulation assuming 80% of pendulum mass for the adaptive TMD. The results depicted in Figs. 7 and 8 demonstrate that the adaptive TMD with 20% less pendulum mass performs approximately equally well as the passive TMD with 100% of pendulum mass in terms of peak structural acceleration and TMD relative motion for the 1y-RP and 10y-RP winds. Considering the mass reduction of 20%, which reduces the dimensions of the pendulum mass by 10% in both plane directions, the space demand of the adaptive TMD is less than for the passive TMD.

7. Increased Damping to Avoid Impacts on Structure

The feedback gain k_2 of the desired damping force com-



Figure 9. Design and installation of passive TMD in Baku Tower in Baku, Azerbaijan.

ponent in Eq. (2) is disproportionally increased in the real-time controller when the relative motion amplitude of the pendulum mass is greater than a defined critical value. As a result, the damping force of the controlled semi-active oil dampers is disproportionally increased which additionally decelerates the pendulum mass and therefore avoids impacts of the pendulum mass on the structure.

8. Optimum TMD Design for Minimum Space Demand

Both passive and adaptive TMD systems need a proper and simple design in order to minimize costs and installation space. Within this context crucial issues are the inclination of the oil dampers, the design of the TMD mass as simple as possible to minimize machining costs, cable anchors with variable clamping units and a robust hang-off beam construction (Fig. 9).

9. Conclusions

The adaptive TMD outperforms the passive TMD in terms of structural acceleration reduction without obtaining increased pendulum relative motion. This improved performance is the result of the real-time frequency and damping tunings of the adaptive TMD by the semi-active oil dampers. Due to the semi-active nature and the smart valve system of the controlled oil dampers the adaptive TMD is unconditionally stable and fail-safe. The enhanced efficiency is preferably used to reduce the pendulum mass of the adaptive TMD to lower costs and space demand. The maximum mass reduction to guarantee at least the same performance as the passive TMD is approximately 20% which cuts the costs of the TMD by approximately 10% to 15%. This cost reduction applies to TMD masses on the order of 300 tons and greater as for such TMDs the overall costs are dominated by the costs of the mass and hydraulic dampers and not be the costs of the control hardware. The reduced mass of the adaptive TMD safes costs on the structural side on the order of 20% of the costs of passive TMDs. Finally, the reduced footprint size of the adaptive TMD increases the economic benefit of the building as more room for penthouses is available. Considering these economic benefits and the fail-safe behavior of the semi-active oil dampers, the presented adaptive TMD represents a strong damping tool for tall buildings where the modal mass is extremely big and costs are of highest priority.

Acknowledgements

The authors gratefully acknowledge the support of MAURER SE, Munich, Germany, MAURER ENGINEERING GmbH, Munich, Germany and Maurer Switzerland GmbH, Zurich, Switzerland.

References

Ali, A. M., Alexander, J., Ray, T. (2019). Frequency independent hysteretic dampers for mitigating wind-induced vibrations of tall buildings. Struct. Control and Health Monit., DOI: 10.1002/stc.2341.

Aly, A.M. (2016). The Use of Bracing Systems with MR Dampers in Super Tall Buildings. International Journal of High-Rise Buildings (IJHRB), 5, 31-41.

Aly, A.M. (2014). Vibration control of high-rise buildings for wind: a robust passive and active tuned mass damper. Journal of Smart Structures and Systems, 13, 473-500.

Asami, T. and Nishihara, O. (2003). Closed-Form Exact Solution to H_{inf} Optimization of Dynamic Vibration Absorbers (Application to Different Transfer Functions and Damping Systems). Journal of Vibration and Acoustics, Technical Briefs, 125, 398-411.

Den Hartog, J.P. (1934) Mechanical Vibrations. McGraw-Hill Book Company, The Maple Press Company, York, PA.

Kang, J., Kim, H.-S., Lee, D.-G. (2011). Mitigation of wind response of a tall building using semi-active tuned mass

dampers. Struct. Design Tall Spec. Build., 20, 552-565.
Kim, S.-M., Wang, S, Brennan, M.J. (2011). Robust broadband vibration control of a flexible structure using an electrical dynamic absorber. Smart Mater. Struct. 20, 075002.
Pinkaew, T. and Fujino, Y. (2001). Effectiveness of semi-active tuned mass dampers under harmonic excitation. J. Eng. Struct., 23, 850-856.
Rezaee, M., Aly, A.M. (2018). Vibration Control in Wind Turbines to Achieve Desired System-Level Performance under Single and Multiple Hazard Loadings. Structural Control and Health Monitoring, DOI:10.1002/stc.2261.
Soong, T.T. and Dargush, G.F. (1997) Passive Energy Dissipation Systems in Structural Engineering. John Wiley & Sons, Chichester, England.
Weber F. (2014). Semi-active vibration absorber based on real-time controlled MR damper. Mechanical Systems and Signal Processing, 46(2), 272-288.
Weber, F., Maślanka, M. (2014). Precise Stiffness and Damping Emulation with MR Dampers and its Application to Semi-active Tuned Mass Dampers of Wolgograd Bridge. Smart Mater. Struct., 23, 015019.
Weber F., Distl H., Fischer S. and Braun C. (2016a). MR Damper Controlled Vibration Absorber for Enhanced Mitigation of Harmonic Vibrations. Actuators 2016, 5; DOI: 10.3390/act5040027.
Weber F., Huber P., Distl H. and Braun C. (2016b) Real-time controlled TMD of Danube City Tower. Proceeding of the CTBUH (Council on Tall Buildings and Urban Habitat) International Conference 2016, Shenzhen, Guangzhou, Hong Kong (China), 16-21 October 2016.
Weber F., Distl H., Spensberger S., Benicke O., Huber P. and Braun C. (2017) New Real-Time Controlled Semi-Active Tuned Mass Damper for Human, Vortex and Wind Excitations. Proceedings of the International Footbridge Conference, Berlin, Germany, September 6-8.
Weber F., Huber P., Michalski A., Distl J. and Braun C. (2018) New Reduced Mass Controlled TMD for Tall Building Vibration Mitigation. Proceedings of the CTBUH (Council on Tall Buildings and Urban Habitat) 2018 Middle East Conference, Dubai & Abu Dhabi, UAE, 20-25 October 2018.
Zemp, R., de la Llera, J. C., Roschke, P. (2011). Tall building vibration control using a TM-MR damper assembly: Experimental results and implementation. Earthquake Engineering & Structural Dynamics, 40, 257-271.