# Analysis of effectiveness of steel chimneys vibration dampers using surveying methods

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**Abstract.** When compared to rigid reinforced concrete chimneys, steel industrial chimneys prove to be more susceptible to aerodynamic excitation. European standards and ISO standards impose high regime with regard to their protection against the impact of normal mode of vibration caused by wind excitation. In order to effectively prevent the occurrence of this phenomenon, vibration dampers are installed on structures. The same standards recommend the need, and establish the rules, for conducting direct measurements characterizing the dynamics of slender structures.

The paper deals with the problem of determining the actual dynamic characteristics (vibration frequency and logarithmic decrement of damping) of steel chimneys equipped with vibration dampers. Measurement methods were reviewed, and their advantages and disadvantages were analyzed with regard to their use in the diagnosis of high dynamic structures. Examples of dynamic characteristics were presented on the basis of the results of tests, which were performed when adjusting the dampers on two steel chimneys with different structure in terms of their design, and with different dynamic parameters. The results obtained using three instruments were assessed in terms of the degree of consistency of dynamic characteristics, which were determined experimentally. The data were acquired with the use of contact and non-contact methods, such as ground-based interferometric radar, robotic total station and MEMS accelerometer.

**Keywords.** Steel chimney, vibration, damping, dampers, surveying

## 1 Introduction

### 1.1 Dynamic loads of steel chimeys

Due to the current rigorous environmental regulations, advanced technological solutions regarding flue gas filtration, as well as economic considerations, steel industrial chimneys are an important alternative to heavy reinforced concrete chimneys. For single- and multi-flue steel chimneys, there is a large number of design solutions that allow for some freedom to shape the manner of their installation and use. There are freely supported structures, guyed or in a tripod, or surrounded by a truss housing. Further differences result from the manner of connecting the elements, or the applied technology of thermal protection and the cross-sectional shape. Steel chimneys, like any other building structure or its parts, are subjected to a variety of external and internal factors which load the structure. There are static and dynamic influences. The static ones do not cause significant acceleration of the structure. The dynamic ones, on the other hand, induce significant acceleration and hence inertia forces which strain the structure.

Among the dynamic loads, the wind load is particularly important in the case of steel chimneys characterized by considerable slenderness. The occurrence of the effect of aerodynamic excitation (a consequence of the so-called Kármán vortex street), can lead to the emergence of the resonance phenomenon which, combined with very poor natural damping of steel chimneys, often leads to the formation of vibrations with high amplitude, which is dangerous to the structure. In extreme cases, the amplitudes may reach such values, that the structure will immediately be destroyed, but more frequently they weaken its strength and result in unexpected failure occurring at a completely different time. In order to prevent the undesirable influence of aerodynamic factors on the structure, mechanical dampers are used, which are installed on the object. The dampers are supposed to reduce the dynamic responses of the structure induced by excitation. There are passive, active, semi-active and hybrid dampers.

The construction standards (EN 1990:2002, EN 1991-1-4:2005, EN 1993-1-9:2005, EN 1993-3-2:2006, EN 13084-1:2007) present the design principles for steel industrial chimneys and identify the situations in which the direct measurement characterizing the dynamics of the structure is recommended. These include, for example: inability to use accurate calculation models, building a large number of similar (typical) structures, a necessity to confirm uncertain calculation assumptions. Eurocode EN 1990:2002 also defines the situations in which it is recommended to control the actual dynamic characteristics of building structures, based on measurements (e.g. for structures which are sensitive to excitation and equipped with vibration dampers).

## 1.2 Dynamic measurement requirements

By recording velocity or acceleration at selected points on the structure during the movement, it is possible to determine dynamic characteristics of the structure, such as the natural frequency (and the related modes of vibration), as well as the logarithmic damping decrements. The frequency range of vibration of building structures depends on the spectral density of excitation and on the mechanical response of the structure. In general it is assumed (ISO 4866:2010), that this range is from 0.1 to 500 Hz, and covers a large variety of natural and artificial sources of excitation. In the case of measuring the vibration of high building structures and bridges, the analyzed frequency range can usually be reduced. The response of the structure to wind excitation, which is particularly significant in the case of steel chimneys, falls within the range of 0.1÷10 Hz. The requirements for vibration measurements, given by the standard ISO 4866:2010, which are essential from the point of view of this paper, are as follows: 1) measurement of the vibration amplitude should be carried out continuously, for long enough, with the accuracy sufficient to determine the content of the spectrum, 2) sampling should be performed with a frequency at least 5 times higher than the highest frequency of vibration, 3) measurement system should allow to estimate vibration frequency with the error of ±0.5%, and damping with the error of ±20%.

## 1.3 The subject of experiment

The publication will present the results of the measurements performed on steel industrial chimneys with different structure. One of the chimneys, freely supported, has a height of 60 meters and symmetrical characteristics of natural vibration (Fig. 1a). The second one, in a tripod, has a height of 120 meters and asymmetrical characteristics of natural vibration on the direction of the support and on the orthogonal one (Fig. 1b). It should be mentioned that the latter one is equipped with a conventional mechanical active mass damper and the mass damper with a specific structure that allows for the damping of two different values of natural frequency. The results of evaluating the operation parameters of the tools used during the measurements, relative to the provisions of ISO 4866:2010, will be discussed. An important aspect of the study is presenting the possibilities and methods of using surveying non-contact measurement tools, comparing the operating characteristics of various types of vibration dampers.

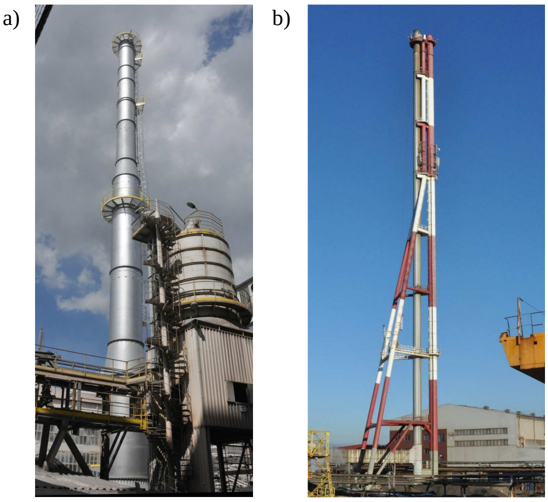

**Fig. 1** The tested steel chimneys: a) freely supported, b) in a tripod.

# 2 Experimental determination of damping

## 2.1 Instruments

The most common type of sensors are accelerometers, among which piezoelectric dominate, as the most versatile and reliable ones due to the range of amplitudes and frequencies. Their advantages include: high resolution, low noise level, wide frequency range. The disadvantages are temperature drift and the need for frequent calibration. Accelerometers operate in the frequency range from fractions of hertz to 20 kHz. They have to be installed directly on the structure and long-term operation requires power. Today, microelectromechanical sensors (MEMS) are used more frequently (Albarbar et al. (2008)). They are able to measure static acceleration, they are characterized by low temperature drift, they do not need to be frequently calibrated and they have a relatively low price. Compared to piezoelectric sensors, they have a lower resolution, narrower frequency range and a higher noise level. In addition to accelerometers, other types of sensors are used for vibration measurements: resistance strain gauges, electrodynamic sensors, proximity sensors (eddy current, capacitive, inductive, electromagnetic), optical sensors, microphone sensors, as well as photoelectric sensors, string sensors, and others (Fraden (2010)).

Robotic electronic total stations equipped with servomotors use the function of automatic tracking of the moving prism. They can record the spatial position of the moving prism (3D changes in three axes) or its direction (1D changes on one axis). Limitations for sampling frequencies include: velocity of servomotor operation, rate of automatic measurement of the angle and distance, and the rate of recording and transmitting data. The work of these instruments is hindered by: rain, fog, strong insolation. The nominal sampling frequency of these total stations is 10 Hz. The example of monitoring of slender structures using the surveying methods has been presented by Kopáčik et al. (2013).

The ground-based radar interferometry (GB-SAR) technique is used to measure both static and dynamic displacements of structures (Neitzel et al. (2012), Piniotis et al. (2013)). The displacements are observed as phase differences of waves ($\lambda$ = 17.4 mm), transmitted by radar and scattered by the structure. A lot of points on the structure can be observed simultaneously by the device, thanks to the applied wave modulation (Pieraccini (2013)). Range resolution, which is the minimum distance between the separately observed points, reaches 0.5 m. Sampling rate is up to 200 Hz, and the range of operation – up to 1 km. However, these parameters are interdependent (Gocał et al. (2013)). Displacement measurement error is 0.1 mm, provided properly strong wave reflections. Observations can be performed without access to the structure. An important limitation is the ability to measure displacement in only one direction – along the radar axis. Moreover, it may be problematic (especially when compared with measurements using sensors and surveying instruments) to pinpoint the location of an observed point. It is limited to the value of the range resolution (0.5 m – in the best case). Nevertheless, a clear identification of the observed point can be achieved by installing radar reflectors on the structure but it means the need for direct access to the structure. The example of monitoring of slender structures using the radar has been presented by Gikas (2012).

## 2.2 Calculations

In order to determine the logarithmic decrement of damping $\Lambda$ the obtained measurement results have been processed using fitting the continuous function into a set of discrete values, according to the equation:

$$y = A \cdot \exp(-\beta t) \cdot \sin(\omega t + \varphi) + c \qquad (1)$$

where: $A$ – amplitude, $\beta$ – the vibration damping coefficient, $t$ – time, $\omega$ – the frequency of vibration in radians, $\varphi$ – phase, and $c$ – the signal shift.

Non-linear regression was applied, using the method of least squares to fit the model function. The goodness of fitting the damped exponential function into the recorded observation data sets was expressed using two parameters – adjusted *R*-squared and root mean square error (RMSE). Their values were calculated separately for each experiment.

On the basis of fitting the function, parameters $A$, $\beta$, $\omega$, $\varphi$, $c$ were determined together with their errors. Both $\beta$ and $\omega$ values were used to calculate the natural frequency $f$ of the chimney vibrations and the logarithmic decrement of damping $\Lambda$:

$$f = 1/T = \omega/(2\pi) \tag{2}$$

$$\Lambda = \beta T = \beta / f \tag{3}$$

The errors of these values ($\sigma_f$ and $\sigma_\Lambda$) have been determined in accordance with the error propagation law based on the errors of the parameters $\beta$ and $\omega$ determined using non-linear regression.

# 3 Freely supported chimney

## 3.1 Field test

Taking into consideration the current design principles for steel industrial chimneys, the practical application of several methods discussed above was presented. The results of the measurements were analyzed, which were carried out to verify the dynamic characteristics of as-built structure of a new, 60-meter-high steel chimney (Fig. 1a) during the installation and tuning of the system of mass vibration dampers (Fig. 2a). Tuning of the dampers is necessary due to the slight differences between the calculations and the actual values of the natural frequencies of the chimney The tuning process allows to suppress resonance vibrations more effectively.

The following instruments were used for the measurements: IBIS-S interferometric radar, Leica Nova MS50 total station and 3-axis MEMS accelerometer, created on the basis of commercially available electronic components. The radar measurement was performed with a frequency of 165 Hz. The total station measurement was performed with the actual sampling rate of 5.5 Hz (carried out by observing the EDM prism installed on the top of the chimney). MEMS sensor was sampling at a frequency of 50 Hz. The measurements were implemented for the vibrations of the undamped chimney and after activating the vibration dampers. The direction between non-contact instruments and the top of the chimney was denoted as X, and the axis orthogonal to it was marked as Y (Fig. 2b).

It is possible to point out the advantages and disadvantages of different devices from the graphs presenting a sample of vibration observations (Fig. 3). Ground-based interferometric radar has a high sampling frequency, but it allows to observe displacements in one direction only (X axis). Robotic total station gives a much lower sampling, but it allows to observe displacements in two directions. On the other hand, the accelerometer installed on the top of the chimney has a fairly high sampling frequency, it can perform observations in two axes, but due to the operation of the recording and analyzing software, it allows to record several seconds of the observed phenomenon.

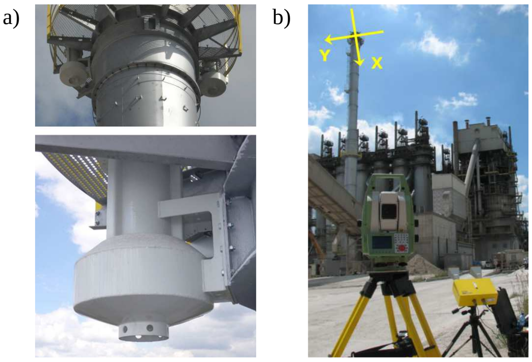

**Fig. 2** The experiment of dampers assessment: a) dampers mounted on the structure, b) non-contact instruments position.

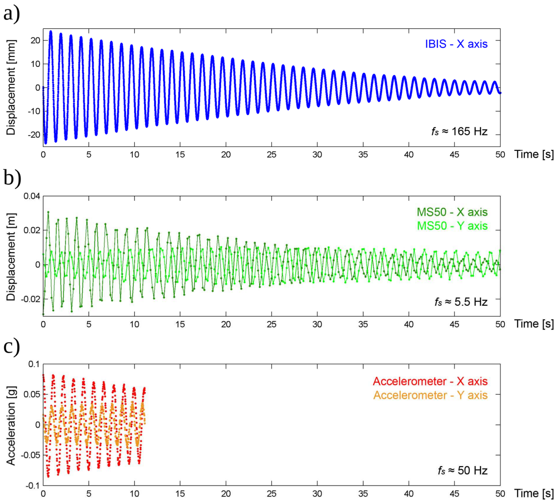

**Fig. 3** Record of damped vibration based on the observation using: a) IBIS-S radar, b) MS50 total station, c) MEMS accelerometer.

## 3.2 Data analysis

Figure 4 demonstrates a sample record of the excitation of vibrations in the X direction by all the instruments during the excitation of vibrations damped by the ultimately tuned damper. The discrete values from the measurement were marked in black, and in blue – a graph of a function of the damped harmonic motion, fitted into the data set.

The obtained results present a very good fitting of model functions to the discrete data in the case of the observations carried out with the radar and the accelerometer. They do not exceed 1 mm and 2 mg of RMSE, respectively. In the case of the total station observations, the fitting is worse and it falls within the range 1÷6 mm. The details of fitting are presented by Kuras et al. (2014).

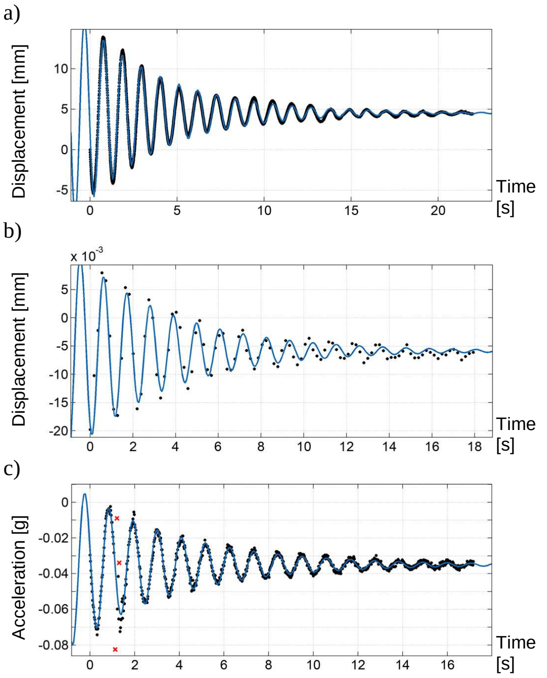

**Fig. 4** The damped harmonic function fitted in the set of observations recorded during damped vibrations using: a) IBIS, b) MS50, c) MEMS (red points represent outliers).

The dynamic characteristics, including their errors $\sigma_f$ and $\sigma_\Lambda$, were calculated for the various setups of the dampers, based on the observations from different instruments. All the values from several records were averaged and summarized in Tables 1 and 2. The effectiveness of the damper is noticeable as the value of $\Lambda$ increasing together with tuning the damper. Due to the fact that the IBIS radar measures displacements in one direction only, it is impossible to analyze the vibrations in the Y axis.

An important conclusion from the experiment may be drawn from the calculation results – the errors of determining the values of natural frequency and logarithmic decrement of damping, in most cases satisfy the requirements of the standard ISO 4866:2010 and they do not exceed 0.5% and 20%, respectively. The values of the errors obtained by the interferometric radar and the accelerometers are much smaller than the ISO standard values. In the case of the MS50 total station, the requirements of the standard are not satisfied for some cases, especially for strong damping of vibrations. It can be assumed that this is the effect of recording a set of observations which is too small due to a quick fading of the phenomenon and low sampling frequency.

**Table 1.** Dynamic characteristics determined in the test

| Dampers setup | Axis | IBIS | | MS50 | | MEMS | |
|---|---|---|---|---|---|---|---|
| | | VIBRATION FREQUENCY | | | | | |
| | | $f$ [Hz] | $\sigma_f$ [%] | $f$ [Hz] | $\sigma_f$ [%] | $f$ [Hz] | $\sigma_f$ [%] |
| Inactive | X | 0.905 | 0.01 | 0.905 | 0.14 | 0.905 | 0.02 |
| | Y | – | – | 0.896 | 0.15 | 0.905 | 0.02 |
| Initially tuned | X | 0.926 | 0.01 | 0.918 | 0.50 | 0.925 | 0.03 |
| | Y | – | – | 0.900 | 0.71 | 0.924 | 0.03 |
| Finally tuned | X | 0.922 | 0.03 | 0.894 | 0.57 | 0.924 | 0.10 |
| | Y | – | – | 0.888 | 0.63 | 0.924 | 0.10 |
| | | LOG. DAMPING DECREMENT | | | | | |
| | | $\Lambda$ | $\sigma_\Lambda$ [%] | $\Lambda$ | $\sigma_\Lambda$ [%] | $\Lambda$ | $\sigma_\Lambda$ [%] |
| Inactive | X | 0.038 | 0.3 | 0.062 | 13 | 0.035 | 3 |
| | Y | – | – | 0.072 | 12 | 0.041 | 2 |
| Initially tuned | X | 0.13 | 0.2 | 0.17 | 17 | 0.13 | 2 |
| | Y | – | – | 0.21 | 20 | 0.13 | 2 |
| Finally tuned | X | 0.22 | 0.6 | 0.22 | 16 | 0.22 | 3 |
| | Y | – | – | 0.23 | 17 | 0.22 | 3 |

## 4 Chimney in a tripod

### 4.1 Field test

Another experiment was conducted on a steel chimney with a height of 120 m (Fig. 1b). This structure is untypical due to the kind of its support which makes it asymmetrical (Ciesielski et al. (1996)). It has different vibration frequencies in the main direction and in the direction orthogonal to it.

The chimney is equipped with a mechanical damper in the form of a pendulum with heavy mass, suspended at the top of the chimney, between the flue pipes (Fig. 5). As a result of the assessment of the technical condition of the chimney, it was found that this damper might not operate properly during the aerodynamic excitation, so it was recommended to use a different type of vibration dampers. The new approach uses mass dampers (Fig. 6), similar in the design to the dampers described in Chapter 3. The difference was an additional joint on the arm of the pendulum so that the pendulum length, and therefore the vibration period, will be different in the main direction and in the orthogonal one.

For dynamic tests which involved specifying the responses of the dampers (mechanical and mass ones) to the forced vibrations of the chimney, two instruments were selected: interferometric radar IBIS-S and motorized total station Leica MS50 (Fig. 7). This solution was justified on the basis of the research studies presented in Chapter 3.

In the presented test, the position of the instruments relative to the chimney was important, as the construction is asymmetrical and has different natural frequencies in two orthogonal directions. The direction in which the damping was especially important was denoted as X, and the direction orthogonal to it was marked as Y. The radar performed observations only in the X direction, while the total station – both in the X and Y directions (by using an EDM prism – Fig. 6b).

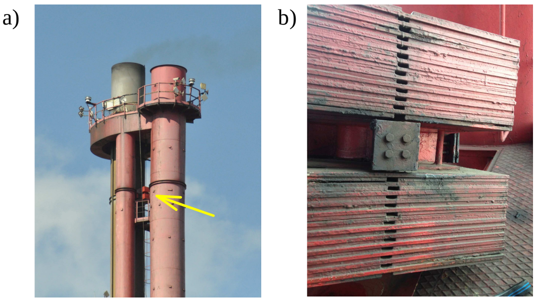

**Fig. 5** The mechanical damper installed on the chimney.

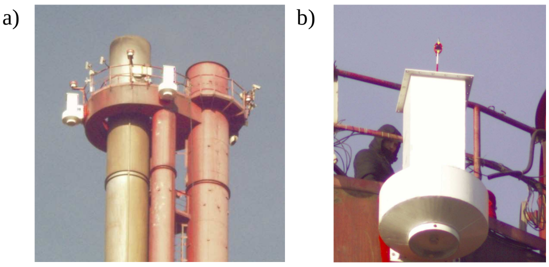

**Fig. 6** The mass dampers installed on the chimney: a) two of three visible, b) EDM prism installed on the pendulum arm.

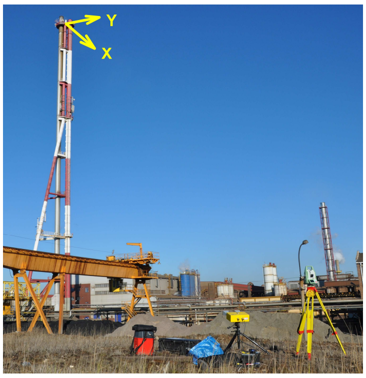

**Fig. 7** Position on radar and total station.

Due to the fact that the chimneys in question are equipped with two vibration dampers which are different in terms of technical solutions, experimental measurements were performed to determine their damping effectiveness in the following options:

- both dampers locked,
- mechanical – unlocked, mass – locked,
- mechanical – locked, mass – unlocked.

The purpose of such a sequence of the conducted observations was to record the reaction of the chimney in the undamped and damped state. The time sequence of the performed experiments has been illustrated in Table 2.

**Table 2.** Time sequence of experiments

| No. | Experiment | IBIS – point on: | MS50 – point on: | Fig. |
|---|---|---|---|---|
| #1 | Synchronization of clocks | top of the chimney (X axis) | top of the chimney (XY axes) | 8 |
| #2 | Both dampers blocked | | mechanical damper (XY axes) | 9a |
| #3 | Mechanical damper active, mass damper blocked | | mechanical damper (XY axes) | 9b |
| #4 | Mechanical damper blocked, mass damper active | | mass damper (XY axes) | 9c |

## 4.2 Data analysis

The essence of the non-contact measurements was an independent, but simultaneous, record of displacements of the chimney and dampers.

Therefore the measurements had to be synchronized in time. Firstly, only the dynamic behavior of the chimney and its strong excitation with locked dampers were observed, at the same time with IBIS and MS50. The EDM prism was installed on top of the structure so that it represented the displacements of this part of the chimney which was subject to radar observations. The record of the same displacements (Fig. 8) excited in the X direction (experiment #1) using both instruments was intended to synchronize their clocks, i.e. to identify the time offset between the clocks which ensured the highest correlation of the signals.

Having observed the synchronization, the EDM prism was taken down from the top of the chimney and placed on the mass of the mechanical damper. Then, experiments #2 and #3 were performed, which involved the simultaneous recording of the vibrations of the chimney (using IBIS) and of the mechanical damper (using MS50) – locked and unlocked. The excitation was induced in the X direction, and the diagrams additionally present the movement of the damper in the Y direction. Lack of the damping phenomenon with the locked damper is visible as the compatibility of the displacement values of the chimney and the damper, as well as the slow decay of vibrations (Fig. 9a). After unlocking the mechanical damper, the occurrence of damping in the form of a greater vibrations amplitude of the damper than of the chimney can be observed, as well as a weaker response of the structure to similar dynamic excitation (Fig. 9b). However, not quite correct operation of the damper can be noticed as the phase shift of approx. 50° between vibration of the damper and the chimney.

Another experiment (#4) was made to estimate the effectiveness of damping using a mass dampers. For this purpose, the mass dampers was unlocked, and the mechanical one – locked. The EDM prism was placed on the pendulum of the mass damper. In this position, the excitation in the X and Y directions were induced (Fig. 9c). As in experiment #3, the damping effectiveness can be assessed based on a poor response of the structure to dynamic excitation. This time, however, the phase shift of approx. 205° is noticeable, which proves the opposite direction of the pendulum movement with respect to the chimney and thus – the proper operation of the damper. However, the chimney response in #4, visible as the vibration amplitude, is greater than in #3 despite similar forcing.

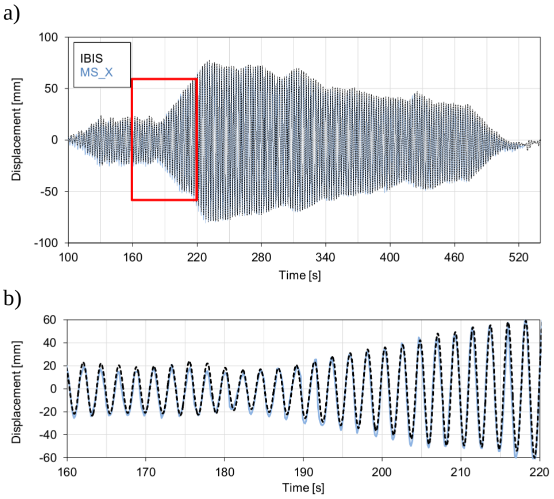

**Fig. 8** Results of observations of the displacements performed to synchronize the clocks.

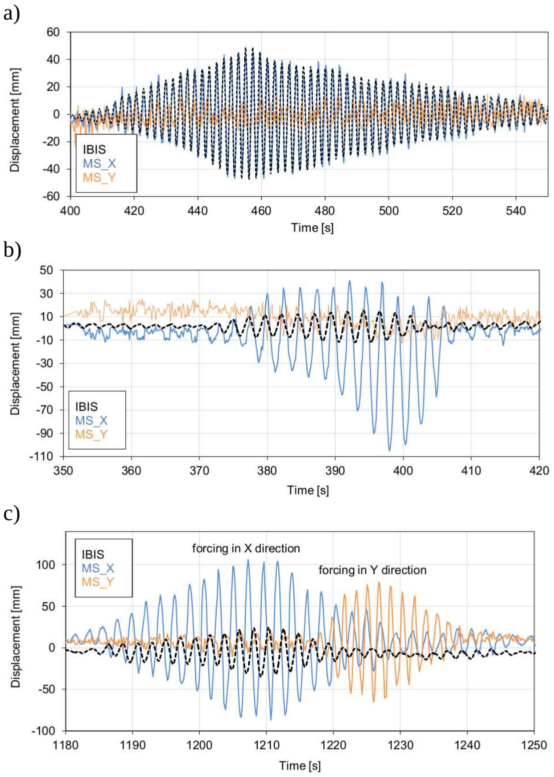

**Fig. 9** Results of observations of the displacements in experiment: a) #2, b) #3, c) #4.

Figure 10 presents a sample records of the excitation of vibrations in the X direction by the IBIS radar. The data analysis was performed based on several samples. The obtained results (Tab. 3) present quite good fitting of model functions to the discrete data.

The changes of dynamic characteristics are visible together with the work of dampers. However, the low number of oscillations recorded in experiments #3 and #4, as the consequence of damping, might be not enough to reliably determine the logarithmic decrement of damping.

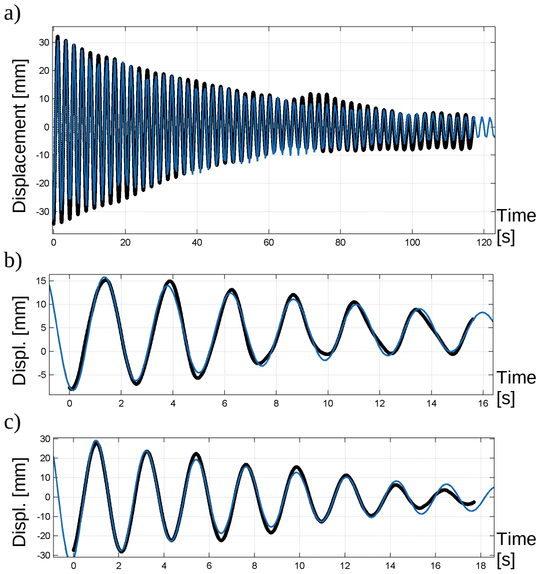

**Fig. 10** The damped harmonic function fitted in the set of observations recorded using IBIS radar during experiment: a) #2, b) #3, c) #4.

**Table 3.** Results of tests performed on chimney H=120 m

| Experiment | Dynamic characteristics | | Goodness of fit | |
|---|---|---|---|---|
| | $f$ [Hz] | $\Lambda$ | Adj. $R^2$ | RMSE [mm] |
| #2 | 2.27 | 0.043 | 0.984 | 1.8 |
| #3 | 2.39 | 0.19 | 0.964 | 0.9 |
| #4 | 2.21 | 0.22 | 0.978 | 2.0 |

## 5 Conclusions

Based on the conducted research, it was found that interferometric radar and robotic total station are useful for dynamic measurements of steel chimneys. The experiment was carried out on the freely supported chimney and it confirmed the conformity of the obtained results regarding the amplitude, frequency and damping of vibrations. As a result, it was possible to use these instruments to study a chimney in the tripod, which involved an independent record of the movements of the chimney and the dampers. The measurements were preceded by synchronization of the clocks in both instruments, carried out basing on the observations of the same phenomenon. The instruments confirmed their usefulness in assessing the accuracy of tuning dampers and effectiveness in damping the vibration of steel chimneys.

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