Chapter 8

Use of tuned mass dampers (TMD) to reduce vibrations caused by wind on the spire of a tower building

Wiesław Fiebig
Wroclaw University of Science and Technology

Christian Meinhardt
Gerb Schwingungsisolierungen GmbH Co KG, Berlin

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Abstract
The paper presents results of the use of tuned mass dampers to reduce vibrations caused on the spire of the Varso Tower building. Based on the literature, the description of the wind forces that cause vibrations and the basis for the selection of the TMD parameters have been presented. To verify the effectiveness of the new TMDs, the structural damping ratio of the spire with installed and activated TMDs has been determined by measuring the ambient vibrations of the spire. The natural frequencies were determined using the commercial signal processing software ARTEMIS, which incorporates Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification Methods. Three TMDs have been tuned for the first three natural frequencies. The recorded accelerations were analyzed and the structural damping ratios for the relevant modes were determined, which were found to be above the target values.

Keywords: tower building, spire vibration, wind-induced vibration, tuned mass dampers (TMD)

1. Introduction

Spiers are mounted on many tall buildings, which perform an architectural function but are also used to place e.g. radio transmitters, radars, etc. The Varso Tower building is 310 m high and is currently the tallest building in the European Union. The height of the spire is 80 m. Figure 1 shows a list of tall buildings with spires.

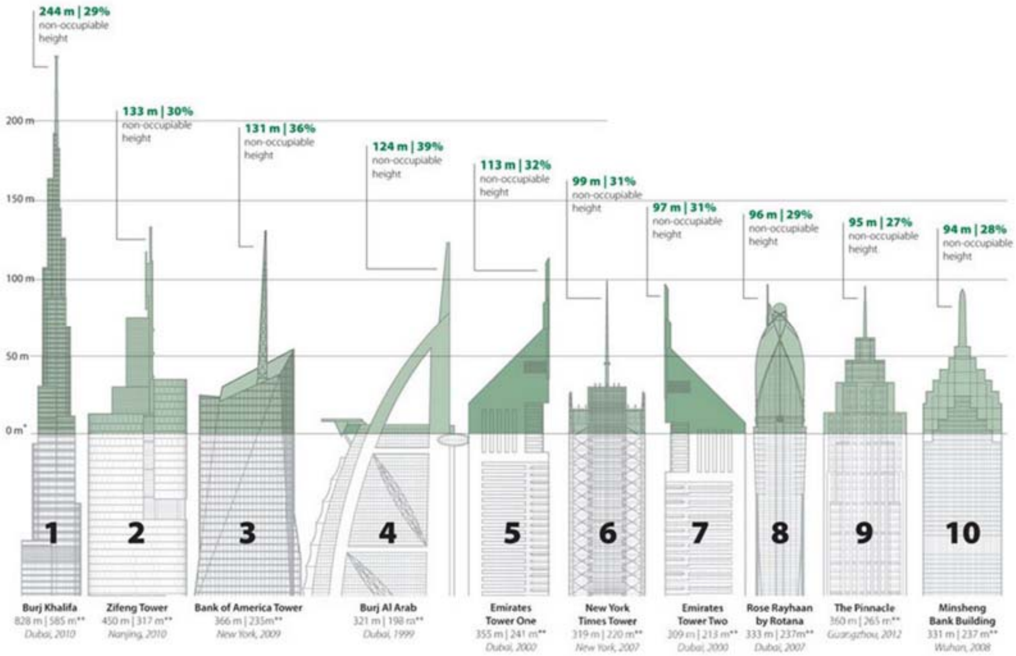


Figure 1. Tall buildings with spiers [1]

Figure 2 shows the view of Varsow Tower building with the spire. An important issue is the determination of the spire natural frequenicies and the damping of the needle's structure as they determine the increase in vibration amplitudes during resonance vibrations. Vibrations are excited due to the wind flow. The paper will describe the excitations from the wind, the selection of TMD parameters, their design and experimental tests aimed at determining the natural vibrations of the spire (Enhanced Frequency Domain and Stochastic Subspace Identification Method). Finally, information on the effectiveness of the TMD in damping the needle's vibrations is given.

Figure 2. View of the Varso Tower building with spire

2. Wind loads in tall buildings

In tall buildings, the different loads shown in Figure 3 occur during airflow [2]. These are the forces resulting from the interaction of forces from the wind with respect to the structure of the building. During the flow around the round elements, turbulence occurs as shown in Figure 3.

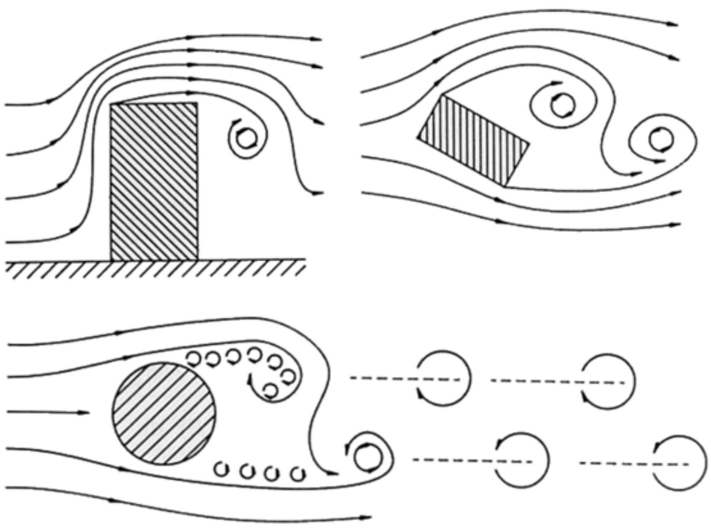


Figure 3. Wind Excitation [2]

Wind excitation acting on the building structure and on the spire has a stochastic nature similar to white noise [2]. It can be assumed that the wind force is the sum of the mean wind vector $v(z)$ dependent from the height and a dynamic, or turbulence, component $v_{dyn}(z,t)$:

$$v(z,t) = v(z) + v_{dyn}(z,t).$$

When the air flows around the spire, its bending vibrations occur, and at natural frequencies, due to the resonances higher amplitudes can be observed.

3. Dynamic model of TMD

The calculation of TMD parameters as effective mass, stiffness of spring elements, tuning frequency and damping ratio can be determined based on two degree of freedom model shown in Figure 4.

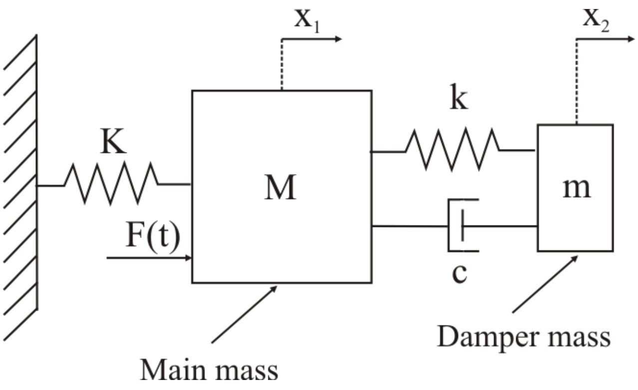


Figure 4. Dynamic model of TMD

The equations of motion for the system from Figure 4 are as follows:

$$M \cdot \ddot{x_1} + c \cdot (\dot{x_1} - \dot{x_2}) + K \cdot x_1 + k \cdot (x_1 - x_2) = F_0 e^{i\omega t} \tag{1}$$

$$m \cdot \ddot{x_2} + c \cdot (\dot{x_2} - \dot{x_1}) + k \cdot (x_2 - x_1) = 0. \tag{2}$$

Solutions can be defined as:

$$x_1 = \bar{x}_{o1} \cdot e^{i\omega t} \tag{3}$$

$$x_2 = \bar{x}_{o2} \cdot e^{i\omega t} \tag{4}$$

$\bar{x}_{o1}, \bar{x}_{o2} \rightarrow$ complex vibration amplitudes of masses *M* and *m*.

After introduction of terms (3) and (4) in (1) and (2) can be written:

$$-M \cdot \omega^2 \cdot \bar{x}_{o1} + i \cdot \omega \cdot c \cdot (\bar{x}_{o1} - \bar{x}_{o2}) + K \cdot \bar{x}_{o1} + k \cdot (\bar{x}_{o1} - \bar{x}_{o2}) = F_0 \tag{5}$$

$$-m \cdot \omega^2 \cdot \bar{x}_{o2} + i \cdot \omega \cdot c \cdot (\bar{x}_{o2} - \bar{x}_{o1}) = 0. \tag{6}$$

The complex amplitude of the vibration of mass M is given by:

$$\bar{x}_{o1} = F_0 \frac{(k - m\omega^2) + i \cdot \omega \cdot c}{[(-M\omega^2 + K)(-m \cdot \omega^2 + k) - m\omega^2 \cdot k] + i \cdot \omega \cdot c \cdot (-M \cdot \omega^2 + K - m \cdot \omega^2)} \tag{7}$$

and the magnitude as:

$$|\bar{x}_{o1}| = F_0 \sqrt{\frac{(k - m\omega^2)^2 + \omega^2 \cdot c}{[(-M\omega^2 + K)(-m \cdot \omega^2 + k) - m\omega^2 \cdot k] + \omega^2 \cdot c^2 \cdot (-M \cdot \omega^2 + K - m \cdot \omega^2)}}. \tag{8}$$

Damping reduces the vibration amplitudes in the resonance ranges and increases the frequency ranges in which vibration reduction occurs.

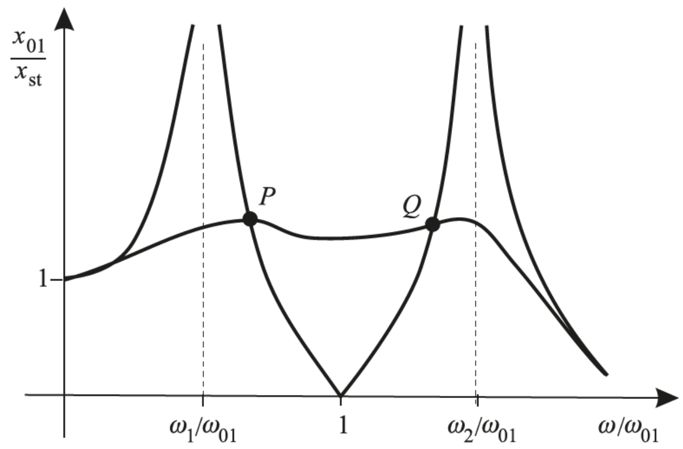


Figure 5. Vibration amplitude of the main mass

In addition to the TMD and its damping coefficient *c*, the efficacy of TMD strongly depends on the ratio between the structures mass and the TMD mass $\mu = m/M$. By comparing the results, the optimal values (minimum amplification) can be found for the TMD parameters.

Information on the optimal damping of TMD can be found in the available literature. In [3, 4] it is indicated that to obtain optimal damping the intersection points of the frequency characteristics P and Q should be at the same value of the coefficient of the amplitude amplification (Figure 5).

There are two basic parameters of the TMD frequency ratio and damping ratio ($\xi = \frac{c}{2\sqrt{km}}$) which should be considered.

The frequency ratio is defined as:

$$\alpha = \frac{\text{natural frequency of the damping mass}}{\text{dominant frequency of the main mass}}.$$

The optimal frequency ratio is given by [3]:

$$\alpha_{opt} = \frac{1}{1+\mu}. \tag{9}$$

The optimal damping ratio can be obtained depending on the character of the excitation force [4] :
▪ for the periodic excitation force:

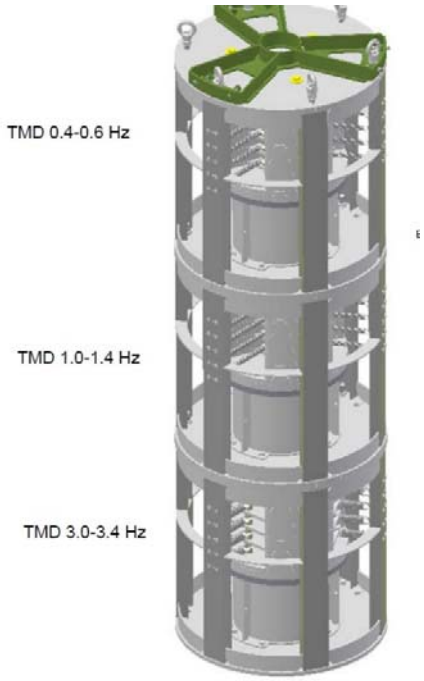
$$\xi_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)}} \tag{10}$$

▪ for random excitation force:

$$\xi_{opt} = \sqrt{\frac{\mu(1+3\mu/4)}{4(1+\mu)(1+\mu/2)}}. \tag{11}$$

4. Description of TMD

The TMD damper consists of 3 segments to suppress the three basic natural frequencies around 0.5 Hz, 1.2 Hz and 3.2 Hz (Figure 6). These frequencies have been established from vibration measurements.



a)

b)

Figure 6. View of the TMD used in the spire; a) CAD model, b) photo

A TMD design procedure follows the following main steps:

1. Establish the desired responses of the structure and the TMD for design loads.
2. Choice TMD's mass, m, and determination mass ratio μ.
3. Determine the optimum tuning frequency ratio, α_{opt} expressed as the ratio between the optimal frequency and dominant structural frequency.
4. Calculation of the spring constant k.

5. Determine the optimal damping ratio of the TMD, ξ_{opt}.
6. Calculation of the damping constant c.
7. Determine the performance of a TMD.

The vibrating mass in all three segments of TMD was 750 kg (the total mass of every segment was 1300 kg) and the damping ratio 14-16%.

5. Determination of the structural damping ratio with installed TMDs

For the vibration test a Data logger box has been used. The measuring system complies with the device standard DIN 45669 C3 HV1-80 and is shown in Figure 7 and consists of:

- **Sensors:** ADXL3552 triaxial accelerometer
- **Data Acquisition:** Data Translation DT9837B
- **Analyzer software:** MATLAB R19.

Figure 7. The Wireless transducer for vibration measurements

To verify the effectiveness of the new TMDs, the structural damping ratio of the spire with installed and activated TMDs has been determined by measuring the ambient vibrations of the spire for a time period of 1000 seconds. The spire was dynamically excited by the ambient wind, which causes a broad band stochastic excitation of the spire. This enables one to determine all relevant vibration modes.

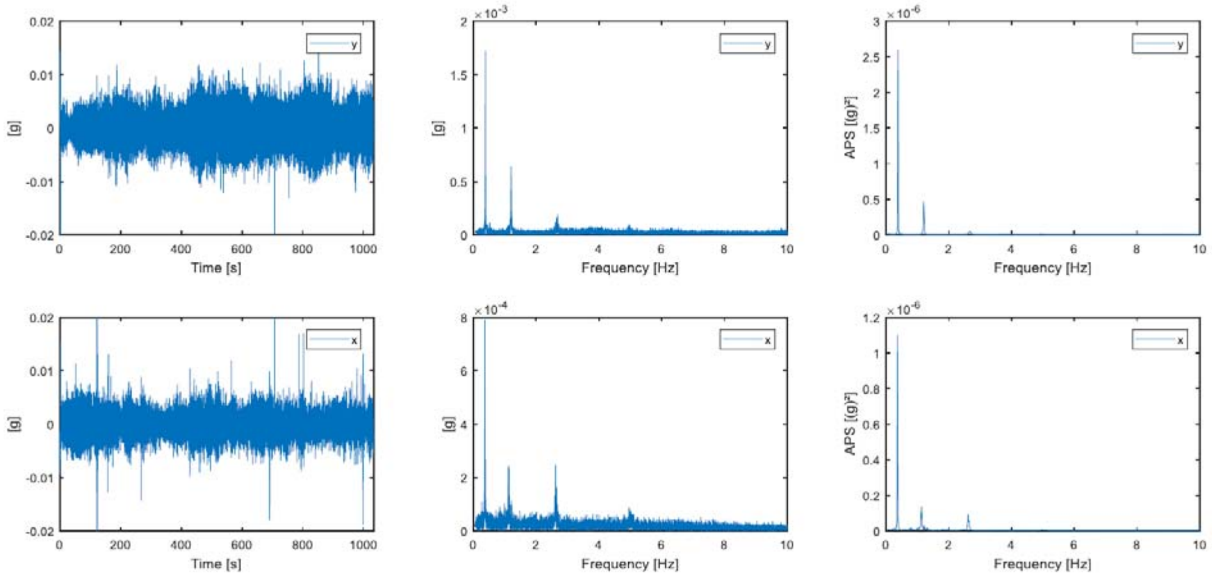


Figure 8. Results from Vibration Measurements

Figure 8 shows the time histories of the horizontal accelerations (x- and y- direction) recorded at the spire as well as the corresponding frequency spectra and the averaged Auto-Power Spectra (APS). The results obtained from the experimental modal analysis are presented in Table 1.

Table 1. Natural frequencies, modal masses and damping (logarithmic decrement δ) of the spire

Mode	f_i [Hz]	m_{Modal} [kg]	mass ratio	achieved damping δ	TMD Displacement +/- [mm]
1	0,452	15709	0,048	0,45	95
2	0,488	15011	0,050	0,32	100
3	1,148	10152	0,074	0,33	80
4	1,252	10261	0,073	0,5	65
5	1,591	10335	0,073	0,26	80
6	1,97	10227	0,073	0,14	*80**
7	2,199	9949	0,075	0,12	*80**
8	2,43	9681	0,077	0,11	*80**
9	2,597	9522	0,079	0,085	*80**
10	3,116	9001	0,083	0,38	*80**
11	3,256	8881	0,084	0,41	*30***
12	3,343	8815	0,085	0,62	*30***
13	3,467	8726	0,086	0,56	*30***
14	3,676	8595	0,087	0,51	*30***
15	4,058	8404	0,089	0,41	*30***
16	4,223	8340	0,090	0,31	*30***

** undamped max deflections +/- 320 mm*
*** undamped max deflections +/- 200 mm*

It can be seen that first three modes per direction are being dominantly excited and could be identified by the ambient vibration tests. The following dominant natural frequencies have been identified:

$$f_1 = 0{,}45 \text{ Hz}, f_2 = 1{,}2 \text{ Hz}, f_3 = 3{,}2 \text{ Hz}.$$

6. Methods and results

In addition, natural frequencies were determined using the commercial signal processing software ARTEMIS [5] which incorporates enhanced frequency domain decomposition and Stochastic Sub-space Identification Methods. Enhanced frequency domain decomposition (EFDD) and the Stochastic Subspace Identification [6] are widely used techniques for output-only modal parameter identification. The EFDD method is based on the computation of response spectra. Long records are, therefore, required to keep low the error on spectrum estimation low and to extract modal parameters in a reliable way. Commissioning Report – Spire Varso Tower – HB Reavis Construction PL.

The stochastic subspace identification algorithm was applied to identify structures using an output-only model. Stochastic Subspace Identification methods work in time domain and are based on a state-space description of the dynamic problem. The system identification results at different model orders are compared to distinguish true structural modes from spurious modes in the so-called stabilization diagrams.

The stochastic subspace identification (SSI) method is considered as a robust output-only identification technique compared to other available methodologies [7]. SSI algorithms identify a stochastic state-space model of the structure. The resulting model can be then translated into a more convenient structural model form for engineering interpretation of the results. The state-space model can be related to both modal model and Finite Element (FE) model formulations. The method works in the time domain and is based on a state space description of the dynamic problem assuming a linear behavior of the structure and a time invariant dynamic response of the system due to a white-noise excitation. The systemidentification results at different model orders are compared to distinguish true structural characteristics modes from spurious modes in the so-called stabilization diagrams (Figure 9).

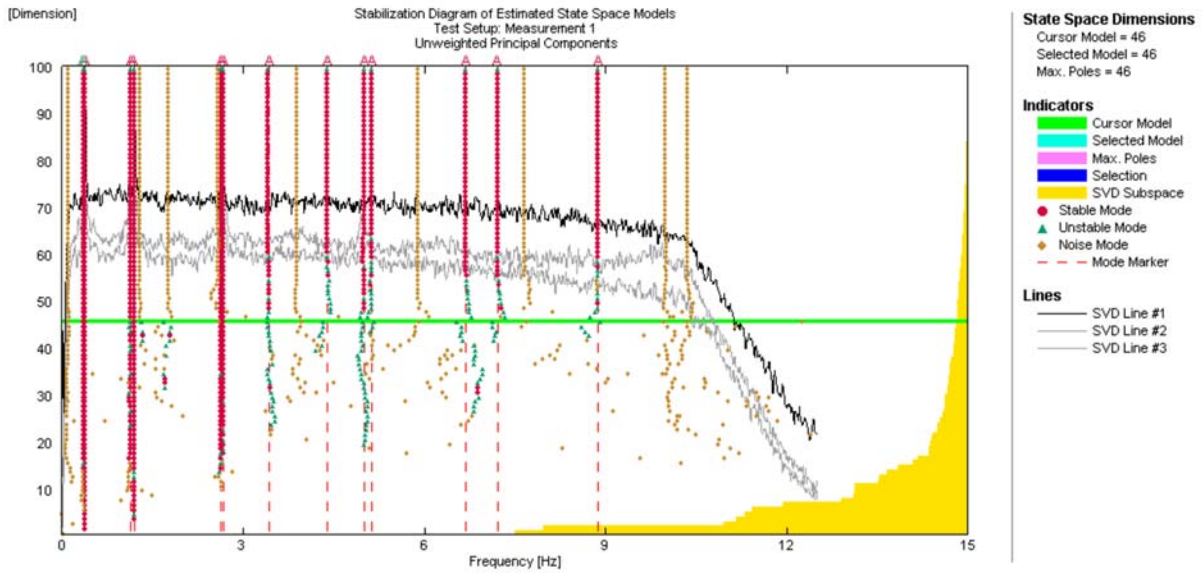


Figure 9. Stabilization Diagram of Estimated Space Models

These diagrams are a popular way to select the identified system model, as the true structural modes tend to be stable for successive model orders, fulfilling certain stabilization criteria that are evaluated in an automated procedure. The identified modes and the damping ratios for each mode are summarized in Table 2.

Table 2. Identified natural frequencies of the spire and damping ratios (after mounting of TMD)

Mode	Frequency [Hz]	Std. Frequency [Hz]	Damping Ratio [%]	Std. Damping Ratio [%]	Comment	Creation Date & Time
SSI-UPC Mode 1	0.3574	0.0008265	2.335	0.0443	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 2	0.3816	0.0005408	2.593	0.0326	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 3	1.138	0.005474	2.488	0.0372	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 4	1.205	0.00139	1.819	0.0309	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 5	2.622	0.00158	0.789	0.07871	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 6	2.665	0.001482	1.789	0.1307	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 7	3.418	0.00489	4.395	0.0958	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 8	4.392	0.002204	2.801	0.04616	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 9	4.995	0.001441	1.303	0.09564	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 10	5.13	0.003569	3.72	0.02741	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 11	6.688	0.001415	3.469	0.01628	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 12	7.209	0.01179	3.441	0.04448	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 13	8.874	0.0008495	4.776	0.04722	Found automati...	26-03-2021 14:05:17

7. Summary and conclusions

Measurements were performed at the completed spire of the Varso Tower in Warsaw /Poland to verify the effectiveness of the installed, tuned, and activated TMDs. The effectiveness of TMD can be assessed by determining the overall structural damping and comparing it with the target value. According to [2] an overall structural damping ratio of d = 0.08, respectively. D = 1.273% is required to effectively reduce vortex shedding induced spire vibrations.

The recorded accelerations were analyzed with an Operational Modal Analysis (OMA) software and the structural damping ratios for the relevant modes were determined and found to be above the target values. Accordingly, it can be concluded that the TMDs are fully effective and a resonant vortex-shedding excitation of the spire can be avoided.

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