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# REDUCTION OF STEEL CHIMNEY VIBRATIONS WITH A PENDULUM DAMPER

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**Abstract:** Karman vortices observed around chimneys may induce dangerous structural vibrations at certain wind velocities. The aim of this paper is to analyse the effectiveness of a pendulum damper in reducing vibrations of a steel chimney. A two-degree-of-freedom non-linear model is used to simulate the behaviour of the structure equipped with a damper. The results of the study show that the use of a pendulum with tuned frequency leads to significant reduction in structural response.

**Keywords:** vibration, pendulum damper, steel chimney

## 1. Introduction

Masts, industrial chimneys and steel towers are structures particularly sensitive to the dynamic effect of wind. The reason why vibrations affect wind-exposed structures, not to mention air blasts, could be vortical excitation resulting from the aerodynamic properties of a given structure. This is particularly relevant for steel objects characterized by small structural damping.

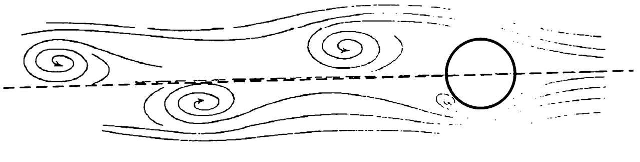

**Figure 1.** Karman vortices' track

During circulation of a fluid substance (liquid or gaseous) round a cylindrical obstacle, the substance's flow behind the obstacle becomes irregular. This is where vortices occur, as presented in Figure 1. Such vortices, referred to as Karman vortices [1], take alternately clockwise and anticlockwise directions. Determined by a wind pressure force, they descend the cylinder regularly. Flowing round the cylinder, they result in the rise of a force that affects the cylinder in a direction perpendicular to the direction of the stream flow. Due to the properties of the stream, the descent of the vortices is a self-excited process. Generally, it does not entail danger of damage to the structure. The problem arises however, when the frequency of detaching vortices overlaps the natural frequency of the structure, which may result in damage due to the resonance effect. At the wind velocity of the order of 50km/h, resonance vibrations due to Karman vortices regularly affect industrial steel chimneys [1, 2].

Research works examining the vortical excitation problem, aimed at the formulation of an analytical model, have been carried out for many years now [3, 4]. In a number of studies, the problem of vibrations and their damping has been resolved with reference to the wide spectrum of excitation. Pfeiffer [5] has considered a rigid body approach to model the dynamics of mechanical systems. In his paper, a test with a real steel chimney, which was bent with a steel rope, has been presented. A pendulum has been arranged which damps the oscillations at the top of the chimney. When the rope is released, the chimney starts to vibrate. The damper's parameters have been optimized to achieve the best damping efficiency. The results of the experiments compare well with the corresponding theory. There are also design standards [6] applied for structural calculations. From a practical perspective, however, the major issue is verification of the results of numerical model simulations when compared with the real behaviour of structures equipped with a damping system [7]. One can also find informative study works with databases on steel chimney vibrations due to occurrences of the vortical effect [8]. However, in spite of numerous studies dealing with the issue, the problem of vortical excitation remains unresolved. It still happens in engineering practice that despite design calculations complying with standards which reveal only minor susceptibility of a structure, vibrations due to Karman vortices may cause considerable displacements of an industrial chimney top. This is why the search for an appropriate analytical model applicable to the engineering design practice, simple yet precise enough, is still relevant.

According to a scientific-technical expertise [9], resonance vibrations due to Karman vortices were also observed in a steel, welded, freestanding chimney located in Gdansk (Figure 2). The chimney is 76.80m high, with an inside diameter of 2.9m. Its shaft consists of nine segments connected with joints using high resistance prestressed bolts. The chimney's foundation is an octahedral reinforced concrete slab 2.00m thick and 10.0m wide. The slab is based on a net of 21 Vibro type piles, each 500mm in diameter and 22.0m long. The fundamental slab is topped with 4.0m wide octahedral reinforced concrete base that stands out 5.50m above the surrounding area. A project considering the use of a mechanical pendulum damper of transverse vibrations was one of solutions considered in the expertise [9]. It was eventually rejected as not practical enough, since it requires full tuning of the damping element with the chimney. According to the expertise, this may involve both multiple adjustments depending on the wind conditions over a long span of time and the replacement of components of the damping system, which may prove difficult due to the chimney's continuous operation. Thus, to resolve all doubts concerning the performance of the damper, long-term, expensive research should be carried out in an aerodynamic tunnel. Therefore, the pendulum damper project was abandoned in favour of fixing a spiral linear turbulence

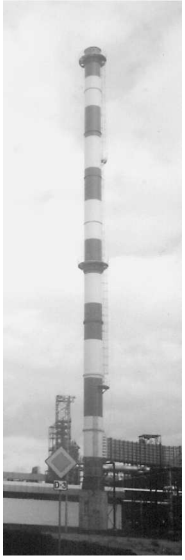

**Figure 2.** Overall view of the chimney

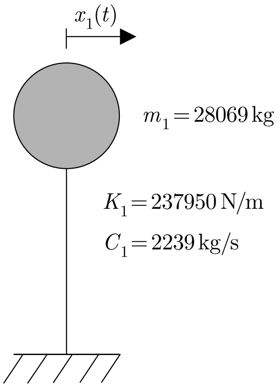

**Figure 3.** One-degree-of-freedom model of the chimney

simulator on the chimney shaft, which was of prime significance as the steel structure of the chimney shaft and the pile structure of the existing foundation are of limited capacity. However, an additional damper had to be designed since the application of the linear turbulence simulator proved insufficient [10].

The aim of the present paper is to analyse the effectiveness of a pendulum damper in reducing vibrations induced by Karman vortices in the above-mentioned steel chimney. The intention of the study is to use a simple yet sufficiently precise analytical model applicable to engineering design. Therefore, a two-degree-of-freedom non-linear model is used in the presented analysis to simulate the response of the structure equipped with a damper.

## 2. Model of the chimney

The performance of the chimney demonstrated by Figure 2 can be simulated by applying a simple, one-degree-of-freedom discrete model (Figure 3). Equivalent mass, $m_1$, lumped at the top, can be obtained from the following formula [11]:

$$m_1 = 0.23 \cdot M, \tag{1}$$

where $M$ stands for the total mass of the chimney [9]. Values of the stiffness coefficient, $K_1$, and the damping coefficient, $C_1$, can be derived from the following formulae [12]:

$$K_1 = 4\pi^2 \frac{m_1}{T^2}, \tag{2}$$

$$C_1 = 2\xi \sqrt{m_1 \cdot K_1}, \tag{3}$$

with values of the natural period ($T = 2.158$s) and the damping ratio ($\xi = 0.0137$) determined on the basis of *in situ* measurements of the chimney's displacement under the external exciting force [10].

The dynamic equation of motion for the model presented in Figure 3 can be expressed as:

$$m_1 \cdot \ddot{x}_1(t) + C_1 \cdot \dot{x}_1(t) + K_1 \cdot x_1(t) = p(t), \tag{4}$$

where $x_1(t)$, $\dot{x}_1(t)$, $\ddot{x}_1(t)$ are the horizontal displacement, velocity and acceleration of the chimney top, respectively, and $p(t)$ stands for external dynamic load. To solve Equation (4), MATLAB computer software was used. A preliminary analysis proved that the model of one-degree-of-freedom adapted here is sufficiently precise to simulate the structure's performance. Figure 4 shows the displacement time history of the chimney top after an initial forced displacement of 6.5cm. The deviation between displacement values measured after 5 and 10 cycles of simulated vibrations and the results of experiment [10] obtained for the real structure averaged 1%.

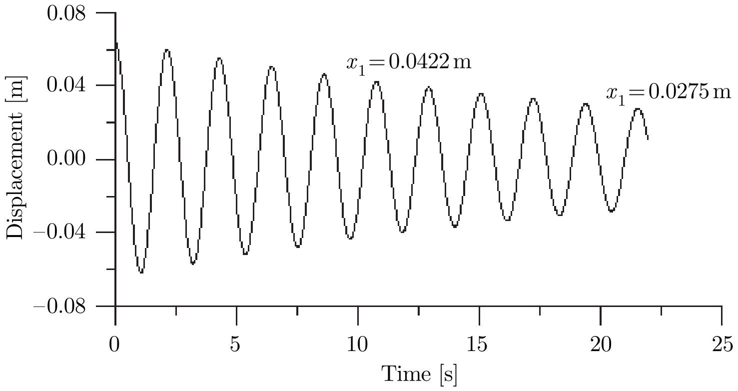

**Figure 4.** Displacement time history of the chimney top for an initial displacement of 6.5cm

## 3. Model of the chimney with a pendulum damper

In the absence of significant improvement in the chimney's performance following the installation of a linear turbulence simulator, other methods of reducing transverse vibrations in the structure resulting from Karman vortices were considered. One of the methods, mentioned earlier in this paper, is to suspend a pendulum under the platform at the top of the chimney, with frequency of vibrations matching the structure's first natural frequency. In this case, the pendulum excited by the chimney's motion would move with a phase shift leading to a reduction of the structure's vibrations. A numerical analysis of this problem was conducted using a non-linear model of two degrees of freedom presented in Figure 5. The dynamic equation of motion for such a model takes the following form:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \cdot \begin{bmatrix} \ddot{x}_1(t) \\ \ddot{x}_2(t) \end{bmatrix} + \begin{bmatrix} C_1 & 0 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} + \\ + \begin{bmatrix} K_1 + K_2\big(x_1(t), x_2(t)\big) & -K_2\big(x_1(t), x_2(t)\big) \\ -K_2\big(x_1(t), x_2(t)\big) & K_2\big(x_1(t), x_2(t)\big) \end{bmatrix} \cdot \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} p(t) \\ 0 \end{bmatrix}. \tag{5}$$

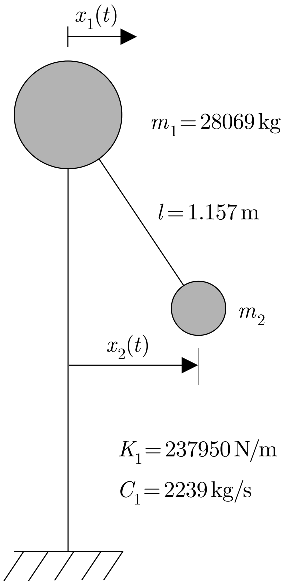

**Figure 5.** Two-degree-of-freedom model of the chimney with a pendulum damper

In the above equation $x_2(t)$, $\dot{x}_2(t)$, $\ddot{x}_2(t)$ are the horizontal displacement, velocity and acceleration of the pendulum, respectively, $m_2$ stands for the pendulum mass, and $K_2(x_1(t), x_2(t))$ is the pendulum's equivalent stiffness:

$$K_2(x_1(t), x_2(t)) = m_2 \cdot g \frac{\sqrt{l^2 - (x_2(t) - x_1(t))^2}}{l^2}, \tag{6}$$

where $g$ is the acceleration of gravity and $l$ stands for the pendulum's length. The pendulum's length was determined by tuning the frequency of the chimney's vibrations with the pendulum using the following formula [13]:

$$l = \frac{g \cdot T^2}{4\pi^2} = 1.157\,\text{m}. \tag{7}$$

## 4. Numerical simulations

Using the model of the chimney equipped with a pendulum damper, as presented in Figure 5, the performance of the structure under sinusoidal excitation was analysed (five initial cycles were taken into consideration):

$$p(t) = p_0 \cdot \sin\left(\frac{2\pi}{T} t\right). \tag{8}$$

In Equation (8), a value of $T = 2.158\text{s}$, equal to the structure's natural period, was used and the excitation force amplitude, $p_0 = 4\,210\text{N}$, was matched to obtain a maximum displacement of about twenty centimetres (Figure 6), as displacements measured during vibrations of the real structure proved to be of this order [9].

The analysis involved determination of maximum displacements of the top of the chimney equipped with the pendulum damper, with respect to the value of pendulum mass. Figure 7 presents results of the analysis carried out for the pendulum mass ranging from 500kg to 2 000kg. The application of a pendulum of

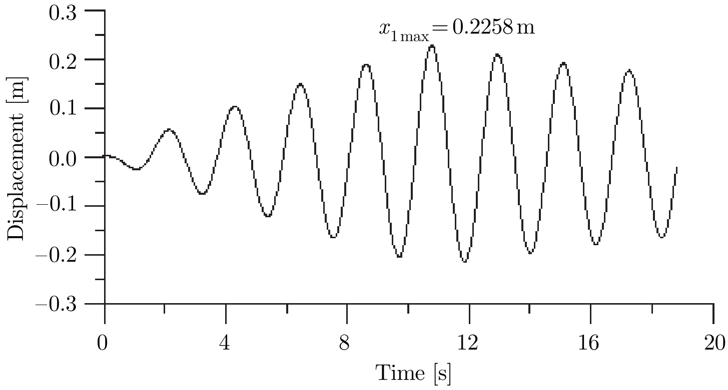

**Figure 6.** Displacement time history of the top of the chimney without a pendulum damper (sinusoidal excitation)

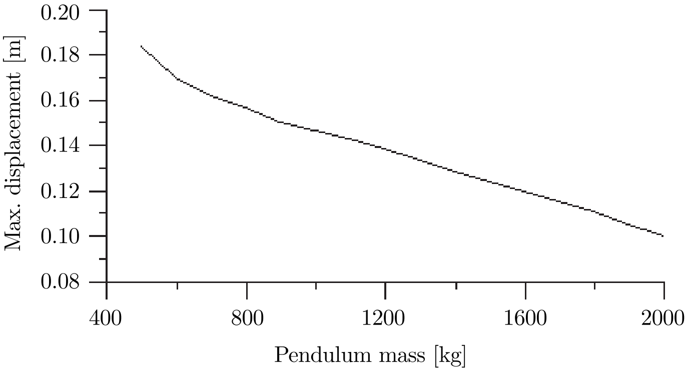

**Figure 7.** Maximum displacements of the top of the chimney equipped with a pendulum damper with respect to the pendulum's mass (sinusoidal excitation)

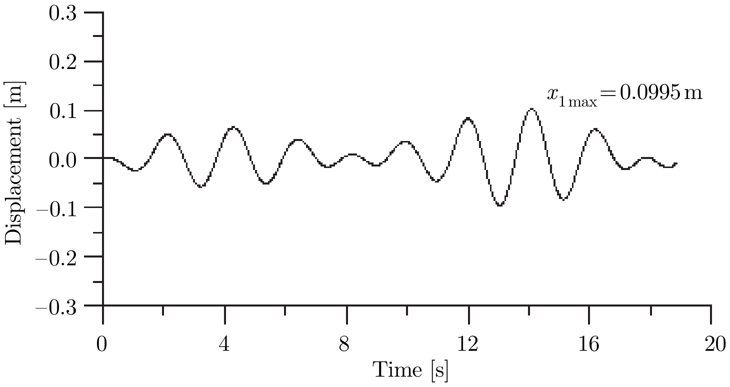

**Figure 8.** Displacement time history of the top of the chimney equipped with a pendulum damper of 2 000kg mass (sinusoidal excitation)

mass lower than 500kg would result in too great displacements and, consequently, in a collision with the platform under which the pendulum is suspended. At the same time, pendulum mass exceeding 2 000kg would be highly problematic with respect to the chimney's capacity [9]. Figure 7 implies that within the range of pendulum mass analysed, the greater the mass, the greater the reduction in the chimney's maximum displacement. For $m_2 = 2\,000$kg (displacement time history presented in Figure 8) reduction in the maximum displacement reached 56%.

## 5. Conclusions

In this paper, the analysis of the effectiveness of a pendulum damper in reducing vibrations induced by Karman vortices in a steel chimney has been conducted. In the analysis, a two-degree-of-freedom non-linear model is used to simulate the behaviour of the structure equipped with a damper. It has been shown that this relatively simple model is sufficiently accurate in simulating the behaviour of the analysed structure, since the deviation between displacement values of the simulated vibrations and the experimental results obtained for the real structure averaged only 1%. Such a simple yet precise structural model has the advantage of being easily applicable in the engineering design practice.

The results of the study presented in this paper demonstrate that the use of a pendulum damper with a tuned frequency leads to a significant reduction in structural response. For the analysed steel chimney equipped with a damper with mass of 2 000kg, the reduction of maximum displacement reached 56%.

In this study, an analysis of one-directional structural response has been conducted. In reality, the chimney's vibrations excite the pendulum's motion not only in the transverse direction but also in the longitudinal direction. This effect should be further analysed in order to asses the problems it may cause.

The technical problems referred to in the introduction to this paper, as well as the effect of possible collisions of a pendulum damper with other structural elements should be taken into consideration at the design stage. However, they do not eliminate the possibility of application of mechanical pendulum dampers to reduce industrial steel chimneys' transverse vibrations.

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