MAURER Tuned Mass Dampers

MAURER tuned mass dampers for Volgograd Bridge

Tuned mass damper types

Problem description

Civil engineering structures may be prone to large amplitude vibrations due to wind and earthquake loading mechanisms because of their slenderness and low inherent damping ratio of approx. 1% (Fig. 1). Without additional damping measures the following problems may arise:

- Wind loading mechanisms may evoke **resonant and therefore large amplitude oscillations in high rise buildings** which **dramatically reduce the comfort** (seasickness) and therefore limit the use of the building.
- Free vibrations of tall buildings after earthquake excitation may cause **low cycle fatigue**.
- Bending and torsional **galloping** and **flatter** vibrations in bridges lead to large amplitude and **therefore dangerous resonant vibrations** (Volgograd Bridge) that may even destroy the structure (Tacoma Narrows Bridge).
- **Human induced vibrations in stadiums, floors, and footbridges** may yield vibration amplitudes that are beyond the acceptable maximum values (Millennium Bridge).

Solutions by MAURER

MAURER offers different types of tuned mass dampers (TMD) with up to 1000 t of tuned mass to optimally solve the vibration problem:

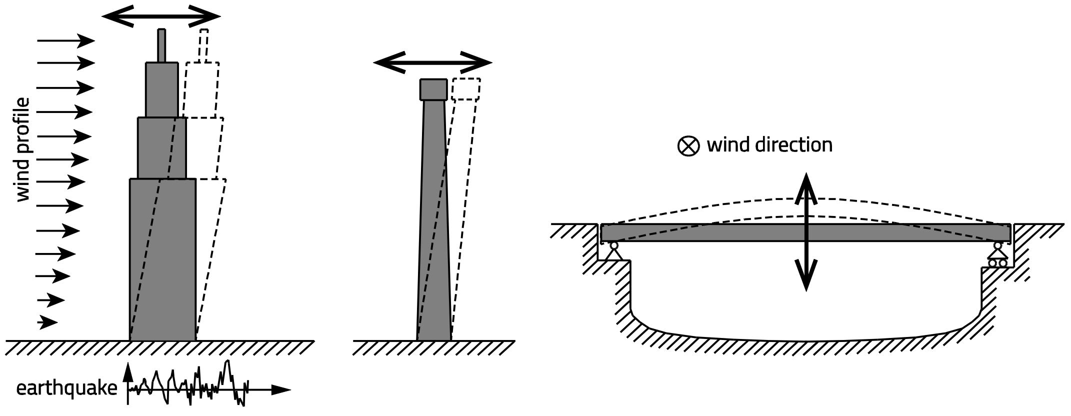
Passive tuned mass dampers:

- ***standardTMD*** : TMDs constructed with springs for the mitigation of vertical and horizontal oscillations of bridges, stadiums and floors and TMDs designed in pendulum form for the mitigation of horizontal vibrations of slender structures (Figs. 2, 3).
- ***foldedTMD*** : TMD constructed by two folded pendulums in order to **significantly reduce the required vertical space** in high-rise buildings (Fig. 3).
- ***compactTMD*** : pendulum TMD with additional inverted pendulum **for minimum required vertical space** in supertall buildings.

Adaptive tuned mass dampers:

- ***controlledTMD*** : real-time frequency and damping controls according to the actual frequency of vibration whereby the **vibration reduction is enhanced** or the **mass ratio can be reduced** (Fig. 2).

(a) wind and earthquake induced structural vibrations: skyscrapers, chimneys, towers, bridges



(b) human induced structural vibrations: stadiums, floors, footbridges

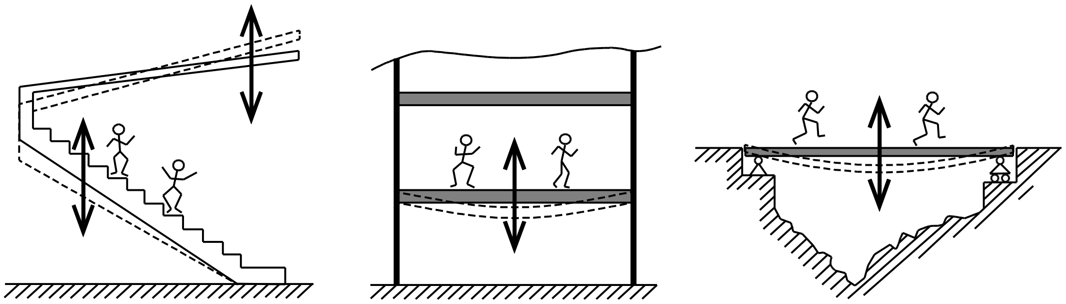


Fig. 1 – Vibrations in civil engineering structures due to (a) wind and earthquake loadings and (b) human induced loading

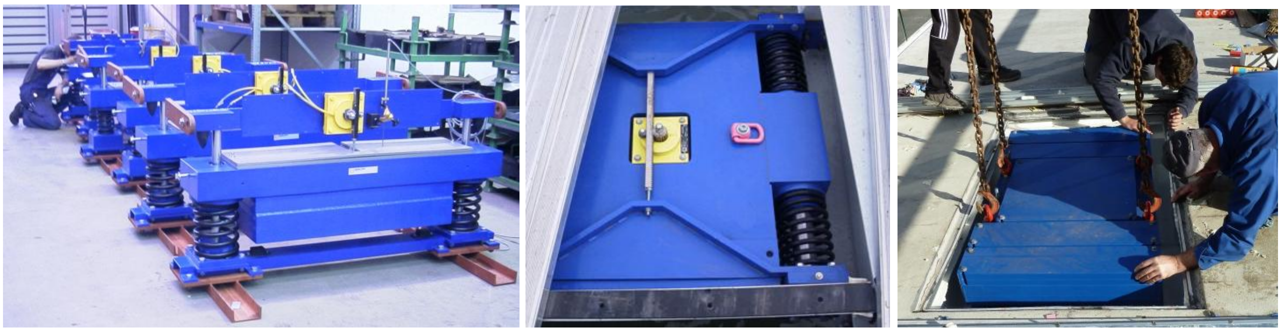


Fig. 2 – *standardTMD* and *controlledTMD* for vibration reduction in vertical and horizontal directions and their precise installation

Fig. 3 – *standardTMD* constructed in pendulum form and *foldedTMD* in workshop in Munich

General advantages of MAURER TMDs

- The different mass damper types guarantee the best solution to the vibration problem.
- Model-based optimal design of all mass damper types by **MAURER** as service.
- Vibration measurement on the structure by **MAURER**.
- Quality control by measurement of TMD properties in the workshop and installed in the structure.
- **MAURER** TMDs are robust, maintenance-free and long-living (>20 years) due to their optimal design, precise manufacturing process and quality controls.

Specific benefits of MAURER TMD types

- *standardTMD* : cost efficient
- *foldedTMD* & *compactTMD* :
  - **significant cost reduction** in high-rise buildings due to minimized height of these TMD types
  - optimal frequency tuning in both main directions due to innovative cable fixation mechanism
- *controlledTMD* :
  - **maximum comfort** in buildings by **improved vibration reduction of up to 80%** compared to passive TMDs
  - same vibration reduction as with passive TMDs but with **reduced tuned mass (75% to 85%** of nominal tuned mass)
  - **monitoring** of structural vibrations included

Optimal design

Input data

The optimal designs of the natural frequency f_2 and damping ratio ζ_2 of TMDs for minimum structural displacement amplitude $\min(X_1)$ and minimum structural acceleration amplitude $\min(\ddot{X}_1)$, respectively, require the knowledge of the following data (Fig. 4):

- the target structural eigenfrequency f_1 including the maximum variation $\pm\Delta f_1 / f_1$ due to the impacts of changing ambient temperature and life loads,
- the associated modal mass m_1,
- the maximum acceptable displacement amplitude X_1^{max} and acceleration amplitude $\ddot{X}_1^{max}$ of the structure, and
- the maximum acceptable relative motion amplitude X_d^{max} of the TMD.

Design parameter

The mass ratio $\mu = m_2 / m_1$ is the crucial design parameter of TMDs. The minimum required mass ratio to ensure that the maximum structural displacements are smaller than X_1^{max} can be computed from the following equation (Fig. 5)

$$\frac{X_1}{P/k_1} = \sqrt{1+\frac{2}{\mu}} \qquad (1)$$

by replacing X_1 by X_1^{max} and solving (1) for μ. The required mass ratio to guarantee $\ddot{X}_1 \le \ddot{X}_1^{max}$ can be estimated from (1) with the consideration of f_1.

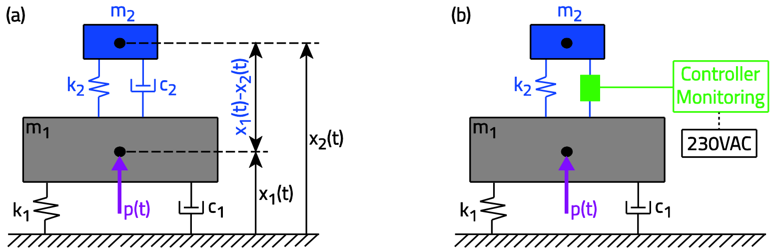


Fig. 4 – Two degrees-of-freedom system: structure with (a) passive TMD and (b) adaptive TMD

- Nomenclature of structure:
  - f_1 : target eigenfrequency [Hz]
  - m_1 : target modal mass [kg]
  - ζ_1 : damping ratio [-]
  - k_1 : stiffness coefficient [N/m]
  - c_1 : viscous damping coefficient [Ns/m]
  - x_1 : displacement [m]
  - X_1 : displacement amplitude [m]
  - $\ddot{X}_1$: acceleration amplitude [m/s^2]
  - p : excitation force [N]
  - P : excitation force amplitude [N]
- Nomenclature of tuned mass damper:
  - μ : mass ratio [-]
  - f_2 : natural frequency [Hz]
  - ζ_2 : damping ratio [-]
  - m_2 : mass [kg]
  - k_2 : stiffness coefficient [N/m]
  - c_2 : viscous damper coefficient [Ns/m]
  - x_2 : (absolute) displacement [m]
  - $x_1 - x_2$: (relative) damper motion [m]
  - X_d : damper relative motion amplitude [m]
- Specifications:
  - X_1^{max} : maximum acceptable displacement amplitude of structure with TMD [m]
  - $\ddot{X}_1^{max}$: maximum acceptable acceleration amplitude of structure with TMD [m/s^2]
  - X_d^{max} : maximum acceptable relative motion amplitude of TMD [m]

Passive TMDs

The natural frequency f_2 and damping ratio ζ_2 of the passive TMD types *standardTMD*, *foldedTMD* and *compactTMD* for **minimum structural displacement** amplitude X_1 are given by Den Hartog's formulae [1]

$$f_2 = \frac{f_1}{1+\mu} \tag{2}$$

$$\zeta_2 = \sqrt{\frac{3\mu}{8(1+\mu)^3}} \tag{3}$$

If the **acceleration** amplitude $\ddot{X}_1$ of the structure is to be **minimized**, f_2 and ζ_2 must be designed as follows

$$f_2 = \frac{f_1}{\sqrt{1+\mu}} \tag{4}$$

$$\zeta_2 = \sqrt{\frac{3\mu}{4(2+\mu)(1+\mu)}} \tag{5}$$

The spring stiffness and the viscous damper coefficient of the oil damper of the *standardTMD* are obtained from (2, 3) for $\min(X_1)$ and from (4, 5) for $\min(\ddot{X}_1)$ as follows

$$k_2 = m_2 (2\pi\, f_2)^2 \tag{6}$$

$$c_2 = 2\zeta_2\, m_2 (2\pi\, f_1) \tag{7}$$

Figs. 5 and 6 depict the vibration reductions of the primary structure in terms of displacement and acceleration, respectively, when the TMD is optimized for $\min(X_1)$ according to (2, 3) and for $\min(\ddot{X}_1)$ according to (4, 5), respectively. The additional acceleration response resulting from the TMD for $\min(X_1)$ plotted in Fig. 6 demonstrates that this design approach does not minimize the structural accelerations.

Figs. 7 and 8 demonstrate that increasing the mass ratio enhances the vibration reduction, makes the TMD more effective within a larger frequency range and reduces the relative damper motion amplitude.

The pendulum lengths, the pendulum rods, the oil dampers and the entire geometry of the TMD types *foldedTMD* und *compactTMD* are model-based optimized by **MAURER** for $\min(X_1)$ and $\min(\ddot{X}_1)$, respectively, by **dynamic non-linear simulation** of the structure with these TMD types.

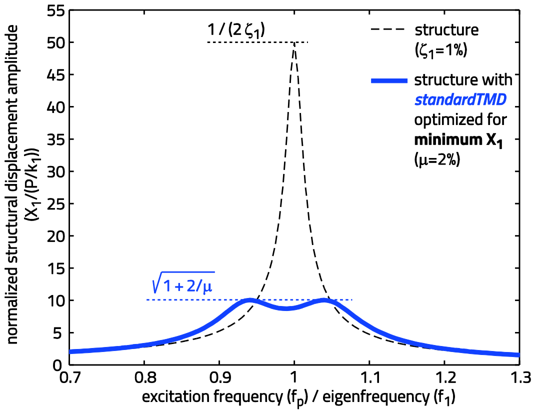


Fig. 5 – Structure without TMD and with *standardTMD* for $\min(X_1)$

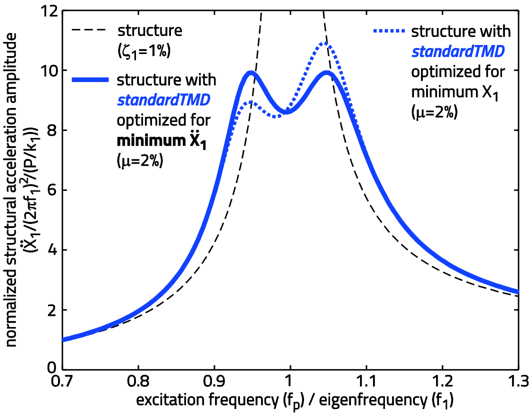


Fig. 6 – Structure without TMD and with *standardTMD* for $\min(\ddot{X}_1)$

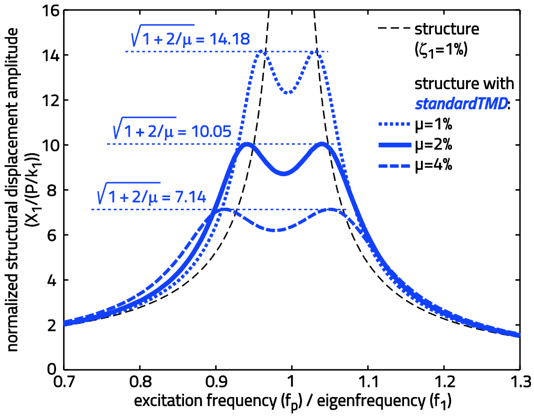


Fig. 7 – Influence of mass ratio of *standardTMD* designed for $\min(X_1)$ on vibration reduction of structure

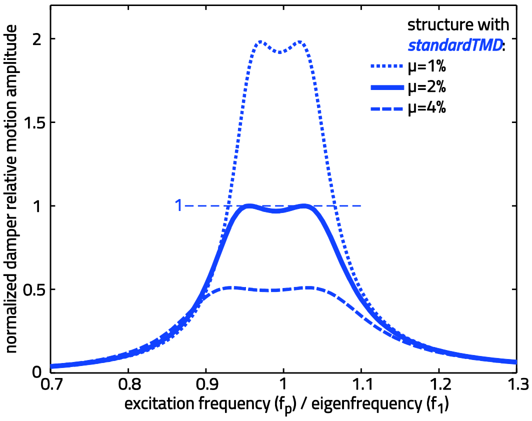


Fig. 8 – Influence of mass ratio of *standardTMD* designed for $\min(X_1)$ on damper relative motion amplitude

Adaptive TMDs

Frequency tuning in real-time

The ***controlledTMD*** is a **MAURER** in-house production [2-5]. Its **controlled** frequency $f_{2\text{–controllec}}$ is adjusted in **real-time** to the actual frequency f_p of vibration according to the principle of the undamped dynamic vibration absorber (Frahm, [6])

$$f_{2\text{–controlled}} = f_p \qquad (8)$$

where f_p may represent a forced frequency or an eigenfrequency of the structure including the variation range $\pm\Delta f_1 / f_1$. Due to the design of the passive spring stiffness $k_2 = m_2 \left(2\pi\, f_1\right)^2$ the actuator must emulate only the differential stiffness (Fig. 4(b))

$$k_{2\text{–controlled}} = m_2 \left(2\pi\, f_{2\text{–controlled}}\right)^2 - k_2 \qquad (9)$$

which minimizes the power requirement of the actuator.

Damping tuning in real-time

The damping ratio $\zeta_{2\text{–controlled}}$ of the ***controlledTMD*** is **controlled in real-time** according to the principle of the undamped dynamic vibration absorber as follows:

- optimal tuning to the actual frequency f_p of vibration and
- minimization by an **adaptive damping control approach** with respect to the actual damper relative motion amplitude X_d and the maximum acceptable damper relative motion amplitude X_d^{max}

$$\zeta_{2\text{–controlled}} = \text{function}\left(f_p, X_d, X_d^{max}\right) \qquad (10)$$

Semi-active damper

$k_{2\text{–controllec}}$ and $\zeta_{2\text{–controlled}}$ are emulated by a semi-active damper whereby the control system is **unconditionally stable** and **fail-safe** [7].

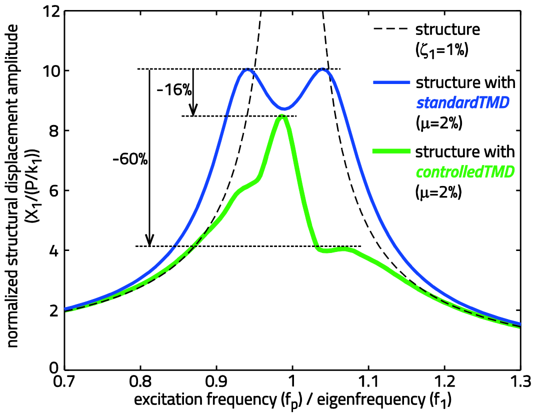


Fig. 9 – Structure with ***controlledTMD*** under **worst case excitation** due to wind or earthquake loadings

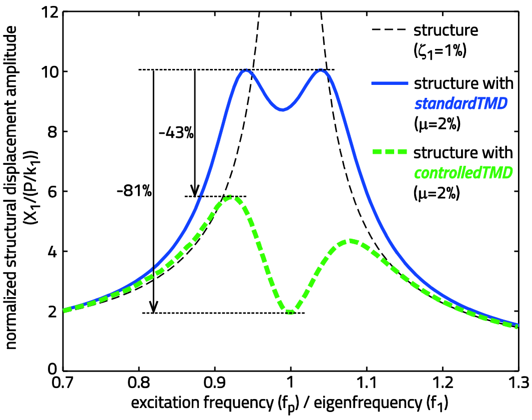


Fig. 10 – Structure with ***controlledTMD*** at **medium to small wind or earthquake loadings** (<50% worst case)

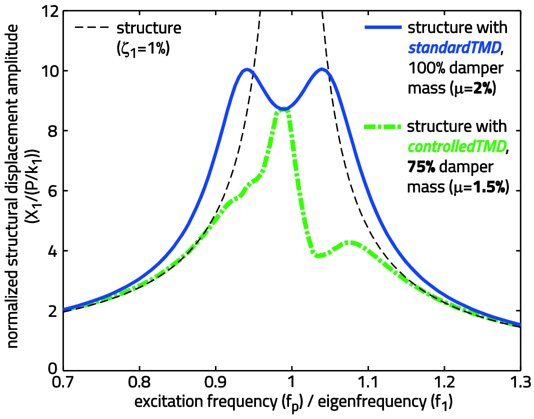


Fig. 11 – Structure with ***controlledTMD*** with **75% of tuned mass** compared to passive TMD (worst case excitation due to wind or earthquake)

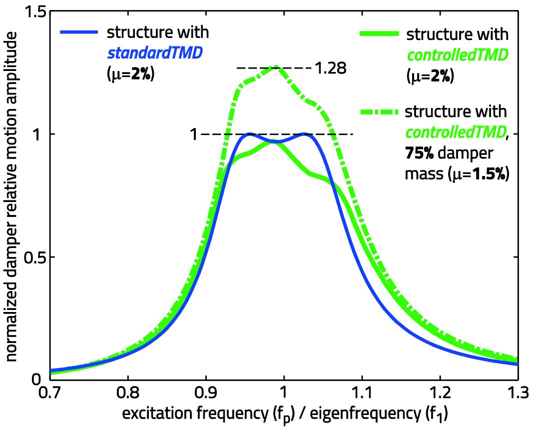


Fig. 12 – Relative motion amplitude of ***controlledTMD*** due to 100% and 75% of tuned mass (worst case excitation due to wind or earthquake)

Key features

- Improved vibration reduction at nominal mass ratio:
  - **vibration reduction enhanced by up to 60%** compared to the passive TMD at worst case excitation due to wind or earthquake loadings (Fig. 9) without augmented damper relative motion amplitude (Fig. 12)
  - **maximum comfort** in buildings due to **improved vibration reduction of up to 80%** compared to passive TMD at medium to small and therefore frequently occurring wind or earthquake loadings (<50% worst case, Fig. 10)
- Same vibration reduction as with passive TMD: **reduction of tuned mass to 75% to 85%** of nominal value at 28% to 16% increased damper relative motion amplitude (Figs. 11, 12)
- Automatic compensation of frequency changes:
  - **changes in target eigenfrequency** of the structure due to the impacts of changing ambient temperature and life loads are **automatically compensated** (Figs. 13, 14)
  - changes in target eigenfrequency of $\pm\Delta f_1 / f_1 \leq \pm 10\%$ and changes in excitation frequency $\pm\Delta f_p / f_1 \leq \pm 15\%$ can be compensated
- **Monitoring**:
  - acceleration $\ddot{x}_1$ and acceleration amplitude $\ddot{X}_1$ of structure
  - damper relative motion amplitude X_d
  - additional states according to client's specifications

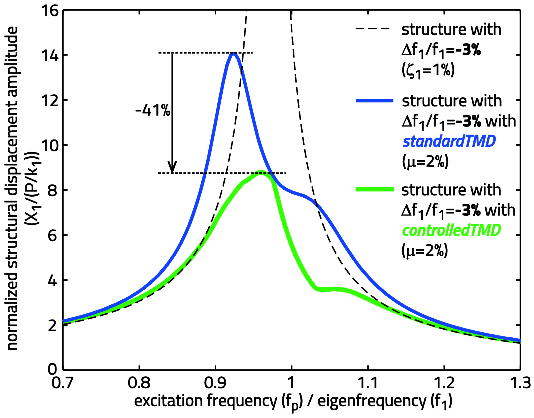


Fig. 13 – Structure with $\pm\Delta f_1 / f_1$ =-3% with *controlledTMD*
(worst case excitation due to wind or earthquake)

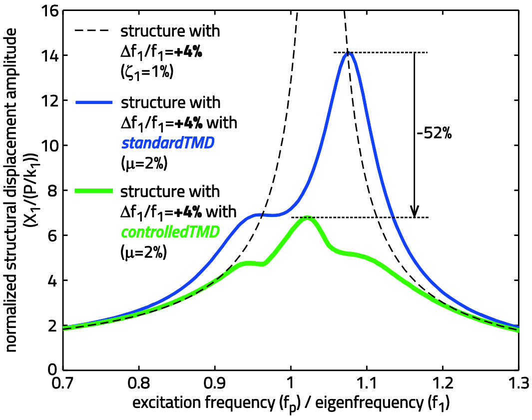


Fig. 14 – Structure with $\pm\Delta f_1 / f_1$ =+4% with *controlledTMD*
(worst case excitation due to wind or earthquake)

Services by MAURER

Based on the wind and earthquake loading analyses of the structure without TMD by the consultant **MAURER** offers the following services:

- Recommendations concerning:
  - optimal TMD type
  - minimum required mass ratio and number of TMDs
  - design of required structural fixation measures
- **Non-linear dynamic simulation with wind or earthquake excitations:**
  - model-based design of evaluated TMD type based on given wind or earthquake loading time histories
  - computation of vibration reduction with evaluated TMD type within entire frequency range and comparison with the maximum acceptable structural acceleration and displacement, respectively
- Installation of TMD and free vibration test as final functional check

References

SOCAR Tower in Baku, Azerbaijan

- The pendulum lengths of the 2-dimensional *foldedTMD* are adjusted for maximum vibration reduction of the first eigenmodes in both main directions at 0.22 Hz and 0.32 Hz (Fig. 15).
- The total height of the folded pendulum including the steel frame construction, cable clamping devices and lead rubber bearings could be reduced from approx. 11 m of the conventional pendulum TMD to approx. 7 m of the *foldedTMD* (Fig. 16).
- The damper mass of 450 tons of the *foldedTMD* corresponds to the mass ratio of 4.5%.
- The steel frame construction of the *foldedTMD* and the passive oil dampers are designed to accommodate damper relative motion amplitudes of up to ±480 mm.
- The *foldedTMD* of the SOCAR Tower is in operation since January 2015.

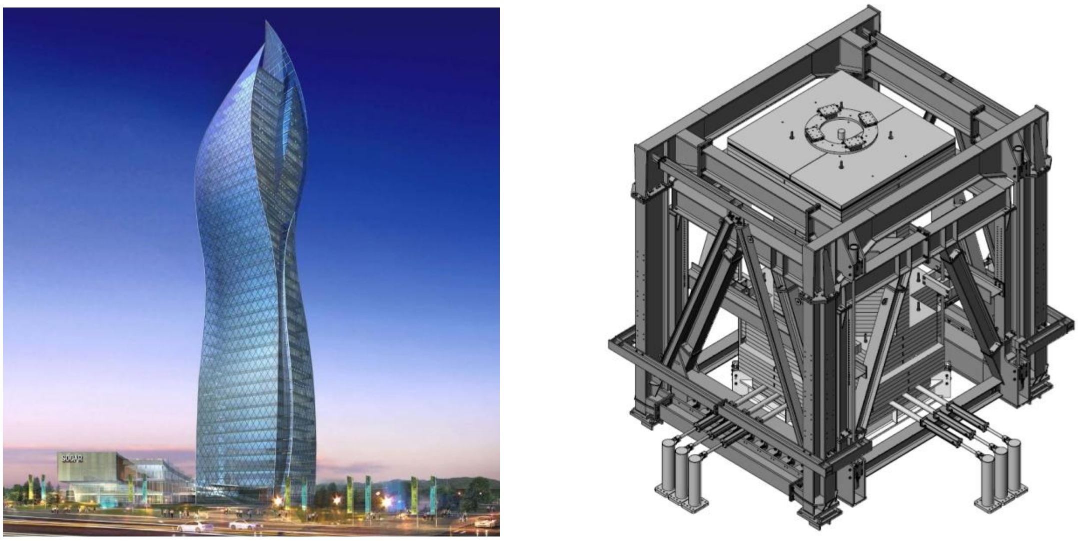


Fig. 15 – SOCAR Tower in Baku, Azerbaijan, and isometric view of *foldedTMD* of SOCAR Tower

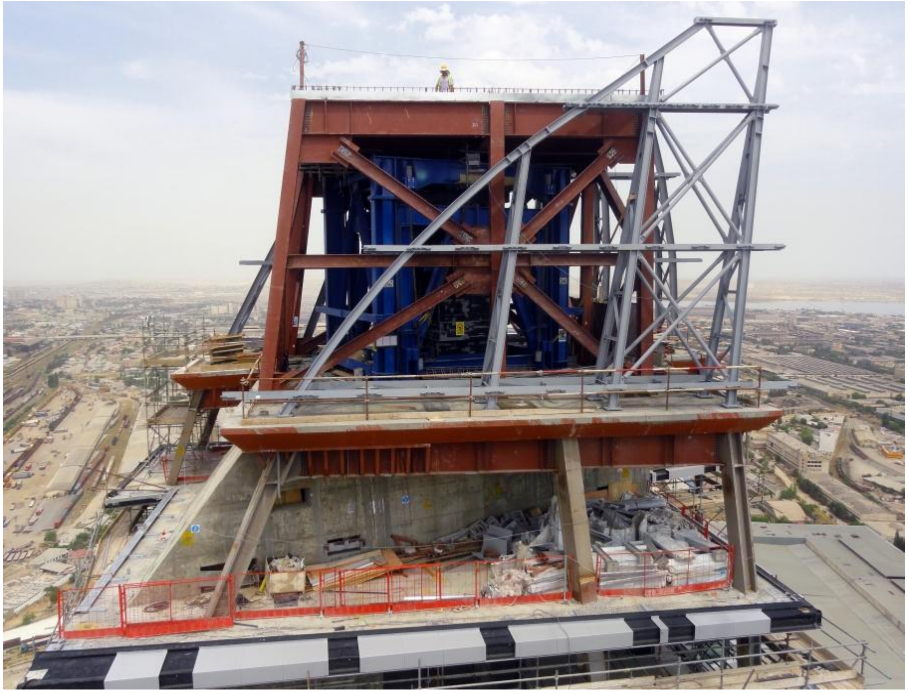


Fig. 16 – *foldedTMD* integrated into pinnacle of SOCAR Tower

Alphabetic Tower in Batumi, Georgia

- The ***standardTMD*** in pendulum form (Fig. 17) is optimally tuned to the eigenfrequency of 0.498 Hz in both main directions of the Alphabetic Tower in Batumi (Fig. 18).
- The damper mass of 62.85 tons of the ***standardTMD*** corresponds to the mass ratio of 3.50%.
- The joints and lengths of the pendulum rods and the cylindrical oil dampers are designed for the maximum damper relative motion amplitude of ±0.24 m.
- The ***standardTMD*** of the Alphabetic Tower in Batumi is in operation since December 2011.

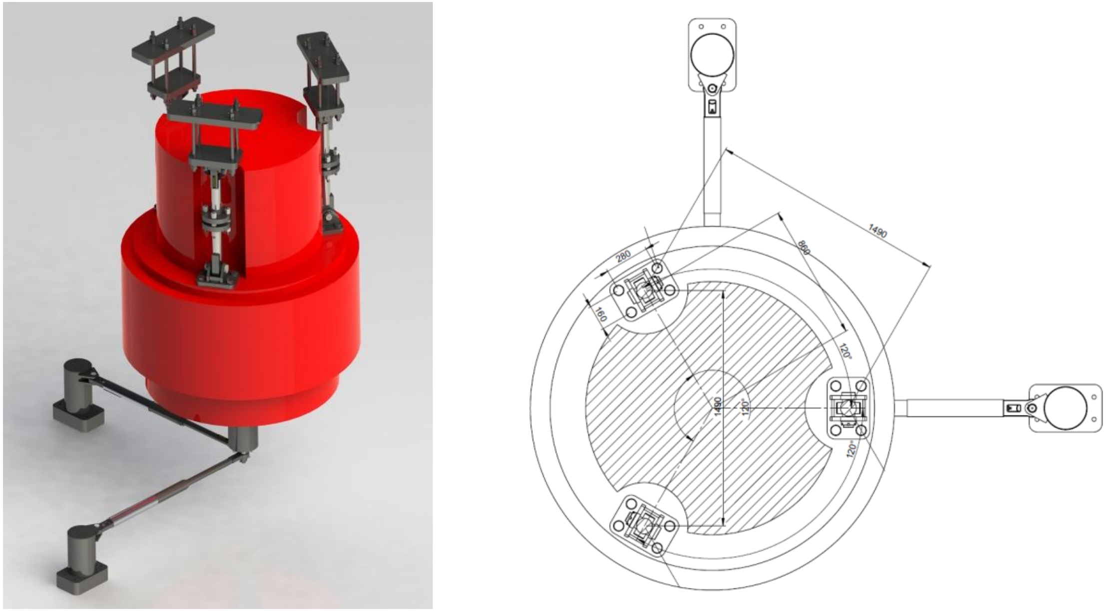


Fig. 17 – ***standardTMD*** in pendulum form of Alphabetic Tower in Batumi, Georgia

Fig. 18 – Alphabetic Tower in Batumi, Georgia

Danube City Tower in Vienna, Austria

- The *controlledTMD* of the Danube City Tower generates optimal frequency and damping tunings in real-time of the first bending mode within the frequency range of 0.17 Hz to 0.21 Hz [4, 5, 7] which was experimentally verified by HIL tests (Fig. 19).
- The control force range of both real-time controlled semi-active dampers is given by the residual force of approx. 3 kN and the maximum force of approx. 90 kN.
- The tuned mass of 300 tons (not delivered by **MAURER**) corresponds to the mass ratio of 0.75%.
- The adaptive damping control approach of the *controlledTMD* increases the damping disproportionately for damper relative motion amplitudes greater than ±0.6 m in order to avoid non-acceptable large damper relative motion amplitudes; additionally, shock impact dampers are installed.
- The *controlledTMD* of the Danube City Tower including the monitoring system is in operation since October 2014 (Fig. 20).

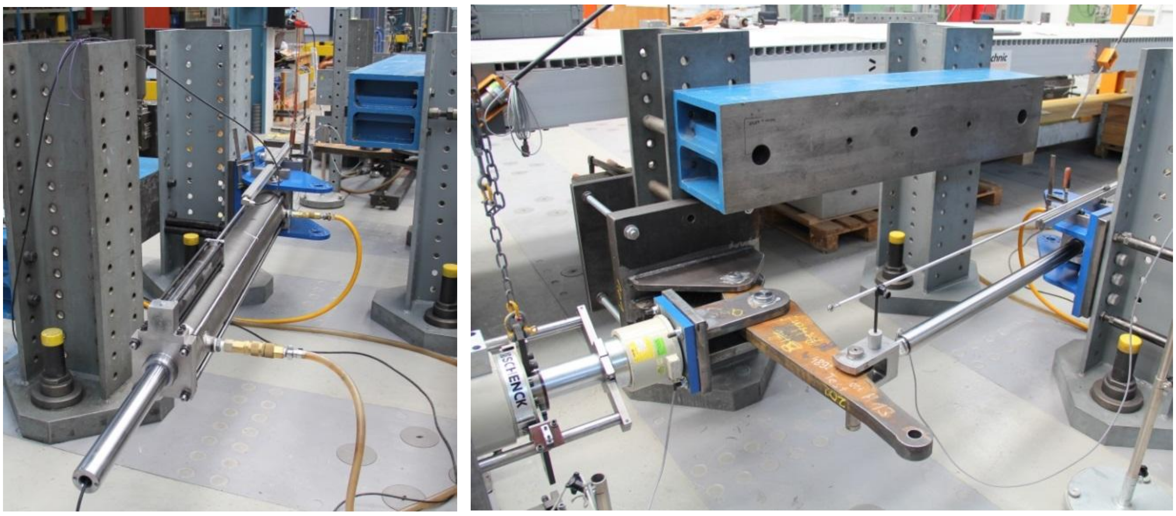


Fig. 19 – HIL tests with semi-active damper of *controlledTMD* of Danube City Tower: overview and kinematic transformation for HIL-tests at large damper relative motion amplitudes

Fig. 20 – Danube City Tower in Vienna, Austria

Volgograd Bridge, Russia

- Field measurements and wind channel tests demonstrated that the first three vertical bending modes at 0.45 Hz, 0.56 Hz and 0.68 Hz are to be mitigated.
- **MAURER** solved this problem by three groups of *controlledTMDs* in bridge fields 3, 7 and 8 as follows:
    - the natural frequencies of the passive mass spring packets are optimally tuned to the eigenfrequencies of the three vertical bending modes and
    - the controlled frequencies of all *controlledTMDs* are adjusted to the actual frequency of vibration which yields the same vibration reduction of the first three vertical bending modes as passive TMDs with 2-3 times more tuned mass.
- The real-time frequency tuning within the frequency range of ±20% relative to the eigenfrequency of the bending mode at 0.56 Hz was experimentally verified at the Universität der Bundeswehr München [2, 3] (Fig. 21).
- The 12 *controlledTMDs* of the Volgograd Bridge including the monitoring system are in operation since October 2012 (Fig. 22).

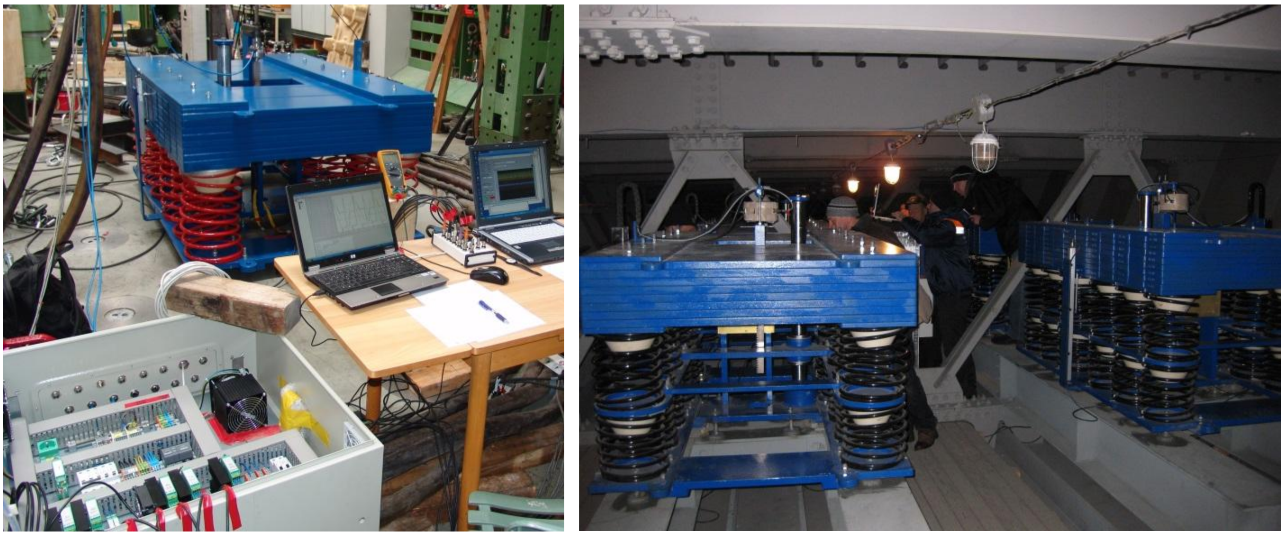


Fig. 21 – Frequency control tests at the Universität der Bundeswehr München with the *controlledTMD* of the Volgograd Bridge and final functional check of the *controlledTMDs* installed in the Volgograd Bridge

Fig. 22 – Volgograd Bridge, Russia

Marina Bay Sands Hotel, Singapore

The *standardTMD* of the Marina Bay Sands Hotel mitigates the vertical vibrations at 0.99 Hz of the "nose" of the Skypark of the Marina Bay Sands Hotel with 5 tons corresponding to the mass ratio of 1.2% (Fig. 23).

Fig. 23 – Marina Bay Sands Hotel with Skypark, Singapore

Olympic Flame Monument, Sotschi, Russia

The *standardTMD* with three times 0.75 tons corresponding to the mass ratio of 13.7% reduces the horizontal oscillations at 1.05 Hz of the Olympic Flame Monument in Sotschi (Fig. 24).

Fig. 24 – Olympic Flame Monument, Sotschi, Russia

AlpSpix, Garmisch-Partenkirchen, Germany

The vertical vibrations at 0.85 Hz of both platforms are mitigated by in total 4 *standardTMDs* with the total tuned mass of 4 x 150 kg corresponding to the mass ratio of 7.2% (Fig. 25).

Fig. 25 – AlpSpix, Garmisch-Partenkirchen, Germany

Olympia Bridge / Ponte Moi, Turin, Italy

Two *controlledTMDs* with 4 tons each reduce the lateral vibrations of the eigenmodes at 0.55 Hz and 0.95 Hz. The mass of 4 tons of one *controlledTMD* corresponds to the mass ratio of 1% (Fig. 26).

Fig. 26 – Olympia Bridge / Ponte Moi, Turin, Italy

Coimbra Bridge, Coimbra, Portugal

Two *standardTMDs* with in total 4930 kg reduce the lateral vibrations at 0.69 Hz and six *standardTMDs* with tuned masses between 1581 kg and 9692 kg mitigate the vertical oscillations between 1.52 Hz and 3.0 Hz (Fig. 27).

Fig. 27 – Coimbra Bridge, Coimbra, Portugal

Footbridge for horticultural show in Tirschenreuth, Germany

The *standardTMDs* with leaf springs mitigate the vibrations of the first two vertical bending modes at 1.69 Hz with 685 kg (μ =4.6%) and 2.6 Hz with 485 kg (μ =3.2%, Fig. 28).

Fig. 28 – Footbridge for horticultural show in Tirschenreuth, Germany

Quality controls

In the workshop

- The motion of each TMD mass is checked for minimum internal friction and free movement.
- The natural frequencies of the mass spring packet and pendulum mass, respectively, are checked by free decay tests (Fig. 29) and fine-tuned if necessary.
- Real-time frequency and damping controls of ***controlledTMDs*** are verified by HIL testing.

In the structure

- The free movement with minimum internal friction and the fine-tuned natural frequency of the TMD are double-checked by free decay tests as final functional checks.
- Functional checks of the real-time controller and monitoring system in case of ***controlledTMDs***.

Fig. 29 – Quality controls in the workshop and at the Universität der Bundeswehr München

Literature

[1] Den Hartog JP. *Mechanical Vibrations*. York, PA: McGraw-Hill Book Company, The Maple Press Company, 1934.

[2] Weber F and Distl H. Real-time controlled tuned mass dampers for Wolgograd Bridge. *Beton- und Stahlbetonbau* 2013; **108**(Heft 6) 362-72.

[3] Weber F, Distl H and Maślanka M. Semi-active TMD Concept for Volgograd Bridge. In: F. Necati, et al. (Eds.), *Topics in Dynamics of Civil Structures* 2013; **4**(10): 79-88. New York: Springer.

[4] Weber F. Semi-active vibration absorber based on real-time controlled MR damper. *Mechanical Systems and Signal Processing* 2014; **46**(2): 272-88.

[5] Weber F. Optimal semi-active vibration absorber for harmonic excitation based on controlled semi-active damper. *Smart Mater. Struct.* 2014; **23**: 095033.

[6] Frahm H. *Devices for damping vibrations of bodies*. US Patent no. 989, 958, 1911.

[7] Weber F. Robust force tracking control scheme for MR dampers. *Struct. Control Health Monit.* 2015; **22**(12): 1373-95.