GEODESIC MONITORING OF TOWER AND MAST STRUCTURES

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1. INTRODUCTION

Slender structures are characterized by their height exceeding by far their maximum width and include both full-walled as well as openwork structures. Towers, chimneys, masts of various intended use are typical examples of slender structures. However, in recent years such group of technological structures has significantly grown and nowadays wind power plants can be seen more often as an element of land and water landscape all over the world.
A number of tower and mast structures, under structure or exploited (Widerski T., et al., 2008) has significantly increased also on Polish territory. Rapid development of renewable sources energy sector has forced the necessity for structure of even higher structures grouped in farms of several or several dozen power plants.
Specification of wind power plants is based upon usage of tower or mast element as a generator load bearing structure (Widerski T., et al., 2005). Such a structure is subject to static and dynamic loads which result in dislocation of individual elements and whole structure. Telecommunication masts have different tasks. They are an individual slender structure with or without stays and are relatively poorly equipped in transmitting–receiving devices and are characterized by less complex load. However, in both presented structures significant dislocations can result in permanent changes in geometry and in pre-emergency and emergency conditions.
Tower and mast structures require realization of periodical inspections of their geometry condition (Structureal Law, 1994). Hence, at the stage of structure and exploitation of such structures measurements of their dislocations are performed. Necessity for such measurements is connected with safety requirements. Structure geometry perturbation can result in catastrophic and costly consequences. The article characterizes loads applied to slender structures, measurement methods and presents measurement results of selected wind power plant and mast dislocations.

2. LOADS OF TOWER AND MAST STRUCTURES

During initial stage of a slender structure project preparation, a designer makes a series of assumptions the structure designed by him should meet. The most important is the assumption of safe load transfer during structure erection (assembly), long-term exploitation and disassembly. It also assumes specific, stage defined, permitted loads and deformations of individual elements or whole structure. In order to specify correct conditions, a type and range of loads the structure shall be subject to and external environmental) conditions characteristics it shall be exploited in, should be known. Tower and mast structure loads include (Kozłowski T., 1965):

- **own weight of structure with equipment,**

- **snow load,**
- **ice load,**
- **pushing and sucking force of wind,**
- **temperature influence,**
- **assembly loads,**
- **catastrophic loads,**
- **loads by operating devices connected with the structure intended use or existing in specific conditions.**

Own weight of structure with its equipment is relatively easy to specify. The manner for determining snow and ice load is specified in the norm (PN-82/B-02000, PN-EN 61400-1). The greatest difficulty is the accurate specification of wind load value (pushing and sucking force of wind) which is of a variable nature in shorter and longer time periods (PN-77/B-2011), in particular with reference to an operating power plant, resulting also in some type of dynamic loads. In accordance with PN (PN-82/B-02000) wind loads have been qualified as short-term, variable loads. As the wind results in the biggest loads for slender structures, the designers attempt to obtain the optimum shape of the structures which shall provide maximum reduction of aerodynamic resistance and the most advantageous relation between the structure weight and its endurance.

In case of the power plant, the wind bears load on the tower and on operating or not operating impeller (blades) with a generator's car (Widerski T., et al., 2008), whilst telecommunication masts are loaded as a whole single unit i.e. a tower with equipment and possible stays.

Vibrations caused by unbalanced turbine impeller and by-flowing air streams are dangerous phenomenon. Eddy excitation loads on towers result in significant dislocations and stress (bending, twisting, spreading and tightening) in its shaft. Transverse forces caused by winds are dynamic, transverse values changing dynamically in short intervals. They cause the most serious danger for tower segments joints, welded joints, openings etc.

Moreover, earthquakes (present also in Poland) (Zębaty Z., et al., 2005) have an adverse effect upon slender structures stability. Even relatively small additional dislocations of such structures foundations caused by earthquakes can result in failure or structure collapse.

The described loads operating on tower and mast structures result in their complex dislocations of temporary or permanent nature. Hence, their monitoring is crucial and should be conducted since the moment of such structures assembly.

3. THE SCOPE AND REQUIREMENTS OF GEODESIC MEASUREMENTS OF TOWER AND MAST STRUCTURES

The manners of observation of slender structures dislocations must include specification of their operation and provide results reliable enough to optimally determine dislocations component values and deformation of selected elements and the whole structure. The scope of necessary measurements is also crucial (Bryś H., et al., 1998). Often the orderers place specific accuracy requirements on geodesists. Thus, only appropriately used technologies and equipment can met the expectations and provide the required accuracy of expected measurement results.

Current determination of dislocations and forecasting dislocations for subsequent loading conditions with the possibility of slender structures failures is the most important task of monitoring of such structure types under exploitation. Vertical line of its geometrical axes is the basic geometrical condition which slender structures must

meet. Performing measurements of dislocations of wind power plants, telecommunication towers etc. aims at determination of quantity and quality changes of their shape and location. Such changes are specified by setting dislocation indexes (translation, rotation) and deformation indexes (e.g. inclination, twist) of inspected structure elements. The indexes are set on the basis of dislocation vectors calculated on the basis of periodical functions of observation of measurement network geometrical elements located on the structure elements under observation. Such observations are usually performed with use of geodesic and photogrammetric methods.
Periodical measurements or constant monitoring of tower and mast structures should simultaneously include:

- **surveyor measurement of benchmarks installed on foundation around the structure shaft,**
- **measurement of stays sags with anchors,**
- **measurement of shaft dislocation, including structure inclination and twist,**

Also the conditions of environmental – external influences on structures such as the wind force, velocity and direction, sunlight etc. should be recorded.

4. TOWER AND MAST STRUCTURES MEASUREMENT METHODS

Plenty of slender structures dislocation (vertical and horizontal) measurement methods are used in geodesic practice. Vertical dislocations depending on the required accuracy, can be realized by geometric or precise leveling method. They are used mostly for observation of foundations dislocations. In case of very tall structures, including among others wind power plants (of height exceeding 120 m) it is recommended t use precise leveling method. Benchmarks, as check points, installed on the foundations should be linked with respect to height with previously mounted local control network, providing correct accuracy regime.
Setting of horizontal dislocations can be conditioned by a series of available measurement methods. A method selection depends upon the object location in the area, visibility, availability and a number of local and accuracy factors. In order to determine slender structures dislocation values one of the following methods can be applied:

- **trigonometric,**
- **photogrammetric,**
- **automatic (inclinometers, accelerometers, electronic levels),**
- **direct projection,**
- **linear or angular indents,**
- **based upon satellite navigation technique.**

Trigonometric method measurement requires observations obtained from three positions located around the structure under monitoring. The distance between individual positions is set by direct methods, and the distance from the position to tower axis and height is set by trigonometric method (Bryś H., et al., 1998). Deviation from vertical line can be set by small angles method.
Preparation of results of dislocations measurements is based upon setting of linear deviation for each measurement level. Set aside graphically specified linear values of deviations for all directions of observation levels and draw lines parallel to the direction of a device position – support base axis, on such distances. Directions to the object axis at examined levels, specified in this manner, should cross at single point, setting the actual location of examined structure points in horizontal plane projection. Measurement errors resulting from tower's vibrations, wind influence during observations and the tower structure accuracy result in the fact that three directions set

in this manner, determining single point on the support axis, do not cross in one point, but they set a triangle of errors in the center of which the location of measured point should be assumed.
Upon measuring tower and mast structures one should take into account numerous changes in object deviation with relation to an assumed surface, caused by external factors. Hence, the measurements must be performed in quick and efficient manner on all positions simultaneously. During strong winds, performance of measurements must be avoided (Bryś H., et al., 1998). Measurement works with use of the trigonometric method are recommended during stabile weather conditions, fixed wind velocity and medium sunlight.
Photogrammetric method is just another method possible for use during observations of tower and mast structures geometry changes. Photogrammetric setting of measurement point dislocation value is limited to setting a dislocation which occurred between actual and initial state. Dislocation value is specified by finding three increments of coordinates of measured points on three planes x, y, z. The use of periodical or inventory measurements for setting dislocations or deviations from a standard is based upon analytical determination of check points coordinates and comparison of such points with initial state coordinates or standard coordinates. Bi-image or multi-image method is used for this purpose and spatial dislocations (or deviations) components Δx, Δy, Δz are set. Dislocation component can be set by comparison of coordinates which are set during two measurements or by differential method. In the second case, dislocation components Δx, Δy, Δz are set directly as a function of measured angles, distance changes or background coordinates changes (Sitek Z., 1991).

Monitoring of slender structures dislocations can also be realized with the use of automatic measurement methods. Measurement of the structure deviation with use of inclinometric sensors is based upon recording the structure deviation angle from vertical line set by the Earth gravitation force. Inclinometer's operating principle uses gravitation for driving of a weight located on coding inverter dial. Internal magnetic damping allows for short times of oscillation setting after a weight has deviated. This, in turn, allows for detailed examination of a given structure deviation changes in very short intervals. In case of wind power plants measurement equipment can be installed inside the tower. Obtained measurement information is collected in data bases so it can be supplemented with measurement results from other auxiliary measuring devices e.g. with respect to structure temperature, wind velocity and a number of other factors at a given measurement level.

5. EXAMPLES OF MEASUREMENT OF A WIND POWER PLANT AND A MAST DISLOCATIONS

Monitoring of wind power plants (of height exceeding 140 m – tower + impeller) dislocations and forecasting of further dislocations, including structure stability is extremely important from exploitation and safety point of view. The following are the results of observation of dislocations of a ground slab and a tower of 80 m height in wind power plant of 2MW power, realized by the authors of the hereby paper. Several years of measurement works aim at setting actual dislocations and preparing a forecast for dislocation of power plant main elements.
Wind power plant measurement was realized in two stages. The first stage included leveling of check benchmarks located on ground slab in the power plant under monitoring. Sixteen check points were fixed in the foundation, twelve on external base

edges and four in direct vicinity of the power plant tower jacket (Fig. 1). Measurement results of their dislocations with respect to the initial measurement (prior to the foundation loading) are shown in Fig. 2.
Steel tower vertical dislocations measurement was realized by precise leveling method.

The tower dislocations measurement on four levels was realized by projection method from two positions simultaneously. At wind velocity 8 m/s, tower axis dislocation from vertical line at height 78 m was 0.23 m (Fig. 3).

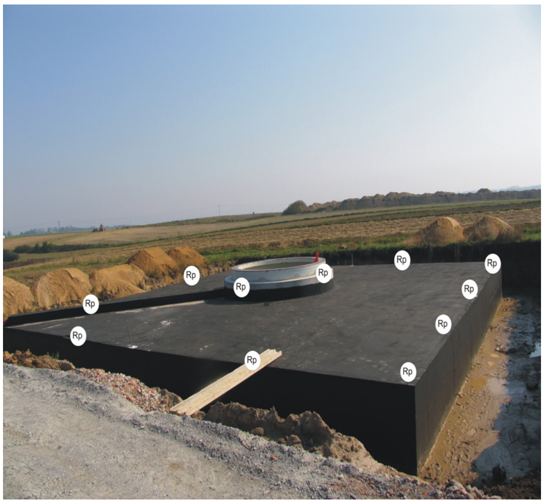
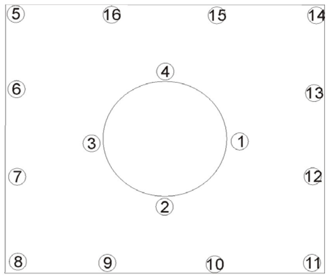


Fig. 1. Distribution of benchmarks on a wind Power plant ground slab.



Vertical dislocations of a ground slab after second measurement session

Nr	dh po II serii
1	- 1,3
2	- 5,6
3	- 0,5
4	+ 3,8
5	- 0,9
6	- 0,6
7	- 0,8
8	- 1,2
9	- 1,0
10	- 1,0
11	- 1,6
12	- 1,5
13	- 1,1
14	- 0,8
15	- 1,2
16	- 0,7

Fig. 2. Results of measurements of vertical dislocations of a ground slab after second measurement session.

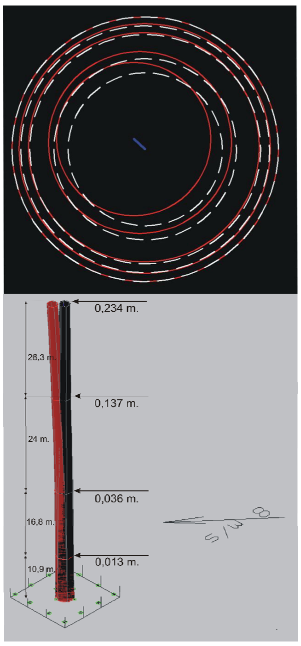


Fig. 3. Real horizontal dislocation of wind power plant tower at wind velocity of 8 m/s.

For comparison, course and results of control measurements of tele-transmission mast with tower height of 60 m are presented below. Measurement was taken by DIAZ company from Gdańsk oat the order of one of mobile telephony operators.
Measurement was taken in accordance with the norm (BN-69/2940-01) and included:

- **measurement of shaft twist on at least three levels, including the highest segment (permitted value of deviation in relation to location in a place at distance L is 1/2000 x L),**
- **measurement of tower/mast axis deviation at ca. 18 rn of a tower, including the highest segment, (permitted value of deviation for a tower 1/1000 x H, permitted value of deviation for a mast is for the first lower span 1/2000 x H for remaining spans 1/1500 x L1),**

- **measurement of non – perpendicularity of a tower curb – one measurement per a curb (permitted value of deviation is 1/750 x L1),**
- **measurement of deviation of tower axis from vertical setting in segments joining points, including the top of the highest segment (permitted value of deviation is 1/400 x L according to (ITB DB-90/02)),**
- **checking the level of ground slabs foundation.**

Measurement of spot footing of a transmitter tower was realized by geometrical leveling method. In order to do this characteristic points were selected on their surface which were then leveled during measurement. Outline of horizontal setting of a tower ground slabs (Fig. 4) presents levels of tower ground slabs height and levels of spot footing level. Leveling measurement was taken from one measurement position in order to avoid height transmission errors. The expected accuracy was achieved by the method assumed. After leveling of spot footing, measurement of vertical line of a mast from three positions was performed. Observation positions were selected in order for vertical angles during structure observation not to exceed 30° – 45°. Adopted shape of measurement network provided the best setting ability for the object geometry. The observation results are presented in the outline of control measurement of a the tower vertical line (Fig. 5). Permitted deviation from vertical line of the examined object was 60 mm. Dislocations of the examined object were within the permitted range of deviations.

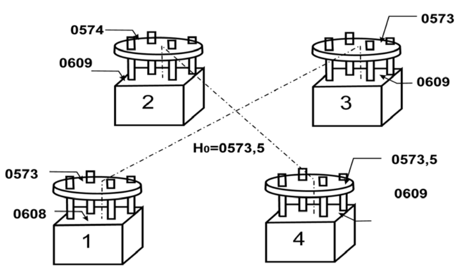


Fig. 4. Outline of horizontal setting of a tower ground slabs (DIAZ company Gdańsk).

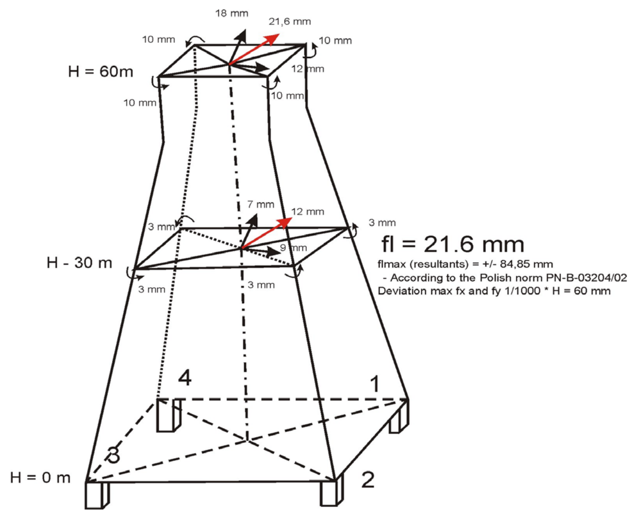


Fig. 5. Outline of control measurement of a tower vertical line (DIAZ company Gdańsk).

6. CONCLUSIONS

Environmental (extreme) external factors adversely influence operating conditions of slender structures. Insufficient knowledge on structure load value and investors' aim to reduce investment costs can lead to structureal catastrophe. Currently, designing of wind power plants structures and masts is based upon mathematical models. Despite their significant reliability newly built power plants and masts are prone to failures. It is connected with insufficient abilities of programs for verification of load accumulated

with respect to long-term exploitation, situations which are difficult to foresee and "human" errors. In case of wind power plants, the designers specify their exploitation period to be ca. 20 years. However, importing of used and partially highly exploited wind turbines to Poland is becoming more popular. In order to verify calculations for the newly built structures and to monitor "reactivated" wind power plants it is necessary to perform geodesic observations of deviations of these structures which are often subject to extreme environmental loads. Monitoring of geodesic slender structures in particular under intensive loads such as wind power plants and masts is necessary for providing safety of their operation and of persons present in the vicinity. Detailed geodesic observations of dislocations can also influence the methods of evaluation and setting structureal loads which wind power plants and masts are subject to.

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