Analysis of cooling tower’s geometry by means of geodetic and thermovision method

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Abstract. Safe operation of thin-walled objects requires a regular monitoring of their technical condition. Geodetic measurements performed with a terrestrial laser scanning allow to determine the geometrical shape of the tested object with very high detail. Thermovision, as an auxiliary method, allows identification of places particularly exposed to changes in geometry caused by thermal influences. This paper presents a combination of both methods to analyse the geometry of reinforced cooling tower with a height of about 170 m. Laser scanning was performed from 11 stations arranged around the cooling tower, and the acquired point clouds were combined and unified in terms of density. Comparing the actual shape of the shell with the theoretical model, the values of geometrical imperfections were calculated. Thermograms were made by means of the thermovision camera, with particular emphasis on the lower part of the shell. The analysis of the imperfections’ distribution and the location of the largest temperature differences allowed to identify the most threatened places on the cooling tower shell.

1. Introduction

Cooling towers constitute a necessary equipment for every large industrial plant and they are a permanent element of the industrial landscape of Europe, as well as entire world. Usually, cooling towers are used to cool the water in an auxiliary circulation, whose intended purpose is to cool (through a heat exchanger) the main closed circulation of process water, which is used in the production processes. Most commonly, cooling towers can be found in conventional and nuclear power plants, chemical plants and steel mills [8]. There are several types of cooling towers. The most common are cooling towers with a theoretical model in the shape of a one-sheet rotational hyperboloid [12]. They allow to achieve good operating parameters with limited consumption of construction materials. The thickness of reinforced concrete walls of the cooling tower’s shell changes along with the height [2]. For the most part of the shell, thickness of the walls usually amounts to over a dozen of centimetres, while the total height of the object sometimes reaches 180 m. Due to this reason, cooling towers belong to the so-called thin-walled objects. During operation, the object’s structure is exposed to a series of unfavourable factors, such as: chemical corrosion of concrete, corrosion of exposed reinforcing bars, variable hydraulic load, wind load [13]. Additionally, during winter period, there’s a large difference of temperatures between the hot water inside and the cold air outside the cooling tower. Uneven settlement of the foundations also increases the shell’s effort state. Unfavourable operating conditions result in the need to conduct regular control of the object’s technical condition, including control of geometrical shape of the cooling tower’s shell. The first control measurements start at the initial stage of construction and end with comprehensive inventory measurement after...
completion of the construction. Any detected incompatibilities between the theoretical shape and the actual shape may be the cause of subsequent construction disaster, which occurred in the past [18, 19]. Stability of the structure’s setting is controlled by regular geodetic measurements of vertical displacements of cooling tower’s foundations, as well as by performance of additional geotechnical studies and analyses, e.g. measurements of vibrations described in the paper [17] or dynamic monitoring [20].

2. Measurement methods of geometry of the cooling tower’s shell

Geodetic measurements allow to determine the actual shape of the cooling tower’s shell. The most commonly used measurement methods are shortly described below.

Classic techniques are based on angular-linear measurements. Originally, these were the theodolite measurements of directions tangential in relation to the shell’s lateral surface (the so-called surrounding tangents method) [21]. The measurement was carried out from at least 3 positions around the cooling tower and it did not require the signalling of controlled points on the shell. This method was used to measure objects, whose surface can be approximated using the quadratic equations [1]. During the calculations, it was necessary to take into account the fact that external shape of the shell is measured, while the theoretical model is inside the thickness of shell’s walls. Additionally, the visible outline of edges of the cooling tower is a spatial curve, which is not located in the vertical plane [4]. There were also problems with the correct identification of edges of the cooling tower during aiming with instrument’s telescope at grey surface of the concrete, in the background of cloudy sky.

Development of electronic tacheometers, especially the introduction of reflectorless rangefinders, supplanted the surrounding tangents method for the benefit of polar measurements with trigonometric measurement of height. Depending on the needs, one of the following options is used: irregular distribution of measurement points on the shell or ordered set of points in the form of a series of horizontal and vertical cross-sections. It should be emphasized that controlled points are not signalled, while the average distance between points on the shell amounts to a few metres. Subsequent stage in the development of measurement instruments was the appearance of motorized reflectorless tacheometers, which significantly reduced the duration of field works, by allowing for the measurement of several adjacent vertical cross-sections from a single position of the instrument.

Terrestrial laser scanning is another improvement of classic methods. Principle of operation of the scanner is similar to the motorized tacheometer, but the scanner allows to measure even a million points in one second [11]. A cloud of points is registered at each scanner position. Each measured point has X, Y, Z coordinates in the local scanner layout, colour (described by RGB parameters) from the taken photos and a parameter that describes the intensity of laser beam reflection. Connecting individual positions of the scanner into one cloud of points is called the registration of clouds. The resulting cloud usually requires cleansing, which is done by the removal of unnecessarily scanned elements, noise and points representing false reflections [7, 9].

Photogrammetric techniques are based on terrestrial or low-level stereoscopic photos. Camera processing allows to achieve a cloud of points representing the cooling tower’s shell. Photogrammetry is characterized by advantages resulting from documentary value of photos and possibilities of camera re-processing of previously obtained photos. Moreover, it’s a quick method that allows you to visualize the whole object in a short time. At the same time, this method is quite expensive, if the number of photogrammetrically measured points does not significantly exceed the number of traditionally determined controlled points. The disadvantage of this method is the necessity to take a large number of photos that overlap each other in the horizontal and vertical plane, as well as the limited resolution of photos, which translates into limited accuracy in determining the coordinates of points on the tested surface.

Thermovision technique has a lot in common with photogrammetry, however it differs in the range of recorded spectrum. The primary purpose of thermovision measurements is not to build a 3D model of the object (although it’s possible), but to determine the value and distribution of temperature of the measured object [3]. Thermovision cameras allow to detect (in indirect manner) potential hazards in
the form of changes on the tested surface early enough that it’s possible to plan repair works without any problems, thus avoiding the costs of production downtime or the effects of unexpected failures [5]. Diagnostics can be carried out with full hydraulic load. Diversity of detected changes and damages of concrete is much greater than in the case of typical visual inspections. Thermovision measurements are also applicable during scientific research regarding thermodynamic processes, where they improve the quality of acquired information about heat exchange or cooling conditions [6]. Generally, it can be concluded that thermovision measurements enable easy, quick and safe control of processes associated with generation or transmission of energy, regardless of difficulties with access to the monitored object [15]. Some laser scanners have integrated thermovision cameras and this allows to colour measured points according to the distribution of temperatures [14].

3. Methods for calculating geometrical imperfections

Geometric imperfections are defined as deviations between the actual shape of the cooling tower’s shell and the theoretical model of this shell, which for the hyperboloidal cooling tower is determined by formula (1):

\[
\frac{(x-x_0)^2}{a^2} + \frac{(y-y_0)^2}{a^2} - \frac{(z-z_0)^2}{c^2} = 1
\]

where: \(x, y, z\) - the coordinates [m] of any point on the surface of the rotational one-sheet hyperboloid; \(x_0, y_0, z_0\) - coordinates [m] of the hyperboloid’s centre of symmetry; \(a, c\) - the real and the imaginary semi-axis [m] of the hyperboloid.

As mentioned earlier, the theoretical model is located inside the thickness of shell’s walls and the results of geodetic measurements describe the actual shape of external surface of the cooling tower’s shell (figure 1).

![Figure 1. An example of cooling tower in power plant](https://cdn.pixabay.com/photo/2017/10/15/18/29/cooling-tower-2854748_960_720.jpg)

Therefore, it’s necessary to introduce appropriate correction during calculations, which will take into account half of the shell’s wall thickness. Moreover, the external surface of the shell is not smooth, but it consists of several dozen or several hundred cut cones representing subsequently performed cycles of concreting. Depending on the used calculation approach, the values of imperfection are determined in three-dimensional space or in the case of flat approach – by separately considering each vertical axial cross-section. Fitting of the theoretical model is usually performed using the least squares method with known or approximated dimensions of the semi-axis of theoretical
hyperboloid. Approximation of dimensions of the semi-axis may occur in the case, when there’s no design documentation or the actually performed structure significantly differs from the design assumptions. In the case of uneven distribution of significant local deformations of the shell, it’s worth to use methods of robust estimation [16]. The calculated values of geometrical imperfections are compared with the results of previous measurements, therefore the continuation of previous calculation method is important. The obtained results should be presented in a clear manner. Most frequently, the charts are prepared in the form of horizontal cross-sections presenting radial deviations from theoretical circles for the preset heights. Additionally, the figures of vertical cross-sections, developments of lateral surface of the cooling tower’s shell in cylindrical projection, spatial models and isoline maps presenting the distribution of imperfections are performed.

4. Description of field tests and method of their development

The research object was reinforced concrete, hyperboloid cooling tower with the height exceeding 100 m. Measurements of geometrical shape of the cooling tower’s shell were carried out with the use of terrestrial laser scanning. The pulse scanner Leica ScanStation C10 was used for this purpose. During preparatory works, a geodetic network was established in the form of an angular-linear network consisting of 12 points. Each point was a tacheometer station, from which all visible points of the network were aimed at. Angular-linear measurements were carried out in two sets using a motorized electronic tacheometer with the following accuracy: angle measurement ±2", distance measurement in the reflector mode ±(2 mm + 2 ppm). In each set, the measurement in two telescope positions (in two faces) was conducted, with double measurement of distance in each telescope position. Heights of the points in network were measured with the use of technical levelling and code leveller with measurement accuracy ± 1mm/1 km of double levelling. The results of network measurements were strictly adjusted using the least squares method [10]. Mean error of the horizontal position of the control points after adjustment did not exceed ±1.6 mm and on average it amounted to ±1.2 mm, while the mean error of determining the height of the control points did not exceed ±0.8 mm and on average it amounted to ±0.7 mm.

Measurement with the use of laser scanner was carried out from 11 positions located on the control points or between them. On average, 7 HDS targets were measured at each position, which were used as points linking individual positions. Assumed average density of the point cloud amounted to 3 cm. Registration of individual positions was carried out in two stages (so-called nested registration) in the Leica Cyclone software. The first stage consisted of combining all scanner positions in the local system, with simultaneous use of two types of connections: joint HDS target and cloud-to-cloud method. Mean Absolute Error for this stage of registration amounted to 2.3 mm. Subsequently, the second stage of registration was carried out by fitting the point cloud into the coordinate system of the geodetic control points (Mean Absolute Error amounted to 8.3 mm). After further unification of the cloud, its cleansing was carried out through removal of interferences and unnecessarily scanned elements. For the purpose of further development, the cloud density was reduced and unified. From the original set of 47 million points, 31 thousand points were left with an average density of approx. 1 m. A theoretical model of the cooling tower’s shell was generated for similar density on the basis of design parameters. The model took into account half of the wall thickness in such manner, so that the theoretical model would represents external surface of the cooling tower’s shell. By comparing the actual geometry (described by the point cloud) with the theoretical model (MESH-type surface) in a precisely defined coordinate system, the distances from the point to the surface were calculated. These distances can be treated as the values of normal imperfections. Negative value of imperfection means indentation of the shell into the cooling tower’s interior, while the positive value of imperfection means bulging of the shell outside. The results of calculations are presented in figure 2 and figure 3, where each point is assigned with a colour corresponding to the determined value of imperfection.
Simultaneously with the measurement of geometry, the thermovision photo of the cooling tower’s shell was taken. The range of thermovision camera allows to take photos only in the lower part of the cooling tower (figure 4 and figure 5). Photos of the upper part of the cooling tower’s shell can be taken from higher level - a boom or unmanned aerial vehicle (drone). In the range of field works only photos from the ground level were taken, because there was no possibility to take photos from higher levels. It should be noted that a large distance from the measuring object reduces accuracy of the temperature measurement and it may cause noise. Interference may be also caused by other objects located in the surroundings of the measurement. In the framework of research works, the selected thermovision images were processed by applying them on the point cloud. For this purpose, sets of points unequivocally identifiable on the thermovision image and on undiluted point cloud were used. After mathematical processing, it was possible to assign colours from the thermogram to the cloud points (figure 6 and figure 7).

5. Analysis of the obtained results and discussion
Calculated values of geometrical imperfections of the cooling tower’s shell are contained in the range from -142 mm to +144 mm. In figure 2 and figure 3, the red colour represents the biggest bulges of the shell, while the blue colour - the largest indentations. The majority of calculated imperfections have
negative values (indentations). Positive values of imperfections are noticeable primarily at the supports of the cooling tower shell and they usually exceed +100 mm. For the most part of the shell, the values of imperfections do not exceed several centimetres and they rather have irregular distribution. These imperfections may result from slight inaccuracies arising during the construction of the cooling tower. Irregularities in the distribution of points, which are visible in the upper part of the cooling tower, result from difficult conditions occurring during the measurement. The cooling tower was operated and clouds of water vapour, as well as paint coatings used on the shell, hindered the reflection of the laser beam.

![Figure 6. View of thermal image imposed on the cloud of points obtained from scanner](image)

![Figure 7. View of point cloud in the color of reflection intensity](image)

Analysis of thermovision photos allows to detect areas with differentiated temperature on the cooling tower, especially high temperature of elements of the installation distributing hot water, as well as adjacent elements of the cooling tower’s structure (figure 8). Heterogeneous thermal load may cause the occurrence of additional stresses in the structure. Possible changes in the thickness of the shell walls, cavities or cracks in the concrete will result in uneven distribution of temperatures. No signs of potential damage to the shell were observed for the tested object (figure 7 and figure 9). Only interferences in the distribution of temperatures on the cooling tower’s shell appeared near the bottom of the shell and near the assembly places of the warning lamps.

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6. Conclusion
The studied cooling tower was measured with the use of two independent methods. Terrestrial laser scanning provided a credible and dense representation of the actual shape of external surface of the cooling tower’s shell. The speed of measurement, as well as the detailed description of object’s geometry constitute unquestionable advantage of laser scanning in relation to the classic tachymetric measurements. However, the water vapor and some paint coatings make it difficult to reflect the laser beam and limit the actual measuring range. Thermovision allowed to identify places that are characterized by particular thermal load and exposed to the occurrence of discontinuities in the concrete shell. Thermovision measurement is fast and does not require the involvement of a large number of people nor advanced equipment. The combination of both methods allows direct comparison of geometry and temperature and creates the possibility of conducting additional analyzes, e.g. regarding changes of these parameters over time. It is also possible to indicate particularly vulnerable places on the cooling tower shell, which should be measured more often or with a greater concentration of measurement points. The values of the shell’s geometric imperfections supplemented with thermal data in combination with measurements of foundation settlements and material tests of concrete constitute the basic information for the evaluation of technical condition of the cooling tower by the constructors.

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