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Real-Time Controlled TMD of Danube City Tower

多瑙河城市大厦实时自控型调频质量阻尼器TMD

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Abstract | 摘要

Since 2014, a MAURER controlled TMD has mitigated the first bending mode of the Danube City Tower in Vienna, Austria. It consists of a pendulum mass of 300 tons and a semi-active damper that adjusts in real-time frequency and damping to the actual frequency of vibration according to the principle of the undamped dynamic vibration absorber, whereby the MAURER controlled TMD outperforms the passive TMD by up to 68%. The significantly greater efficiency of the MAURER controlled TMD also allows reducing its tuned mass to 80% or less of the nominal value of passive TMDs. The MAURER controlled TMD with reduced mass outperforms the passive TMD with nominal mass by up to 64% and reduces the space demand for the device. It is therefore concluded that the MAURER controlled TMD is an effective tool for the vibration mitigation of supertall buildings where the modal masses can become very big.

Keywords: Adaptability, Automation, Damping, Human Comfort, Tuned Mass Damper, and Vibrations

2014年，装备有MAURER自控型调频质量阻尼器减缓了奥地利维也纳多瑙河城市大厦的第一个弯曲模态。该MAURER自控型调频质量阻尼器由一个300吨的单摆式质量体和半主动阻尼器组成，可依照无阻尼动力减振器原理，根据实际振动频率实时调节频率和阻尼，因此MAURER自控型调频质量阻尼器性能优于被动型调频质量阻尼器高达68%。MAURER自控型调频质量阻尼器显著提高的效能允许自身调频质量减小到被动型调频质量阻尼器的标称值80%左右。减小了质量块的MAURER自控型调频质量阻尼器在性能上超过带标称质量块的被动型调频质量阻尼器性能的64%，并减少了装置所需空间。因此，可得出这样的结论，MAURER自控型调频质量阻尼器对减缓那些模态质量可变得很大的超高建筑物的振动是一种有效的工具。

关键词：适应性、自动化、阻尼、人体舒适度、调谐质量阻尼器、振动

Introduction

Tall buildings may be susceptible to large wind-induced amplitude oscillations due to their low inherent damping characteristics and slenderness. The excited modes typically vibrate at frequencies in the vicinity of 0.2 Hz and below because of the extremely large modal masses of these buildings and their slenderness. The resulting building vibrations diminish the comfort in the building or may even lead to seasickness of the building occupants whereby the proper use of the building is no longer guaranteed. A similar problem may occur during the free oscillations of tall buildings in their fundamental bending mode after earthquake excitation. Due to the large vibration amplitudes of such modal oscillations, low cycle fatigue of building components may become relevant.

The common measure against unacceptably large structural vibrations is the installation of tuned mass dampers (TMD), tuned liquid column dampers, and tuned sloshing dampers at or close to the location of maximum kinetic

介绍

高型建筑物较低的固有阻尼特征和细长形，易遭受风力引起的大幅振荡。因为这些建筑物质量和高宽比极大，激发模式在频率0.2Hz附近及以下发生典型振动。产生的建筑物振动降低了建筑物里的舒适度，甚至可导致居住者头晕，由此，建筑物的合理用途不再得以保证。类似的问题也可能在地震后高型建筑物在它们基本弯曲模态中的自由振荡期间发生。由于这种模态振荡的振幅大，可导致建筑物组成部分的低循环疲劳。

防止不允许的大规模结构振动的一般措施是安装调频质量阻尼(TMD)、调频液柱阻尼器或装水的容器（tuned sloshing dampers）。这些阻尼器安装在最大动能处或临近处，也就是靠近顶部的位置（Den Hartog 1934, Soong & Dargush 1997）。这些被动阻尼器的设计参数就是它们的调频质量和质量比，分别选取这些参数，以保证减小的振动以加速度为单位，低于最大容许值。

energy (i.e., near the top) (Den Hartog 1934, Soong & Dargush 1997). The design parameter of these passive dampers is their tuned mass and mass ratio, respectively, which is to be selected to guarantee that the reduced vibrations in terms of acceleration are below the maximum tolerable values.

A TMD with 1% of mass ratio will reduce the response of a building with 1% of critical damping from 50 (normalized value) to approximately 14 (normalized value), which is often sufficient to meet the requirements in terms of acceptable structural accelerations. However, in the case of tall and supertall buildings, the damper mass of 1% of the typical modal mass of the first bending mode may be too heavy and too big regarding the space needed. Therefore, the TMD mass is often selected considerably below 1% for very tall buildings. The drawback is that TMDs with such small tuned masses around 0.6% to 0.8% may not be able to reduce the maximum building accelerations due to the worst case excitation (e.g., wind loading with specified return period), below the maximum tolerable value (e.g., according to ISO 10137:2007 Standard for 1-year return period).

Thus, there is a need for more efficient mass damper concepts that are able to sufficiently mitigate supertall buildings with relatively small tuned masses. One concept is the MAURER controlled TMD that was installed in the Danube City Tower in Vienna, Austria, in 2014 (Bollinger et al 2015). This article shows that with only 80% or less of the tuned mass of passive TMDs, the MAURER controlled TMD leads to a significantly enhanced vibration reduction and requires less space compared to the passive TMD with nominal mass, whereby the MAURER controlled TMD – with up to 1000 tonnes of tuned mass – represents an efficient tool for the damping of supertall buildings.

Concept of the MAURER Controlled TMD

The MAURER controlled TMD consists of a passive mass spring packet with a real-time controlled semi-active damper for the mitigation of vertical or horizontal bridge vibrations, or a passive pendulum mass with a real-time controlled semi-active damper for the vibration mitigation of the targeted bending mode of tall buildings. The force of the semi-active damper is controlled in real-time to adjust both frequency and damping of the MAURER controlled TMD to the actual frequency of vibration. The semi-active damper can either be designed as magnetorheological dampers or as oil dampers with controlled bypass.

具有1%质量比的TMD把具有1%临界阻尼的建筑物的响应从50（规范值）减小到大约14（规范值），这常常足以满足结构允许加速度方面的要求。但是，如果是高型和超高建筑物，阻尼器其典型的首个弯曲模态的模态质量的质量比1%可能就需要的空间而言过大而且过重。因此，对于很高的建筑物，TMD的质量比常常考虑选取1%以下。缺点是由于最强激发情况，比如确定重现期的风载，约0.6%到0.8%这样小的调频质量比的TMD可能不能减小最大建筑物加速度低于最大容许值，例如，按照ISO 10137:2007 1年一遇标准。

因此，有必要提出更为有效的质量阻尼器概念，即能够利用比较小的调频质量充分减轻超高建筑物的振动。一个概念是MAURER自控型TMD，2014年安装在奥地利维也纳的多瑙河城市大厦（Bollinger et al 2015）。这篇论文说明了MAURER自控型TMD只有被动型TMD调频质量的80%或更小，与标称质量的被动型TMD相比，显著减小了振动且仅需要更少空间，因此MAURER自控型TMD调频质量高达1000吨，代表了一种用于超高建筑物减振的有效工具。

MAURER自控型TMD的概念

MAURER自控型TMD由一个被动质量弹簧包加上用于减轻垂直或水平方向桥梁振动的实时控制的半主动阻尼器，或者由一个被动质量单摆加上用于高型建筑物目标弯曲模态的振动减轻的实时控制的半主动阻尼器组成。半主动阻尼器的力实时控制，按照振动的实际频率来调节MAURER自控型TMD的频率和阻尼。半主动阻尼器可被设计为磁流变阻尼器或带有控制旁路的油阻尼器。

MAURER自控型TMD的基本控制方法是为了实际振动频率（Frahm 1911）仿真无阻尼动力减振器的行为特征。因此，其控制目的是双重的：

- MAURER自控型TMD的受控频率必须等于实际振动频率，并且
- MAURER自控型TMD的受控阻 尼要使用约束使其最小化在约束条件下调频质量块的相对运动幅度须不超过本身容许的最大值，例如，奥地利维也纳多瑙河城市大厦，MAURER自控型TMD位移为+/−600mm（Weber 2014（a, b））。

注意：该控制方法使振动减小的效能最大，这一点从事实情况可以看出：如果阻尼力可以减小到零而调频质量块不产生不允许的大幅相对运动，就会带来主结构零响应的结果。 按照这两个控制目标，半主动阻尼器的力必须仿真保证实时频率调整适应所需刚度力和用于适应阻尼调整的所需阻尼力的组合。如果所要求的全部控制力，即所要求的刚度力和阻尼力，是由半主动阻尼器无法仿真的主动力，则程序算法是所要求的刚度力实时频率控制优先。结果是，实际阻尼力大于所要求的阻尼力。

奥地利维也纳多瑙河城市大厦受控的减振

奥地利维也纳多瑙河城市大厦（DC Tower）的数值分析（图1）说明，由于40000吨模态质量在标称频率0.18Hz处的首个弯曲模态所产生的水平振动需要借助一个摆式质量阻尼器减缓。因为可以补偿标称频率的不确定和变化因素，MAURER自控型TMD因其自身频率和阻尼控制的原因被选用。实时频率和阻尼控制已通过混合测试进行了实验性验证，测试保证频率在0.17Hz到0.19Hz范围内（图2）。为此，如果当半主动阻尼器与质量单摆连接并且DC Tower在频率0.17Hz和0.19Hz之间摇摆（Weber 2015），就用半主动阻尼器进行力跟踪试验。图3所示选择的精确的力跟踪结果确认了DC Tower上的MAURER 自控型TMD的频率和阻尼对实际振动频率做了最优调频。成功完成全部混合及质量控制测试后，实时控制半主动阻尼器和两个实时控制单元于2014年夏季被安装到了DC Tower上（图3、4）。

多瑙河城市大厦上MAURER 自控型TMD的减振性能

从实验获得的力跟踪结果（图5）能观察到，唯一有关的力跟踪误差结果源于半主动阻尼器大约3kN的残余力，考虑到最大阻尼力大约是45kN，以及不能用力跟踪控制线路补偿，这个力就很小了，因为它是由阻尼器的密封和磁流变液体摩擦力在零电流时给出的，这代表了半主动阻尼力的一种物理约束。

为了量化用MAURER 自控型TMD对DC Tower的减振改善情况，利用DC Tower的一个动态模型和含残余力导致的控制力跟踪误差的 MAURER 自控型TMD用来计算减振。由于MAURER 自控型TMD非线性自适应阻尼控制方法最大限度地减小了阻尼而不会超过0.6米的阻尼器最大容许相对振幅，所以减振性能取决于激振力的水平，也就是风力级别激发DC Tower振动的水平。因此，模拟执行以下情况：

1. 100%最强（恶劣）激振，10年一遇和风载工程师确立的风载：模型中的激振力按照最大预期风载的100%比例。在此激振水平时，调频质量块的最大相对运动幅度等于自身最大容许值0.6米，因此，实时控制器需要最

The basic control approach of the MAURER controlled TMD is to emulate the behavior of the undamped dynamic vibration absorber for the actual frequency of vibration (Frahm, 1911). Hence, the control goals are two-fold:

- The controlled frequency of the MAURER controlled TMD must be equal to the actual frequency of vibration, and
- The controlled damping of the MAURER controlled TMD is to be minimized with the constraint that the relative motion amplitude of the tuned mass must not exceed its tolerable maximum value, (e.g., +/-600 mm in the case of the MAURER controlled TMD of the Danube City Tower in Vienna, Austria) (Weber 2014(a, b)).

Notice that this control approach maximizes the vibration reduction efficiency, which is seen from the fact that it leads to zero response in the primary structure if the damping could be reduced to zero without getting unacceptably large relative motion amplitudes of the tuned mass. According to the two control targets, the semi-active damper force has to emulate the combination of a desired stiffness force to generate the real-time frequency adaptation, and a desired damping force for the damping adaptation. If the sum of the desired stiffness force and the desired damping force is an active desired force, the active desired force is so-called "clipped" to zero since semi-active dampers can only exert purely dissipative forces. In the case that clipping occurs, the control algorithm is programmed to prioritize the real-time frequency control while the resulting actual damping will be greater than its desired counterpart, since stiffness and damping forces of semi-active dampers are coupled quantities.

Figure 1. The first bending mode of the Danube City Tower in Vienna, Austria, with nominal eigenfrequency at 0.18 Hz is mitigated by one MAURER controlled TMD with a pendulum mass of 300 tons and two real-time controlled semi-active dampers generating precise real-time frequency and damping tunings within the frequency range from 0.17 Hz to 0.19 Hz (Source: MAURER AG)

图1. 奥地利维也纳多瑙河城市大厦的第一个弯曲模态在标称频率0.18Hz处被一个MAURER 自控型TMD 减轻了振动，该TMD带有一个300吨的质量摆和两个实时控制半主动阻尼器，使实时频率和阻尼精确调频在频率0.17Hz到0.19Hz范围内 （来源：MAURER AG）

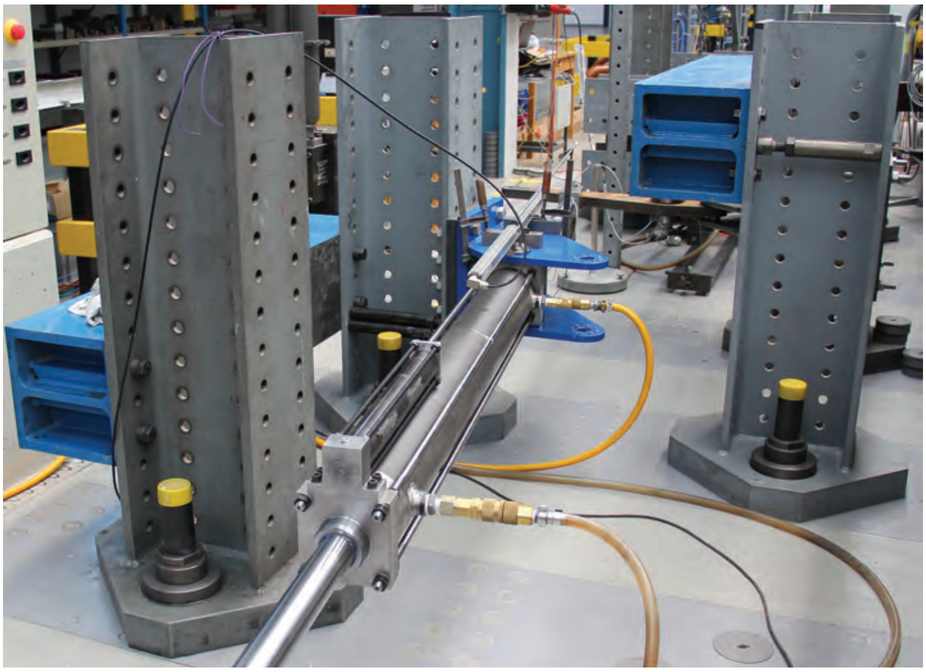

Figure 2. Testing of frequency and damping controls of the MAURER controlled TMD of the Danube City Tower by hybrid testing of the semi-active damper within the entire guaranteed frequency control range from 0.17 Hz to 0.19 Hz (Source: MAURER AG)

图2. 奥地利维也纳多瑙河城市大厦的MAURER 自控型TMD的频率和阻尼控制试验，对半主动阻尼器从0.17Hz到0.19Hz整个有保证的频率控制范围内采用混合测试 （来源：MAURER AG）

Controlled Mitigation of Danube City Tower in Vienna, Austria

The numerical analysis of the Danube City Tower (DC Tower) in Vienna, Austria (Figure 1), showed that the horizontal vibrations due to the first bending mode with a modal mass of 40,000 tons at a nominal eigenfrequency of 0.18 Hz requires mitigation by a pendulum mass damper. The MAURER controlled TMD was selected due to its frequency and damping controls in order to compensate for uncertainties and variations of the nominal eigenfrequency. The real-time frequency and damping controls were experimentally verified by hybrid testing within the guaranteed frequency range from 0.17 Hz to 0.19 Hz (Figure 2). For this, the force tracking with the semi-active dampers was tested as if the semi-active dampers were connected to the pendulum mass and the DC Tower was swaying at frequencies between 0.17 Hz and 0.19 Hz (Weber 2015). The precise force tracking results, of which a selection is shown in Figure 3, confirm that frequency and damping of the MAURER controlled TMD in the DC Tower are optimally tuned to the actual frequency of vibration. After successful completion of all hybrid and quality control

大阻尼来避免调频质量块相对运动幅度过大。按照Den Hartog （1934）最大受控阻尼选取与被动型TMD相等的阻尼，由此可知，MAURER 自控型TMD的和被动型TMD的减振程度在最强激振和标称频率0.18Hz附近，几乎相同 （图6）。

2. 85%最强激振：模型中的激振力按照最大预期风载的85%比例。调频质量块产生的最大相对运动幅度小于自身最大容许值。因此，受控阻尼通过自

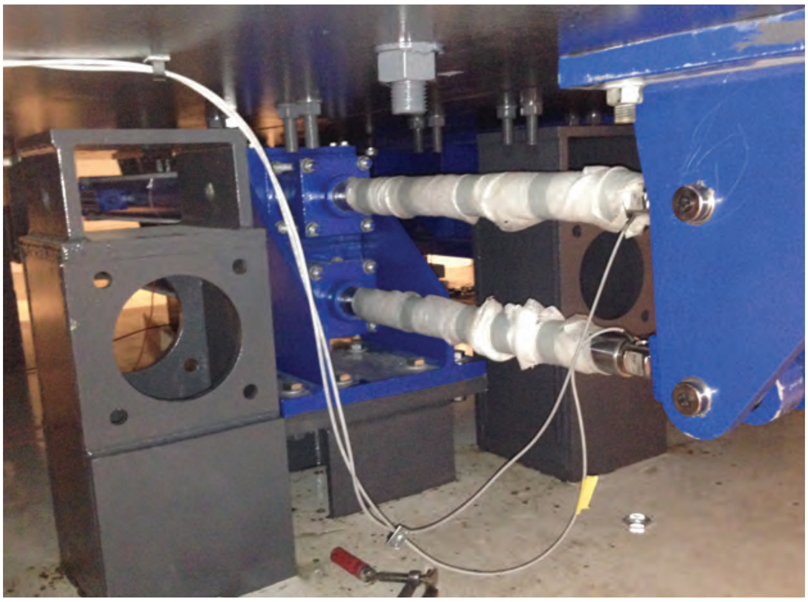

Figure 3. The two real-time controlled semi-active dampers of the MAURER controlled TMD of the Danube City Tower connected to the pendulum mass and the floor（Source: MAURER AG)
图3. 多瑙河城市大厦的MAURER 自控型TMD的两个实时控制半主动阻尼器连接质量摆和地面（来源：MAURER AG）

Figure 4. Real-time control units of the MAURER controlled TMD of the Danube City Tower (Source: MAURER AG)
图4. 多瑙河城市大厦的MAURER 自控型TMD的实时控制单元（来源：MAURER AG）

tests, the real-time controlled semi-active dampers with two real-time control units were installed in the DC Tower in summer 2014 (Figures 3 and 4).

Vibration Reduction Performance of MAURER controlled TMD of Danube City Tower

From the experimentally obtained force tracking results (Figure 5), it can be observed that the only relevant force-tracking error results from the residual force of the semi-active damper of approximately 3 kN, which is small considering the maximum damper force of approximately 45 kN and cannot be compensated by the force tracking control scheme, since it is given by the sealing of the damper and the magnetorheological fluid friction at zero current, whereby it represents a physical constraint of the semi-active damper force.

适应阻尼控制方法减小了，显著提高了MAURER 自控型TMD的减振性能（图7）。

3. 50%最强激振：模型中的激振力按照最大预期风载的50%比例。因为调频质量块产生的最大相对运动幅度远远小于自身最大容许值，MAURER 自控型TMD的受控阻尼通过自适应控制方法被减至最小。最小值限制在被动型TMD阻尼的20%，以保证MAURER 自控型TMD工作稳定（图8）。

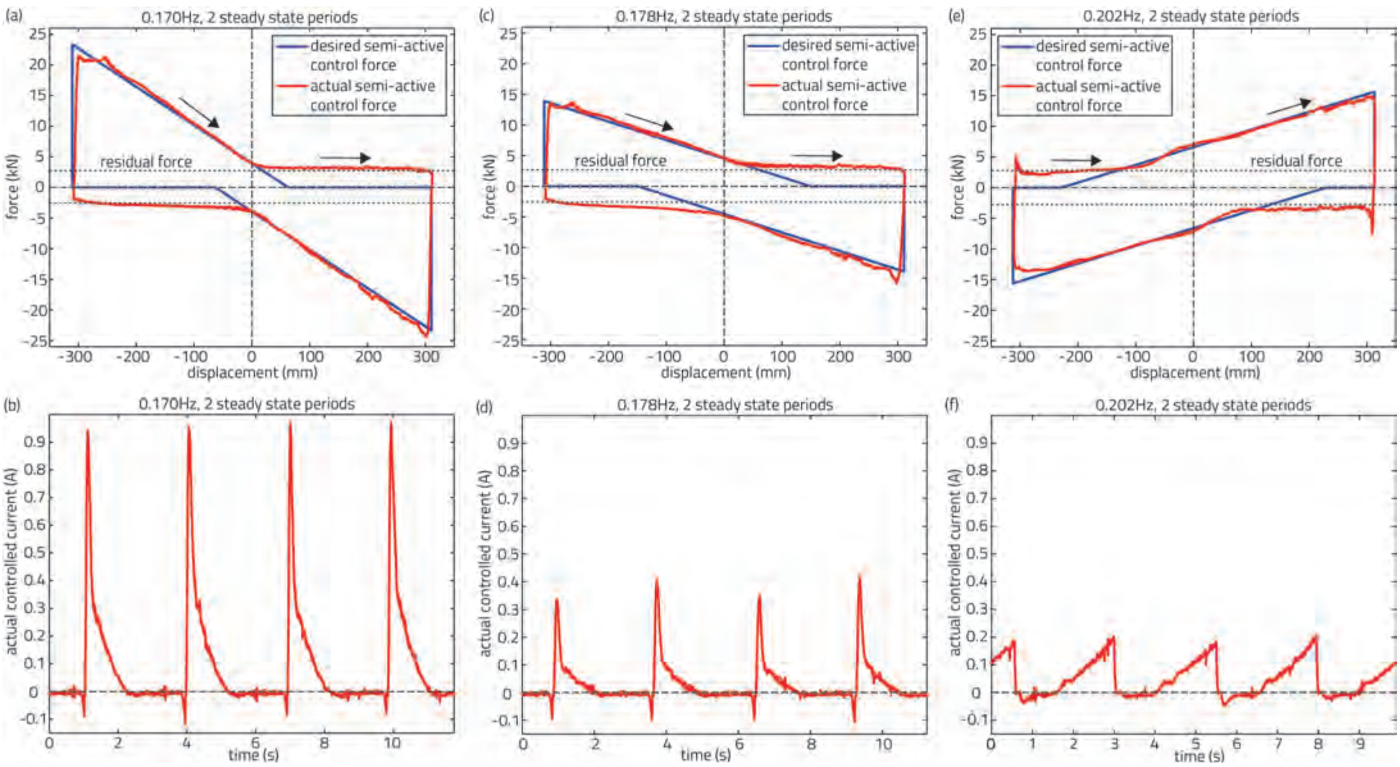

Figure 5. Precise real-time force tracking results within the guaranteed frequency control range from 0.17 Hz to 0.19 Hz confirm the superior mitigation efficiency of the MAURER controlled TMD that is computed by a dynamic model of the Danube City Tower with MAURER controlled TMD（Source: MAURER AG)
图5. 精确的实时力跟踪结果通过多瑙河城市大厦的MAURER 自控型TMD的动态模型进行计算，从0.17Hz到0.19Hz有保证的频率控制范围内确定了MAURER 自控型TMD优越的减振效能（来源：MAURER AG）

In order to quantify the improved vibration reduction of the DC Tower with the MAURER controlled TMD, a dynamic model of the DC Tower with MAURER controlled TMD – including the control force tracking errors due to the residual force – is computed. Due to the nonlinear adaptive damping control approach of the MAURER controlled TMD that minimizes the damping without violating the maximum tolerable relative damper amplitude of 0.6 m, the vibration reduction performance of the MAURER controlled TMD depends on the level of the excitation force, (i.e., the level of the wind forces that excite the DC Tower). The simulations are therefore performed for:

1. 100% of worst case excitation that may be the 10-year return period wind loading and in a more general sense the wind load defined by the wind engineer: The excitation forces in the model are scaled to 100% of the maximum expected wind load. At this level of excitation the maximum relative motion amplitude of the tuned mass is equal to its maximum tolerable value of 0.6 m whereby the real-time controller commands maximum damping in order to avoid too large relative motion amplitudes of the tuned mass. The maximum controlled damping is selected to be equal to the damping of the passive TMDs according to Den Hartog (1934), whereby the vibration reduction magnitudes of the MAURER controlled TMD and the passive TMD at worst case excitation and in the vicinity of the nominal eigenfrequency of 0.18 Hz are almost equal (Figure 6).

2. 85% of worst case excitation: The excitation forces in the model are scaled to 85% of the maximum expected wind load. The resulting maximum relative motion amplitude of the tuned mass is smaller than its maximum tolerable value. Hence, the controlled damping is reduced by the adaptive damping control approach, which significantly improves the vibration reduction performance of the MAURER controlled TMD (Figure 7).

3. 50% of worst case excitation: The excitation forces in the model are scaled to 50% of the maximum expected wind load. Since the resulting maximum relative motion amplitude of the tuned mass is far smaller than its maximum tolerable value, the controlled damping of the MAURER controlled TMD is minimized by the adaptive control approach. The minimization is limited to 20% of the damping of the passive TMD to ensure stable operation of the MAURER controlled TMD (Figure 8).

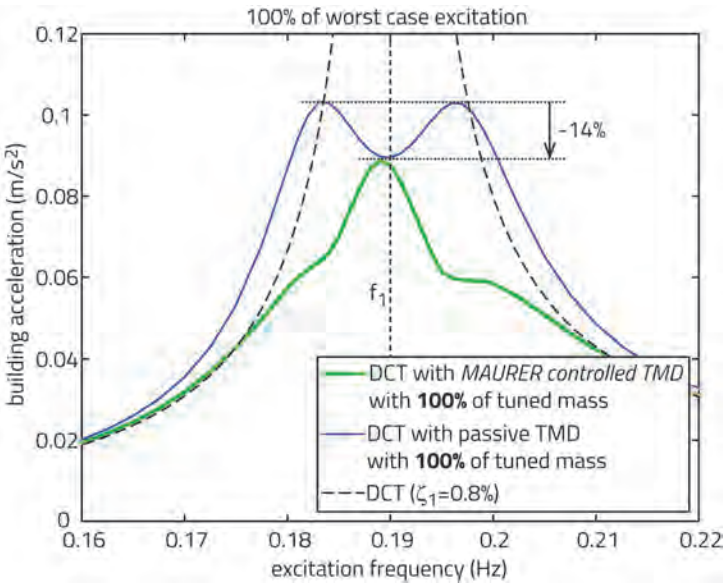

Figure 6. The vibrations of the Danube City Tower with 100% of worst case wind excitation computed with the MAURER controlled TMD set for 100% of tuned mass and 3 kN residual force in the semi-active damper; compared to the results of the passive TMD with 100% of tuned mass (Source: MAURER AG)
图6. 受100%最强风力激振的多瑙河城市大厦的振动用带有100%调频质量，半主动阻尼器内有3kN残余力的MAURER 自控型TMD进行计算，以及与带有100%调频质量的被动型TMD结果的对比（来源：MAURER AG）

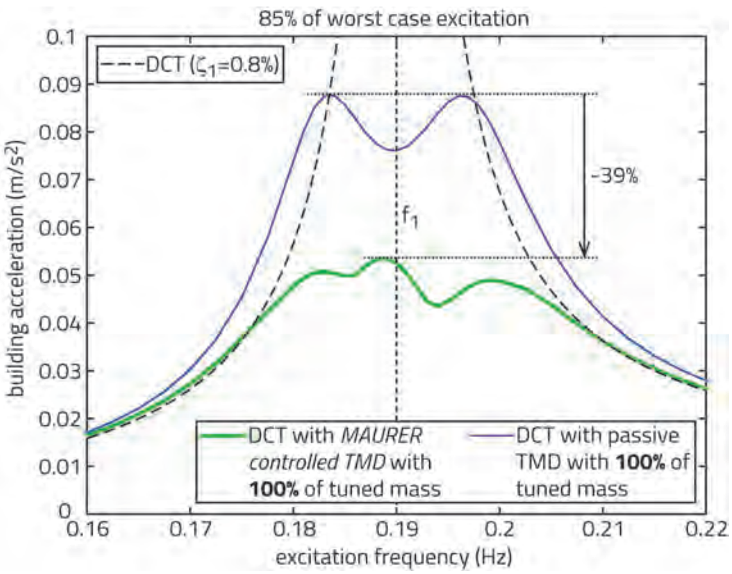

Figure 7. The vibrations of the Danube City Tower with 85% of worst case wind excitation are computed with the MAURER controlled TMD set to 100% of tuned mass and 3 kN residual force in the semi-active damper; compared to the results of the passive TMD with 100% of tuned mass (Source: MAURER AG)
图7. 受85%最强风力激振的多瑙河城市大厦的振动用带有100%调频质量，半主动阻尼器内有3kN残余力的MAURER 自控型TMD进行计算，以及与带有100%调频质量的被动型TMD结果的对比（来源：MAURER AG）

The acceleration responses of the DC Tower with MAURER controlled TMD – depending on the excitation frequency and the different levels of wind loading – are plotted in Figures 6 to 8; the acceleration responses of the DC Tower with passive TMD are also computed as a benchmark. Notice that all simulations with the MAURER controlled TMD are performed assuming 3 kN residual force in the semi-active damper, while the TMD is assumed as a fully linear device without any constraints. The simulation results of all excitation force levels demonstrate the superior mitigation efficiency

装有MAURER 自控型TMD的DC Tower的加速度响应取决于激振频率和风载的不同水平，加速度响应见图6至图8中所示；装有被动型TMD的DC Tower也被作为参照计算。注意，所有用MAURER 自控型TMD进行的模拟都假定半主动阻尼器内有3kN的残余力，而TMD假设为无任何约束的全线性装置。所有激振力水平的模拟结果都论证了MAURER 自控型TMD优异的减振效能。图7和图8论证了MAURER 自控型TMD尤其提高了在较低激振力水平时的减振效果，因为风载较小导致摆幅减小，允许控制阻尼最小，借此弹簧力能够对激振力补偿得更有效。

of the MAURER controlled TMD. Figures 7 and 8 demonstrate that the MAURER controlled TMD especially improves the vibration mitigation at lower excitation force levels because smaller wind loads lead to reduced pendulum amplitudes that allow minimizing the controlled damping whereby the spring force of the MAURER controlled TMD can compensate more efficiently for the excitation forces.

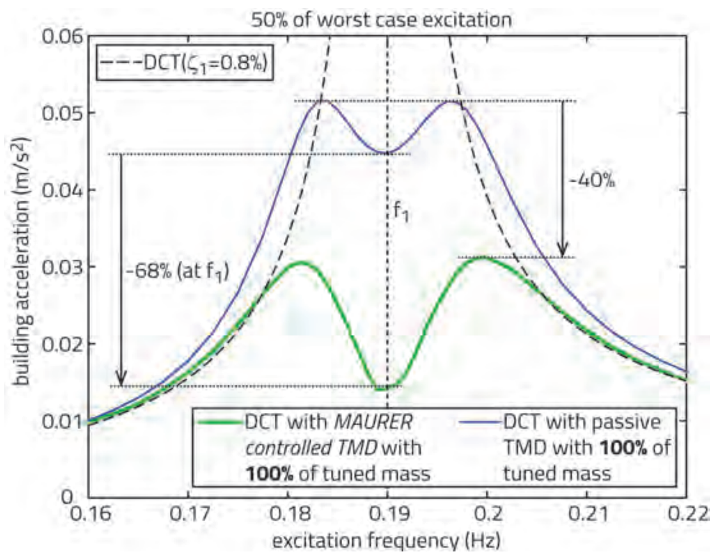

Figure 8. The vibrations of the Danube City Tower with 50% of worst case wind excitation are computed with the MAURER controlled TMD set to 100% of tuned mass and 3 kN residual force in the semi-active damper; compared to the results of the passive TMD with 100% of tuned mass (Source: MAURER AG)

图8. 受50%最强风力激振的多瑙河城市大厦的振动用带有100%调频质量，半主动阻尼器内有3kN残余力的MAURER 自控型TMD进行计算，以及与带有100%调频质量的被动型TMD结果的对比（来源：MAURER AG）

Experimentally Validated Improved Efficiency of MAURER Controlled TMD

The vibration reduction performance of the MAURER controlled TMD compared to the passive TMD is experimentally validated on a 19.2 m long laboratory bridge (Weber & Distl 2013). The tuned mass of 26.325 kg of the mock-up MAURER controlled TMD and the passive TMD, respectively, corresponds to 1.57% of the modal mass of the first vertical bending mode with nominal eigenfrequency at 3.15 Hz. The bridge anti-node displacement responses are normalized by the static deflection due to the measured force of the electrodynamic shaker. The resulting normalized bridge responses are depicted in Figure 9 for the MAURER controlled TMD and the passive TMD, whose normalized response does not depend on the level of excitation due to its linear behavior. The comparison of the experimental results of Figure 9 with the numerical results depicted in Figures 6 to 8 shows a good agreement. The only major difference is that the maximum experimentally obtained improvement of -59% at f1 is smaller than the maximum numerically obtained improvement of -68% at f1. This difference is explained by the fact that the residual force of approximately 4 N of the mock-up MAURER controlled TMD constrains the minimization of the controlled damping more than the residual force of 3 kN of the semi-active damper of the MAURER controlled TMD of the DC Tower.

The concept of the MAURER controlled TMD was first installed in the Volgograd Bridge, Russia, in fall 2011. This bridge with a length of 7.1 km and bridge fields of up to 155 m is one of the longest road bridges in Europe. The Volgograd Bridge underwent severe wind-induced bending vibrations with amplitudes of up to 40 cm in May 2010 which necessitated closing the bridge. Amateur videos of this extraordinary vibration event can be seen on YouTube. Numerical analyses and wind channel tests revealed that the first three bending modes with nominal eigenfrequencies at 0.45 Hz, 0.57 Hz and 0.68 Hz are to be mitigated. In order not to overload the fairly slender

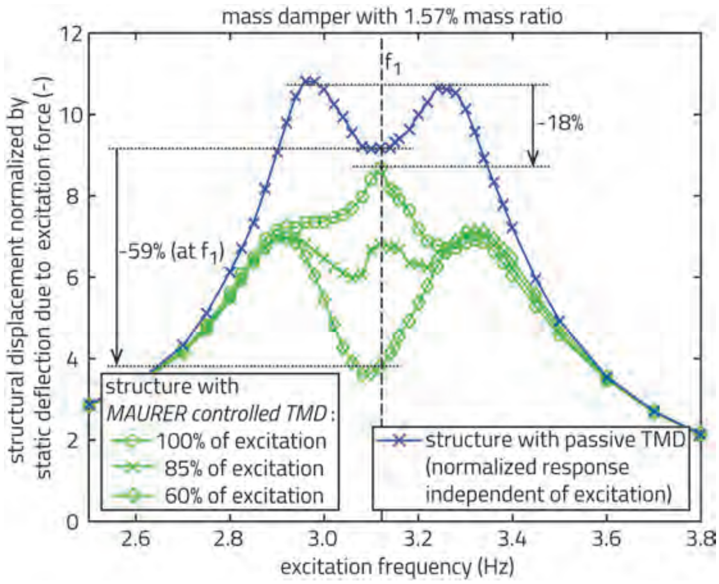

Figure 9. The vibration mitigation efficiency of the MAURER controlled TMD is experimentally verified on a 19.2m long laboratory bridge with a mock-up MAURER controlled TMD and compared to the experimental results of the passive TMD, whose efficiency does not depend on the level of excitation due to its linear behavior (Source: MAURER AG)

图9. MAURER 自控型TMD的减振效能在一条19.2米长的实验室桥梁上通过MAURER 自控型TMD的实物模型进行实验验证以及对比被动型TMD的试验结果，因为自身的线性性质，被动型TMD的效能并不取决于激振等级（来源：MAURER AG）

MAURER 自控型TMD被实验证实提高了效能

MAURER 自控型TMD相比被动型TMD，其减振性能在19.2米长的实验室桥梁上的有效性已经被得以证实（Weber & Distl 2013）。MAURER 自控型TMD和被动型TMD实物模型的26.325kg的调频质量块分别对应1.57%的首个垂直弯曲模态质量，固有频率3.15Hz。由于电动振动器的测量力，桥梁抗结位移响应被静挠度标准化。MAURER 自控型TMD和被动型TMD产生的标准桥梁响应被描绘在图9中，因为自身线性性能，它们的标准响应不随激振力水平而定。图9中试验结果的对照，以及图6至图8中所示的数值结果显示了良好的一致性。唯一的主要不同在于在实验中得到的f1时最大−59%的提高小于数值上得到的最大−68%的提高。这个差异可由该事实解释，MAURER 自控型TMD模型中大约4kN的残余力与DC Tower上MAURER 自控型TMD的半主动阻尼器残余力3kN相比，限制控制阻尼最小值。

2011年秋MAURER 自控型TMD首次安装在俄罗斯伏尔加格勒大桥。该大桥长7.1千米，桥高达155米，是欧洲最长公路桥之一。2010年伏尔加格勒大桥遭受由风引起的剧烈弯曲振动，振幅高达400毫米，大桥不得不关闭使用。这个不可思议的振动事件被业余爱好者拍摄到，视频可以在YouTube上看到。数值分析和风洞试验揭示，最初三个弯曲模态在固有频率0.45Hz、0.57Hz、和0.68Hz处被减轻了。为了不使还算细长的桥面超载，附加质量块由于质量阻尼器的原因，必须最小

bridge deck, the additional mass due to the mass dampers had to be minimized. MAURER solved this task by the innovative solution to split all MAURER controlled TMDs into three groups. The passive natural frequency of the mass spring packets of each group was optimally tuned to the nominal frequencies of the three targeted bending modes. In contrast to the passive tunings the controlled parameters of all MAURER controlled TMDs, (i.e., their controlled frequency and damping), are adjusted in real-time to the actual frequency of vibration. As a result, all MAURER controlled TMDs are optimally tuned to the actual mode of vibration whereby the same vibration reduction of the first three bending modes is obtained as if passive TMDs with approximately two to three times more mass were installed. A similar system is in installed in the Axaiski Bridge, Russia, in operation since 2014.

Improved Efficiency and Reduced Space Demand of MAURER Controlled TMD With 80% of Tuned Mass

The concept of the MAURER controlled TMD allows reducing its tuned mass compared to the passive TMD with nominal mass almost without losing its superior mitigation efficiency. The MAURER controlled TMD in the DC Tower is therefore computed with 80% of the tuned mass (240 tons) and with 3 kN residual force in the semi-active damper, and compared to the performance of the passive TMD with the nominal tuned mass (300 tons). The results of this study are plotted in Figures 10 to 12 for the different wind loadings considered. It is observed that the MAURER controlled TMD with 80% of tuned mass (240 tons) and 3 kN residual force in the controllable damper also outperforms the passive TMD with 100% of tuned mass (300 tons) for all excitation force scenarios. The reduced pendulum mass evokes an increased relative motion amplitude of +0.13 m during worst-case excitation of the DC Tower. However, the increased relative motion amplitude does not lead to an increased space demand of the MAURER controlled TMD as the subsequent calculation demonstrates. Assuming a height of 3 m and steel for the pendulum mass yields a 3.56 m reading for length and width for the 300 tons pendulum mass, while the same assumptions yield 3.18 m for length and width of the reduced mass. Thus, the amplification of the relative motion amplitude of the reduced pendulum mass of 2 x 0.13 m = 0.26 m is more than compensated by the length reduction of -0.38 m. The MAURER controlled TMD with 80% of tuned mass is therefore a highly desirable damping tool for supertall buildings with very

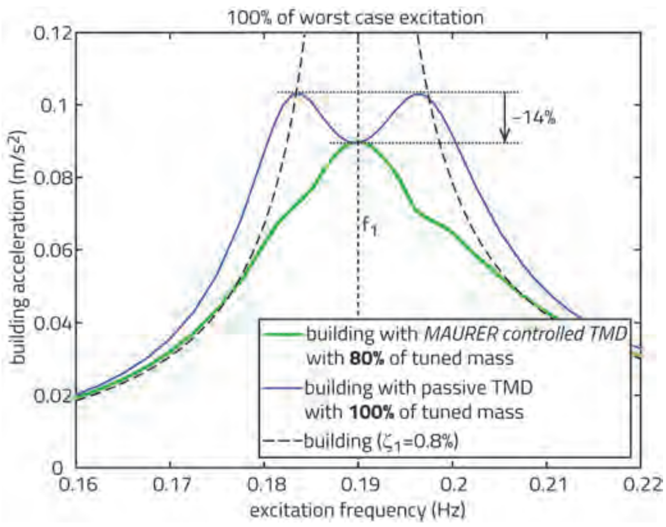

Figure 10. The vibrations of the Danube City Tower with 100% of worst case wind excitation are computed with the MAURER controlled TMD with 80% of tuned mass and 3 kN residual force in the semi-active damper, and compared to the results of the passive TMD with 100% of tuned mass (Source: MAURER AG)
图10. 受100%最强风力激振的多瑙河城市大厦的振动用带有80%调频质量，半主动阻尼器内有3kN残余力的MAURER 自控型TMD进行计算，以及与带有100%调频质量的被动型TMD结果的对比 （来源：MAURERAG）

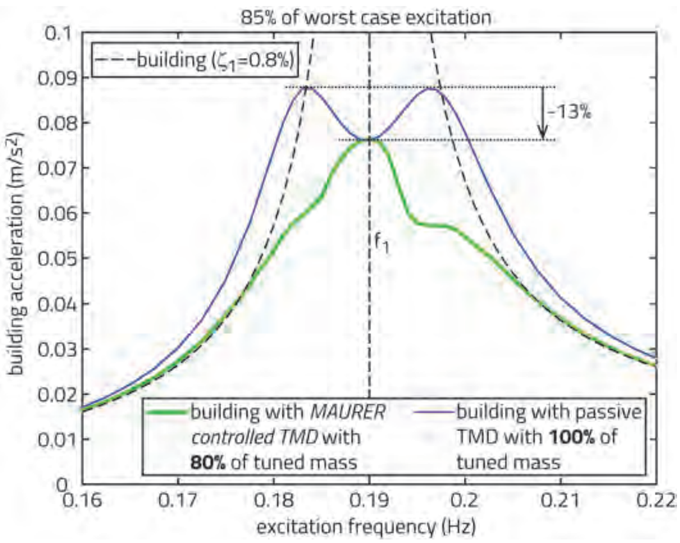

Figure 11. The vibrations of the Danube City Tower with 85% of worst case wind excitation are computed with the MAURER controlled TMD with 80% of tuned mass and 3 kN residual force in the semi-active damper, and compared to the results of the passive TMD with 100% of tuned mass (Source: MAURER AG)
图11. 受85%最强风力激振的多瑙河城市大厦的振动用带有80%调频质量，半主动阻尼器内有3kN残余力的MAURER 自控型TMD进行计算，以及与带有100%调频质量的被动型TMD结果的对比 （来源：MAURERAG）

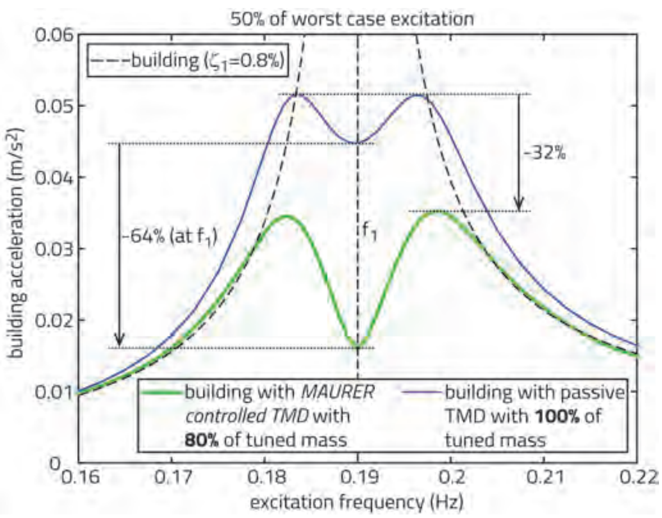

Figure 12. The vibrations of the Danube City Tower with 50% of worst case wind excitation are computed with the MAURER controlled TMD with 80% of tuned mass and 3 kN residual force in the semi-active damper, and compared to the results of the passive TMD with 100% of tuned mass (Source: MAURER AG)
图12. 受50%最强风力激振的多瑙河城市大厦的振动用带有80%调频质量，半主动阻尼器内有3kN残余力的MAURER 自控型TMD进行计算，以及与带有100%调频质量的被动型TMD结果的对比（来源：MAURER AG）

big modal masses because it combines the following two benefits:

- superior vibration reduction compared to the passive TMD with 100% of tuned mass, and
- smaller space demand and reduced costs due to the reduced tuned mass compared to the passive TMD with 100% of tuned mass.

Summary and Conclusion

Based on the principle of the undamped dynamic vibration absorber the control law of the MAURER controlled TMD is formulated for the actual frequency of vibration. Thus, the controlled frequency of the MAURER controlled TMD is equal to the actual frequency of vibration at all instants, and an adaptive nonlinear control approach minimizes the controlled damping of the MAURER controlled TMD without violating the maximum tolerable relative motion amplitude of the pendulum mass. This concept with only 80% of damper mass combines the benefits of reduced static load and reduced space demand of the pendulum mass while the vibration mitigation in the primary structure is enhanced by up to 64% compared to the conventional passive TMD with 100% of damper mass. Thus, the MAURER controlled TMD is especially preferable for supertall buildings where the modal mass is very big, the acceptable vibration limits are low to ensure high comfort, and the available space for the mass damper is limited.

化。MAURER 凭借其创新方案解决了该难题，即把所有MAURER 自控型TMD分为三组。每组质量弹簧包的被动固有频率被最优化地调频到三个目标弯曲模态的标称频率。相比被动调频，MAURER 自控型TMD的控制参数，也就是它们的控制频率和阻尼按照实际振动频率实时进行调节。结果是，所有MAURER 自控型TMD都被最优化地按照实际振动模态进行了调频，借此获得了最初三个弯曲模态相同的减振量，如果是被动型TMD，则需要安装大约2到3倍更多的质量块。类似的一个系统也安装在俄罗斯Axaiski 大桥并于2014年投入使用。

带80%调频质量的MAURER 自控型TMD提高的效能和空间需求的降低

MAURER 自控型TMD相比有标称质量的被动型TMD，允许减小自身调频质量而几乎不损失其优越的减振效能。因此，与标称质量（300吨）的被动型TMD性能相比，安装在DC Tower上的MAURER 自控型TMD以80%的调频质量（240吨）计算并有3kN的残余力在半主动阻尼器中。出于不同风载考虑，这项研究成果在图10至图12中所示。可以观察到，对于所有激振力发生的情况，具有80%调频质量（240吨）且3kN残余力在可控阻尼器中的 MAURER 自控型TMD也在性能上胜过100%调频质量（300吨）的被动型TMD。在DC Tower最强激振情况下，减小的质量摆引起其相对运动幅度增加+0.13米。然而，增加的相对运动幅度不会导致MAURER 自控型TMD所需空间的加大，随后的计算论证了这一点。假设一个高3米的钢制质量摆让出3.56米给300吨的质量摆的长和宽，同时假设让出3.18米给减小的质量块的长和宽。这样，减小的质量摆其相对运动的振幅为2×0.13米=0.26米，大于长度减小0.38米所获得的补偿。因此，对于有很大模态质量的超高建筑物来说，带有80%调频质量的MAURER 自控型TMD是一种非常可取的阻尼工具，因为它结合了以下两个好处:

- 相比有100%调频质量的被动型TMD，拥有优越的减振性能，并且
- 相比有100%调频质量的被动型TMD，空间需求较小，质量块小，成本降低。

总结与结论

在无阻尼动力减振器原理的基础上，MAURER 自控型TMD的控制规律被列成公式来计算实际振动频率。这样，MAURER 自控型TMD的控制频率在所有时刻都等于实际振动频率，并且自适应非线性控制方法使MAURER 自控型TMD的控制阻尼最小而不违反质量摆的最大容许相对运动幅度。与传统的100%阻尼质量的被动型TMD相比，只用80%阻尼质量的概念结合了质量摆静载荷减小和空间需求降低的好处而主结构减振效果提高高达64%。因此，MAURER 自控型TMD更适合于模态质量非常大超高建筑物，允许的振动极限比较低从而保证较高舒适度，以及质量阻尼器可安装空间受到限制的情况。

References:

Bollinger, K., Grohmann M. and Berger, A. (2015). **"The Vienna Donau City Tower – 2000m Flat Slabs as Outrigger Structure for Unique Landmark Building"**, Proceedings of the CTBUH 2015 New York Conference. 540-547.

Den Hartog, J. P. (1934). **Mechanical Vibrations.** 1956 Edition. York, PA: The Maple Press Company.

Frahm, H. (1911). **Devices for Damping Vibrations of Bodies.** U.S. Patent no. 989, 958.

Soong, T. T. and Dargush, G. F. (1997). **Passive Energy Dissipation Systems in Structural Engineering.** New York City: John Wiley & Sons Ltd.

Weber, F. & Distl, H. (2013). "**Real-Time Controlled Tuned Mass Dampers for Wolgograd Bridge",** Beton-und Stahlbetonbau. Vol. 108(Heft 6), 362-372.

Weber, F. (2014a). **"Semi-Active Vibration Absorber Based on Real-Time Controlled MR Damper",** Mechanical Systems and Signal Processing. Vol. 46(2): 272-288.

Weber, F. (2014b). **"Optimal Semi-Active Vibration Absorber for Harmonic Excitation Based on Controlled Semi-Active Damper",** Smart Mater. Struct., Vol. 23: 095033.

Weber, F. (2015). **"Robust Force Tracking Control Scheme for MR Dampers",** Struct. Control Health Monit., Vol. 22(12): 1373-1395.