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DETERMINATION OF DISPLACEMENTS OF SLENDER OBJECTS

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Abstract. In the paper the authors conducted a study on the determination of daily changes in the position of a slender object on example of a power pole. The size of the dynamic deflections was compared to variables of the effect of solar radiation and the wind speed and direction measured during research. To determine these parameters to-date measurements of temperatures on sunny and sheltered side of construction, direction and wind strength were performed. The attempt was made to determine the static deflection in order to compare them to the size of the maximum set forth in the technical standards. The measurement accuracy of the controlled points of the object was compared with values given in the technical instructions.
The authors concluded that deformation measurements carried out in serve weather conditions gave more valuable information in terms of an object endurance. The research is the first step in lengthier measurements. The motivation for this paper is need of rebuild of electric high – voltage lines.

Key words: deformation measurements, reflectorless measurement, slender objects, thermal loads, wind loads

INTRODUCTION

Determination of changes in the position of slender objects and determination of deformation of other facilities is especially important when the instability of these objects directly threaten the safety of humans and other important structures. Land surveying work should be carried out under optimal conditions. However, due to time and financial issues measurements are often made under different wheatear conditions. The determined values of the deviation are affected by static and dynamic changes. Determination of static

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changes are necessary for checking the technical condition of the subject and comparing the results to the assumed maximum deflection. The dynamic changes can be compared to the value of the model one dependent on the design of the mast [Kocierz et al. 2011, Wróbel, Wróbel 2012, Oleniacz et al. 2015].

Dynamic shifts of slender objects are, as we know, mainly the result of two events that may occur during the measurement in varying degrees. These are: heating the surface of the object as a result of sunlight and wind pressure on building structures. Impact directions of these events are different and change over time, and therefore in time of research good practice indicates to pursue them as long as possible. Then an attempt can be made to partially isolate their impact on the direction of oscillation of the object.

A significant difficulty here is the fact that, the direction the top of the object during its journey is generally delayed in relation to the angle of sunlight [Wróbel 2012].

In high – voltage overhead lines constructors used lattice structures poles fixed on four foundations. Nowadays steel tubular utility poles are more frequently used. The major reason is that they are more economic and take up less ground space. They are characterized by a large amount of stem in relation to the small diameter section [Szpindler 2011]. The pole is made of tubular steel solid wall elements, which form a conical structure with a circular or polygonal cross-section. The cross-section is divided into two classes 3 and 4 based on the bending strength [PN-90/B-03200: 2007]. In accordance with the Polish Building Standards [PN-B-03204: 2002, 2007] slender objects must meet a number of design and operational assumptions. Displacement of the top of a tower or mast f_{PB} at h – the height can not be greater than:

$$f_{PB} = \frac{1}{100} \times h \tag{1}$$

In our case with high of the pole equal 70 m f_{PB} – 0,70 m. The value is calculated from measurements carried out in optimal weather conditions.

Geodetic deformation measurement should be done with accuracy calculated from [Technical Instruction G-3 1988]:

$$M_p = r \times m_p \le R \times P \tag{2}$$

where:
M_p – maximum error of a displacement determination,
P – maximum displacement specified for the object or its part in the technical design or the corresponding instructions,
R – parameter defining, what part of the maximum displacement can be limiting error of his appointment (M_p), R decreases the value of P and can take the values:

R = 0.5, R = 0.3 or in our case value $0.01 \le R \le 0.1$ – the measurements used for qualitative and quantitative research the relationship between the magnitudes of displacements and their causes and effects,
m_p – average error of a displacement determination,
r – coefficient whose value depends on the required accuracy of the results and the degree of randomness of the error measurements used to determine the displacement.

Where for P equal:

- 0.997 should be adopted $r = 3$,
- 0.988 should be adopted $r = 2.5$,
- 0.954 should be adopted $r = 2$.

P – probability of correctness.

In this paper I would like to show that this approach is not entirely correct. Displacements of an object during serve whether conditions can give as more valuable information about condition and stability of a structure. Furthermore, the strong wind and temperature highly affects the wires and stable position of the pole itself. The impact of this displacement is topic for another article.

METHODOLOGY

In this section researcher show wind and thermal loads. This two factors are the most important from them all in case of steel structure. After determining the values of loads we can calculate natural position of the pole and compare it with measured one.

Wind loads

Wind load is a short-lived variable load. Its value depends on several factors: geographical positions, type of area, shape, type and proportions of the object. The turbulence of winds in the lower levels of the atmosphere largely arises from interaction with surface features such as buildings, vegetation, ground. The average wind speed over a time period of ten minutes or more, tends to increase with height, while the turbulence tends to decrease with height [Cheung 2007]. Operation of wind force is evenly distributed over the entire surface of the structure in a perpendicular direction to the element. At the same time the forces of friction are created, which are tangent to the large surface of the structure.

In case of high slender object wind load could act as major factor of source of displacements. However, if structure is made of steel we need to consider thermal loads and solar radius as more important factor of displacements.

The wind stress on outer surface of an object is formulated as follows [Eurokod 1, PN-EN 1991-1-4:2008].

$$w_e = q_p(z_e) \times c_{pe} \tag{3}$$

where:
$q_p(z_e)$ – peak wind pressure [Pa],
z_e – reference height for the external pressure,
c_{pe} – external pressure coefficient.

The wind stress on inner surfaces of a structure is given with a quotation [Eurokod 1, PN-EN 1991-1-4:2008]:

$$w_i = q_p(z_i) \times c_{pi} \tag{4}$$

where:
$q_p(z_i)$ – peak wind pressure [Pa],
z_i – reference amount for the internal pressure,
c_{pi} – coefficient of internal pressure.

To calculate the drag coefficient c_f we assumed that the mast has the shape of a circular cylinder of finite length. The resistance is calculated from the formula [Eurokod 1, PN-EN 1991-1-4:2008]:

$$cf = c_{f,0} \times \Psi_\lambda \tag{5}$$

where:
$c_{f,0}$ – drag coefficient of the roll without affecting the free end,
Ψ_λ – impact factor of the free end.

Structural factor $c_s c_d$ for civil engineering construction such as bridges, chimneys and buildings [PN-B-03204:2002, 2007], takes a value of 1.

The formulas from 3 to 5 are needed to calculate forces exerted by the wind. Calculations are based on Eurokod 1, PN-EN 1991-1-4:2008:

$$F_w = c_s c_d \times c_f \times q_p(z_e) \times A_{ref} \tag{6}$$

$c_s c_d$ – structural factor,
c_f – coefficient of aerodynamic force structure or its element,
$q_p(z_e)$ – peak height velocity pressure for a reference to the z_e [Pa],
A_{Ref} – reference surface area of a structure or structural element [m^2].

For other unknowns their value was taken from tables from [Eurokod 1, PN-EN 1991-1-4:2008].

THERMAL LOADS

Researcher determined the thermal loads from thermal pictures of the object taken during the day.

Because of high temperature (around 30–35°C) the differences between one side and the other was significant (up to 10°C). It caused the expansion of material and changes in object height [Eurokod 1, PN-EN 1991-1-5:2005].

For a high building the value of shaft deflection is calculated from an equation [Kocierz 2011]:

$$f_n = \Sigma_{i=1}^{n} \varepsilon_{t,i} \Delta t \frac{h_i}{d_i}\left(\frac{h_i}{2} + \Sigma_{i-1}^{n-1} h_i\right) \tag{7}$$

f_n – shaft deflection in n – th section [m],
Δt – temperature rise [°C],
h_i – height in i – th section [m],
d_i – diameter of buildings in i – th section [m].
$\varepsilon_{t,i}$ – linear expansion coefficient in i – th section [1×°C].

The linear expansion is different for other materials:

Table 1. The linear expansion coefficient εt [PN-EN 1991-1-5:2005]

Material	ε_t [1×°C]
Aluminium	0,0000255
Concrete	0,0000110
Regular steel	0,0000120

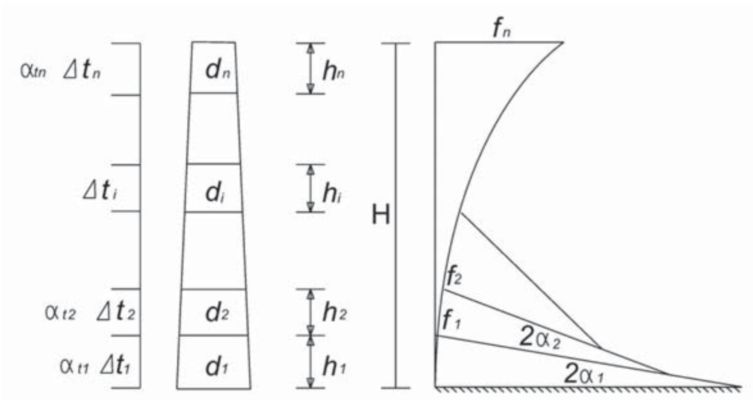

Fig. 1. The division of the building into sections to calculate 6
[Own work based on: Kocierz et al. 2011]

EXPERIMENTAL RESULTS

The utility pole used in this research is located near Wrocław city as part of high voltage line. Measurements was carried out in three consecutive years. For two first years we done survey in optimal condition, then during day with high atmospheric temperatures. Measurements in third year was done only in optimal weather status. This checked correctness of assumptions and natural position of utility pole.

Accuracy obtained from measurements was calculated from formula 2. We substituted to the maximum error of a displacement determination formula, assuming the highest value of probability P, $r = 3$ and $R = 0.05$.

For the value of the displacement limit calculated from the formula (1) average error of a displacement determination of a controlled point can reach 0.012 m. Error of position for the weakest point after the adjustment is 0.0092 m for angle intersection method. So it is clear that using the above-mentioned method, accuracy of measurement is sufficient to determine the deviation of the location of slender object with agreed objectives.

In year 2014 static displacement of apex amounted dx = -78.2 mm, dy = 56.1 mm, dL = 96.2 mm, and in 2015 dx = -141.2 mm, dy = 16.6 mm dL = 142.2 mm. Although these values are different, we can recognize these differences as small: dx = 63.0 mm, dy = 39.5 mm. More reliable seems the results obtained in year 2014, because this measurement was made in the early hours, when the temperature and sun angle had low impact. The designated maximum value of the static deflection of the test object is 700 mm [PN-B-03204: 2002]. It should be recognized that the object is stable.

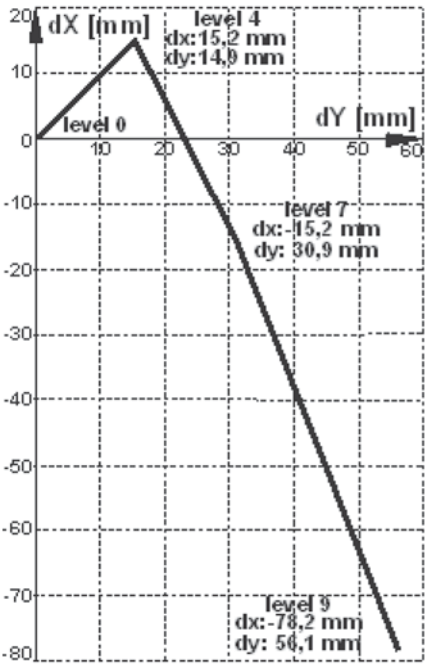

Fig. 2. The position of the utility pole in neutral atmospheric conditions in year 2014

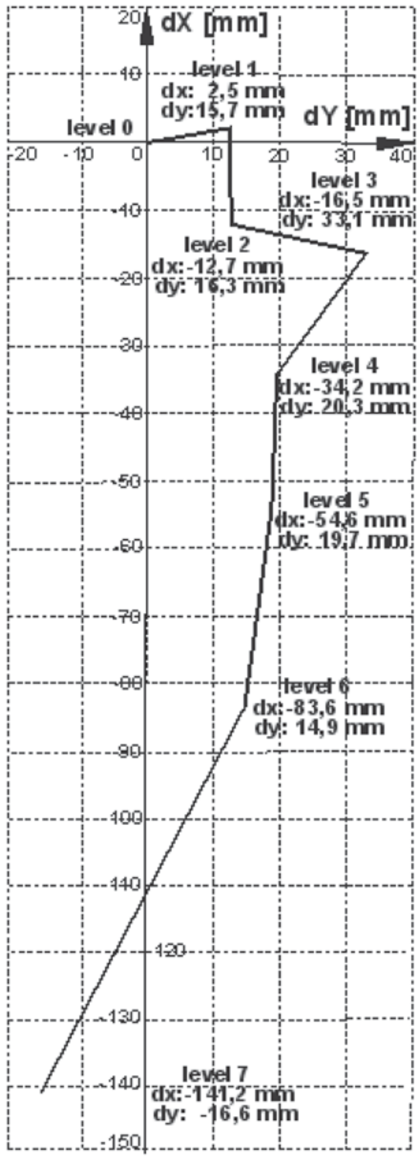

Fig. 3. The position of the utility pole in neutral atmospheric conditions in year 2015 [Own work based on Zasada 2016]

The next step was to calculate a position of the pole from polar measurements in severe weather conditions. The first measurements were carried out in year 2013. Atmospheric conditions were as follow: the temperature from 16 to 22^{o}C, the wind speed max 6m×s, changing solar radius. In year 2014 the conditions were more extreme and the displacements are significantly higher (the temperature from 25 to 35^{o}C, the wind speed max 6m×s). The results are shown in Figure 4 and 5.

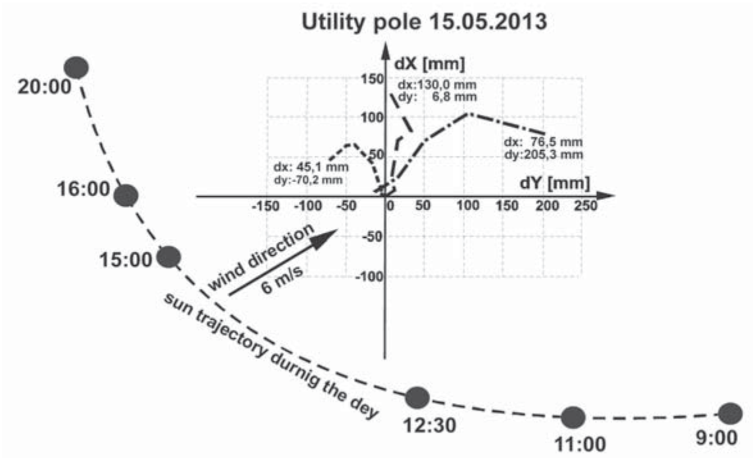

Fig. 4. The displacement values of the utility pole during the day

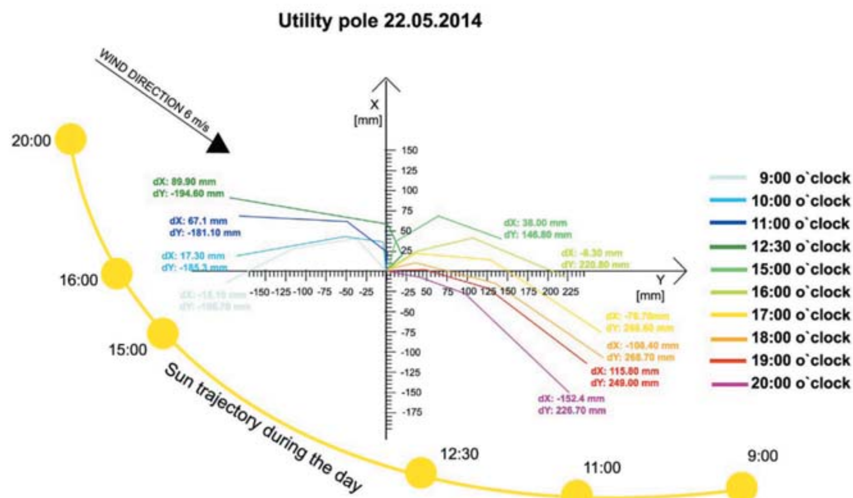

Fig. 5. Displacement of the utility pole during the day in exact time

Looking at Figure 4 and Figure 5 displacements are at the level of 0.22 m in 2013 and 0,28 m in 2014 from the lowest point to the highest, in the same time the maximum daily change of deflection of the object is 0.27 m in 2013 and 0.50 m in 2014.

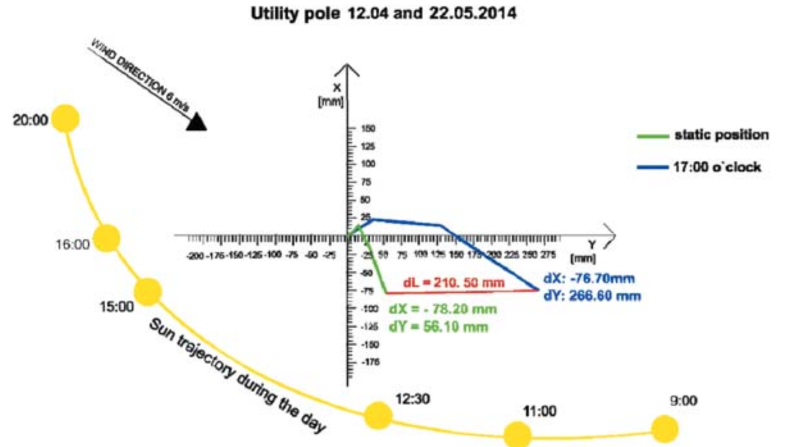

Fig. 6. The comparison of displacement in neutral and serve weather conditions

Then to determine value of displacement caused by loads firstly we calculated wind loads from formulas 3 to 6 and its values are as given in Table 2.

Table 2. The values of wind loads in year 2014

No.	Height H [m]	The diameter of the cross section b [m]	w_{e1} [Pa]	w_{e2} [Pa]	$\sum w_e$ [Pa]	$c_s c_d$	c_f	F_w [N×m]
H_1	2.0	2.54	241.6219	36.2433	277.8651	1	0.0467	28.6752
H_4	26.0	2.26	160.9792	24.1469	185.1261	1	0.0643	280.8699
H_7	44.0	1.90	151.9797	22.7970	174.7767	1	0.0788	204.6795
H_9	70.6	1.60	145.0052	21.7508	166.7560	1	0.0957	295.4490

The force of the wind on the object is in the range of 28 N×m in the lower part of the column to 295 N×m for the top of the building at a height of 70 m above the ground. It gives us the swing of less than 10 mm [Eurokod 1, PN-EN 1991-1-4:2008] calculated in Autodesk Robot Structural Analysis 2013.

The larger values of displacements were caused by angle of radiation and temperature.

To determine the temperature of an object we used thermal infrared camera FLIR X5. Then the temperature of the object was established in the program. To determine the most probable temperature we set up the emissivity of 0.8 and a reflect temperature parameter on 8°C [Sendkowski 2013].

They are calculated below. Taking value of the linear expansion coefficient from Table 1 and data from Table 3 the f_n formula number 7 [Interdisciplinary topics in mining and geology, 2011] has the value in 2013 respectively: 0,06 m, 0,09 m, 0,15 m Table 4. In year 2014: 0,17 m, 0,18 m and 0,22 m Tables 4 and 5.

Table 3. Example of values of measured temperatures. Time: 9:00

Level	Height H [m]	Cross section diameter b [m]	Shaded side [Co]	Sunny side [Co]	Temperature difference [Co]	Temperature difference between levels ΔTShaded [Co]	Temperature difference between levels ΔTSunny [Co]	Partial fn [m]
1	2.00	2.54	31.6	38.7	7.1			
						-4.3	-5.9	0.0019
2	7.00	2.50	27.3	32.8	5.5			
						-6.3	-9.5	0.0466
3	26.00	2.26	21	23.3	2.3			
						-2.5	-2.6	0.0382
4	44.00	1.90	18.5	20.7	2.2			
						-7.6	-8.3	0.1515
5	54.00	1.85	10.9	12.4	1.5			
						-4.5	-0.3	0.0078
6	60.00	1.74	6.4	12.1	5.7			
						-4.2	-0.7	0.0227
7	65.50	1.65	2.2	11.4	9.2			
						0.8	2.5	-0.0968
8	70.60	1.60	3	13.9	10.9			

Table 4. The values of thermal loads in year 2013

Lp.	Time	Value [m]
1	9:00	0.06
2	12:30	0.09
3	20:00	0.15

Table 5. The values of thermal loads in year 2014

Lp.	Time	Value [m]
1	10:00	0.1720
2	12:30	0.1832
3	17:00	0.2257

Analyzing the impact of temperature and wind speed and direction changes on the deflection of the object we assumed that the static deflection is about dx = -78.2 mm, dy = 56.1 mm. The assumption is perhaps imprecise, but defining the precise static deflection is generally difficult.

Change of sunlight have the biggest impact on deflection. It is clearly seen in both figures (Fig. 4 and 5) from year 2013 and 2014. The distribution of these changes is similar, except that in year 2014 the measurement in the afternoon was impossible (too strong sunlight). Various deflection value obtained in both measurements at 17:00 is caused by another direction of the wind and higher temperatures.

In 2014, the dynamic deflection amounted dx = -76.7 mm, dy = 266.6 mm, dL= 277.4 mm. The source of a large part of this excursion is the influence of sunlight calculated for the year 2014 – 225.7 mm. As we can see at Figure 6 the thermal load in plane Y highly influenced the value and direction of apex shift.

It shows how weather conditions affect the value of displacements. The magnitude of limit displacement determination was not crossed. Taking into account the thermal and wind loads we can assume that the largest displacement values results from the one sided sunlight. The predominant direction of the wind is from north-east. As an outcome the natural position of the pole is opposite to this direction.

CONCLUSION

According to generally accepted principles for deformations measurements to determine the position of a static object should be carried out in optimum atmospheric conditions i.e. the temperature of about 18°C, with limited sunlight and during the windless day. However, for a whole picture of the changes of slender constructions and for safety conditions it is important to determine the position of the examined object in extreme weather conditions. The second measurements should on the same object be carried out during strong winds, preferably blowing from different directions, in bright sunlight with changing angle of incidence of solar radius. It gives us information about the possible maximum deflections measured during different atmospheric conditions. The method of measurement in this approach should be simple, accurate and fast to observe dynamic changes.

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WYZNACZENIE PRZEMIESZCZEŃ OBIEKTÓW WYSMUKŁYCH

Streszczenie. W artykule autorzy przedstawili badania dotyczące wyznaczania dobowych wychyleń obiektów wysmukłych zrealizowanych na przykładzie zmian położenia słupa energetycznego. Wielkości wychyleń dynamicznych odnieśli do pomierzonych w czasie trwania pomiarów zmiennych wartości wpływu nasłonecznienia oraz wpływu prędkości i kierunku wiatru. Podjęli też próbę wyznaczenia wychyleń statycznych w celu ich porównania z wielkościami maksymalnymi przedstawionymi w obowiązujących normach prawnych. Do przepisów zawartych w tych normach odnieśli również uzyskane w wyniku pomiarów dokładności określenia punktów kontrolowanych badanego obiektu.
Autorzy doszli do wniosku, że pomiary odkształceń przeprowadzonych w ciężkich warunkach pogodowych dają więcej przydatnych informacji o wytrzymałości obiektu. Badanie jest pierwszym krokiem w ciągu dłuższych pomiarów. Motywacją do napisania tego artykułu jest potrzeba przebudowy linii elektrycznych wysokiego napięcia.

Słowa kluczowe: pomiary deformacji, pomiar bezlustrowy, obiekty wysmukłe, obciążenia termiczne, obciążenia wiatrem

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