

Tuned Mass Dampers Using Wire Rope Isolators

Claude Prost and Bruno Abdelnour, Vibro/Dynamics LLC, Broadview, Illinois

Tall, steel, chimney stacks installed in windy regions are prone to violent vibrations that could lead to stack failure. The source of this vibration is due to the phenomenon called vortex shedding. Controlling the amplitude of vortex-induced vibrations is crucial to avoid catastrophic failure of the chimney and increase its lifespan. One widely accepted design for doing so is the use of hydraulic dampers installed between the top of the chimney and a steel ring. While this is an effective design at limiting a chimney's vibration, it often requires maintenance, and its performance could vary based on temperature. A less known way of controlling chimney vibration is through the use of wire rope isolators (WRIs). When tuned to the proper stiffness and damping, WRIs can be very effective at controlling the chimney's vibration. In addition, WRI-tuned mass dampers (TMDs) offer further advantages such as their maintenance free construction, temperature-independent performance, and extremely long lifetime. Our purpose here is to present a case study where the Socitec Group provided a WRI-based TMD for a chimney stack. The simulation results show that just like hydraulic dampers, WRI TMDs can be very effective at controlling a chimney's vibration.

Tuned mass dampers (TMDs) are commonly used in practice to reduce the amplitude of vibrations experienced by structures. TMDs help prevent structural failures and increase the lifespan of the structure with respect to fatigue.

If tuned properly, much of the vibration energy is transferred to the TMD which in turn is dissipated through its damping. One of the main functions of a TMD is to increase the overall damping of the system, limiting the vibration amplitudes in resonance situations.

TMDs are commonly used in high-rise buildings, bridges, chimney stacks and many other structures. In this article, we will focus on the use of TMDs for chimney stacks under vortex induced vibrations.

TMD Design Theory

TMD design theory is based on a simple model shown in Figure 1. In this model, the main structure has a known linear stiffness and damping. It also experiences a harmonic excitation that is swept across a range of frequencies. A TMD is attached to the main structure to reduce its response across the entire range of excitation frequencies.

In a TMD design, there are three parameters that have to be tuned: its mass, damping, and stiffness. The mass is selected first, and is usually between 1-10% of the main structure mass. For economic reasons, it is better to keep this mass low, but an engineer has to be careful, because by doing so, there is a risk of having excessive TMD motion due to its low inertia. Once the TMD mass is selected, its optimal stiffness and damping can be calculated. The optimal TMD design is a combination of stiffness and damping that minimizes the maximum steady-state response of the main structure across the entire range of excitation frequencies. This is known as the minimax approach. For example Figure 2 shows two different TMD designs, the design represented by the blue curve is the optimal solution, since it minimizes the maximum steady-state response of the main structure compared to the TMD design represented by the orange curve.

If the main structure is undamped and the TMD mass is given, closed-form solutions exist to solve for its optimal stiffness and damping. If the main structure is damped, then closed-form solutions are no longer applicable. Instead, a numerical approach with

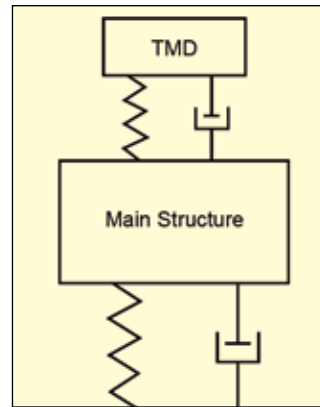


Figure 1. Simple model of main structure with TMD.

design graphs is used to solve for the optimal TMD design.

Interestingly using the minimax approach is also very effective to design a TMD against earthquake excitations. This is not too surprising, since the minimax approach gives the optimal TMD design across a range of frequencies. So it is expected that this design may also work efficiently when the excitation frequencies are applied simultaneously, such as in earthquakes.

TMDs for Chimney Stacks Vortex-Induced Vibration in

Chimneys. Chimney stacks are subject to vortex-induced vibrations. As wind flows past a chimney, it creates a boundary layer. Due to excessive curvature of the chimney, this boundary layer separates. This separation occurs periodically from each side of the chimney, creating low-pressure vortices. The chimney moves toward the low-pressure sides, which causes it to move in the perpendicular direction of the wind flow (see Figure 3).

The frequency at which these vortices separate is directly related to the wind velocity. There's a critical wind velocity at which the vortex-shedding frequency is equal to the first bending mode of the chimney. When this happens, extremely large vibrations may result in the chimney. This is called the lock-in phenomena, also known as resonance. It is crucial that the vibration amplitudes experienced during lock-in conditions are controlled with the use of a TMD, or other methods.

Case Study. The Socitec Group was asked by a customer to design a TMD for a chimney stack. The customer had been using hydraulic dampers, but his request was a solution that requires minimal maintenance, making a good case for wire rope isolators. The customer provided the chimney's data: it is 39 m tall and weighs 9400 kg. Its inherent damping is 0.7% of critical damping, and its first mode is 0.83 Hz. The customer requested a solution in which the displacement amplitude of the chimney does not exceed 60 mm.

Chimney Modeling. To model the dynamics of the chimney, the Socitec Group used its proprietary simulation software, SYMOS. It is a nonlinear, multiple-degree-of-freedom software package using the lumped element method to calculate the response of a system. In SYMOS, each body is assumed rigid, and the interactions between the bodies are incorporated using links that can be nonlinear.

Eight bodies and eight links were used to model the dynamics of the chimney. The rotational stiffness and damping of these links were tuned to match the 0.83 Hz bending mode and the 0.7% inherent damping. The resulting second and third bending modes of the model also matched the data given by the customer. This affirms its accuracy. The critical wind velocities corresponding to each of these modes are 12.5 mph, 71 mph and 197 mph, for modes 1, 2 and 3, respectively. Since wind velocities above 60 mph are not expected in the location of this chimney, only the first mode needs to be controlled by the TMD.

Designing TMDs Using WRIs. To design the TMD for this chimney, the first step is to calculate the generalized mass of the chimney corresponding to the first mode. If the chimney was modeled as

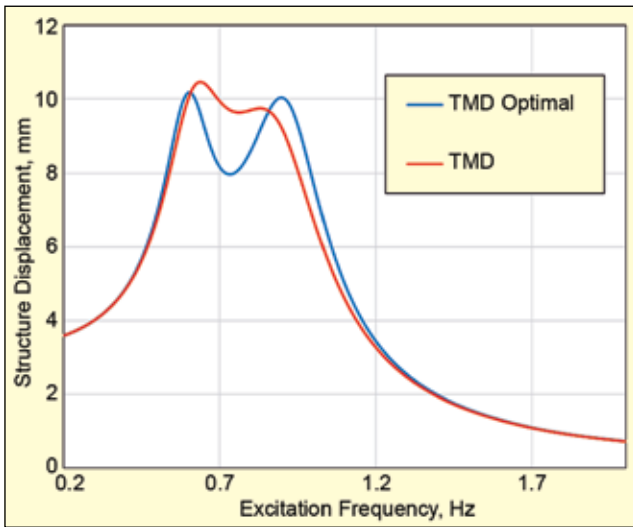


Figure 2. Optimal TMD determined using minimax approach.

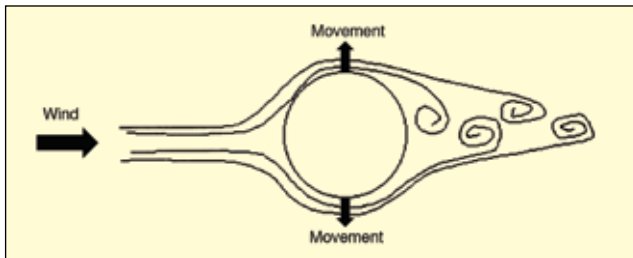


Figure 3. Vortex excitation.

a 1DOF body, then the generalized mass of the first mode would be its total mass. However, since the chimney was modeled as a multi-degree-of-freedom-body, its generalized mass for the first mode has to be calculated using the following matrix equation:

$$M_1 = \phi_{1n}^T M \phi_{1n} \quad (1)$$

where, M_1 is the generalized mass matrix of the first mode; M is the mass matrix of the chimney; ϕ_{1n} is the normalized first mode shape vector; and ϕ_{1n}^T is the transverse of ϕ_{1n} . The first mode shape vector is normalized with respect to the body of the chimney, which undergoes the most motion for that mode of vibration. In this case, it is the body at the top of the chimney.

The calculated generalized mass in this case is 2100 kg. Additionally, the mass of the TMD was given by the customer to be 470 kg. Given this mass and the generalized mass, the optimal total stiffness and damping of the TMD can now be calculated to be 8570 N/m and 26.2% of critical damping.

In this TMD design, we decided to use six WRIs suspended around the top of the chimney and supporting a ring mass, as shown in Figure 4. Therefore, the goal is to supply six WRIs, where their sum of stiffness and damping in shear and roll are as close as possible to 8570 N/m and 26.2% of critical damping, respectively.

A few iterations were needed to get the optimal WRI design; this process entailed manufacturing the WRI and then measuring its stiffness and damping through testing. Once the optimal WRI was determined, its nonlinear tested characteristics (stiffness and damping) were imported into the SYMOS model of the chimney with the TMD. Note, to achieve high enough damping, a special wire construction cable was used.

Simulation Study Results. Simulation studies were performed to compare the response of the chimney alone to the response of the chimney with the WRI TMD. For both studies, the vortex-shedding excitation was assumed as harmonic excitation acting on each of the eight bodies of the chimney. The customer supplied this load, and its distribution is directly proportional to the square of the local wind velocity across the chimney's height.

Results from simulation showed that using the TMD reduced the maximum displacement response at the top of the chimney by a factor of more than 30, as shown in Figure 5. This significant

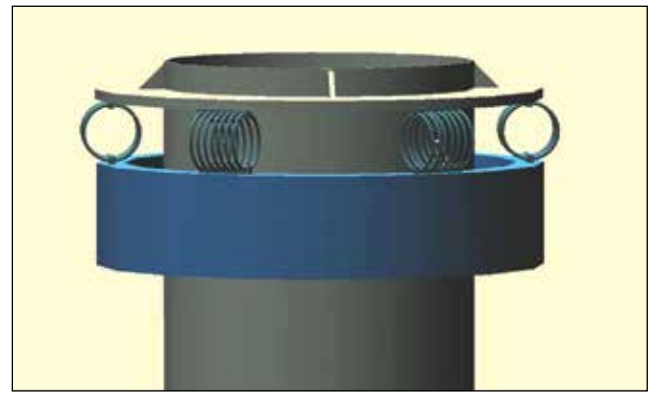


Figure 4. WRI TMD design layout.

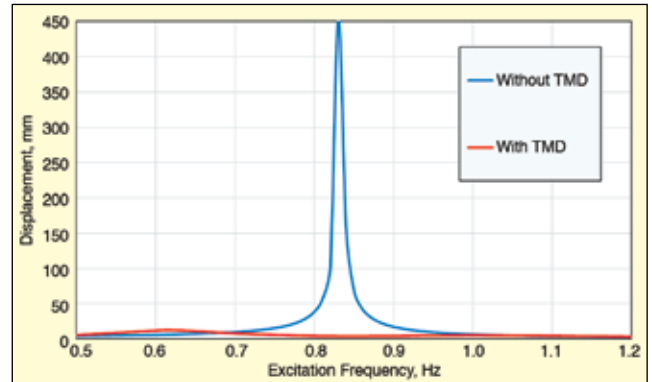


Figure 5. Top-of-chimney response with and without TMD.

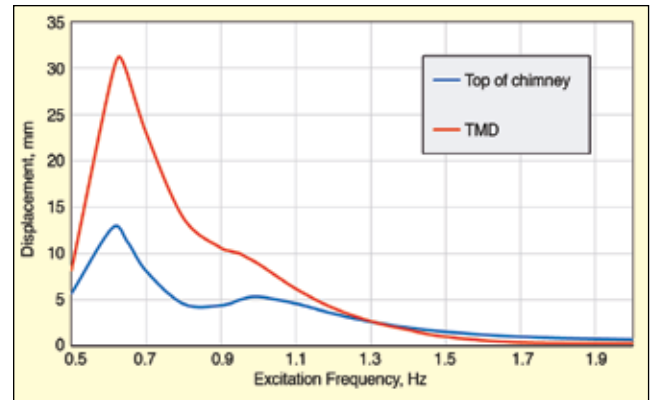


Figure 6. Displacement amplitude response of top of chimney and TMD.

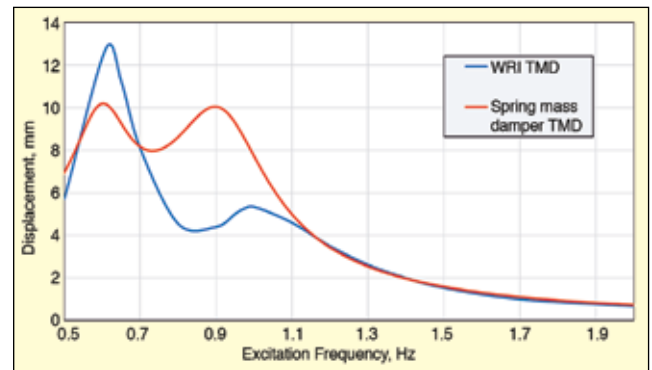


Figure 7. Displacement amplitude response of top of the chimney with spring mass damper TMD versus a WRI TMD.

reduction in motion helps avoid structural failure of the chimney as well as drastically increasing its lifespan. This result goes to prove that a WRI-based TMD can be very effective at controlling chimney vibrations under vortex excitations.

Additionally, the results from simulation of the chimney with the TMD show that the maximum displacement response of the

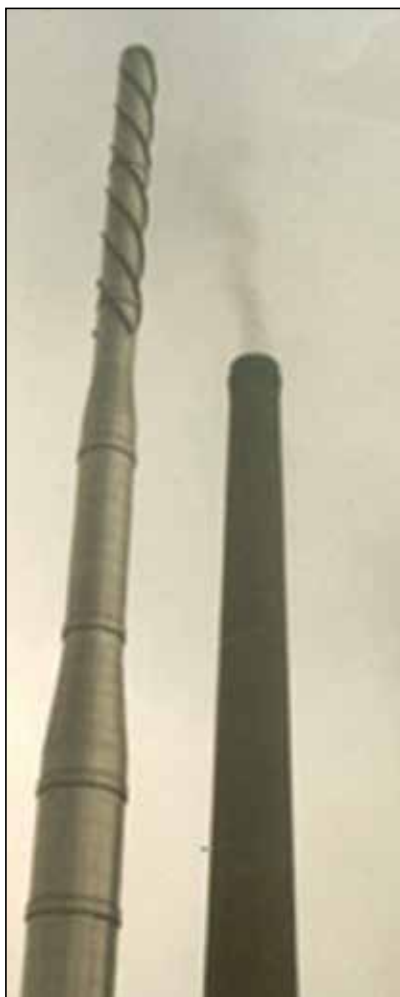


Figure 8. Helical strakes across part of chimney (left) control vortex excitations.

chimney was 12.8 mm and the maximum displacement response of the TMD was 31.2 mm. This is shown in Figure 6, and all motions are predicted to be below 60 mm, satisfying the customer's requirement.

WRI TMD Versus Spring-Mass Damper TMD. To evaluate the effectiveness of a WRI TMD, it is important to compare it to the performance of the best ideal spring mass damper TMD. To do that, a simulation study was run where each WRI was replaced by a spring mass damper with optimal linear stiffness and the optimal linear damping calculated previously. The results are shown in Figure 7.

These results show that the peak displacement response at the top of the chimney is about 3 mm less in amplitude when using a spring mass damper TMD versus a WRI TMD. This is a very subtle difference

especially since, in the region of 0.7-1.1 Hz, the WRI TMD actually performs better compared with the spring mass damper TMD.

Additionally, from a practical standpoint WRI TMDs surpass spring mass damper TMDs. Unlike spring mass dampers, WRIs require no maintenance and have a performance independent of temperature. Also, due to their multidirectional design, WRI TMDs have the same performance independent of incoming wind direction. This is not the case for spring mass damper TMDs, which are inherently unidirectional, making their performance vary depending on incoming wind directions.

Conclusions

Tall steel chimneys installed in windy regions are subject to severe and dangerous vibrations due to vortex shedding. In most cases, adding a tuned mass damper is the most cost-effective way of controlling a chimney's response to vortex shedding. Another way is to use of helical strakes, which break the vortices (see Figure 8). This method is more expensive and only proves to be effective for small stacks with small diameters.

Simulation results showed that WRI TMDs can be very effective at reducing the vibration amplitude of a chimney. The case study showed that by adding a WRI TMD, the vibration amplitude was reduced by a factor of more than 30. Additionally, all motions were calculated to be below 60 mm, which satisfies the requirements by the customer.

WRI TMDs may not be the design that results in the least chimney motion compared with other TMD designs. However, their multidirectional design, maintenance-free construction, and performance under a wide range of temperatures makes them overall among the best TMD designs for such applications. **SV**

The author can be reached at: cprost@vibro-dynamics.com.