

# **MONITORING THE BEHAVIOUR OF VERY TALL STRUCTURES UNDER THE ACTION OF NON-UNIFORM SUNLIGHT. THE CASE OF A 350 M HIGH CHIMNEystack FROM BAIJA MARE, ROMANIA**

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**Abstract:** The upper part of very tall structures has a diurnal movement due to the action of non-uniform sunlight on the building wall. Analysing this movement throughout a day, it can be seen that, in all the cases for the buildings from Europe, the top of the structure is situated at 0 hour in a north-east position with respect to the vertical axis in quiescent condition, and then it goes together with its upper part through an elliptical movement through the 24 hours of the day, but it will not reach the same position at 0 hour of the next day. This paper analyses certain topographic methods that allow registering this movement throughout a day, presenting comparative results. The measurements on a real structure were performed on the highest building from Romania, the 350 m chimneystack from Baia Mare. The results were centralized and compared, and in the end, the complete route throughout a day of the upper third of the structure was established by extrapolation, adding the data concerning the behaviour of the real model to a database, extremely useful for the designers of such structures.

## **1. Introduction**

An important problem in the execution process of tall structures is ensuring verticality, taking into account that their height extends on hundreds of meters. During the execution of tall structures, the disturbing factors – wind, sunlight, non-uniform warming of the structure walls – have an important role in designing on the vertical. The analysis of the influence of these factors raises problems in accurately determining the contribution of each factor to the vertical design of the building axis.

## **2. Tall Engineering Buildings**

### **2.1. Structures that Belong to the Category of Tall Buildings**

The most representative building types from the category of tall engineering buildings are: silos, cooling towers, industrial towers, water towers, telecommunication and television towers, chimneystacks, many storied buildings, and mining extraction shafts.

## 2.2. Tall Engineering Buildings Worldwide

Having a strong impact on the architecture or the environment, tall engineering buildings performed worldwide have become important references, defining the places where they were situated. Thus, from among the first 200 tallest buildings in the world, all above 210 m: 101 are situated in North America, representing 50.4%, 83 are situated in Asia, 41.5%, 9 are in Australia, 4.5%, 4 are in Europe, 2%, 2 are in South America, 1%, and 1 is Africa, 0.5%.

## 3. Controlling the Verticality of the Main Axis of the Building, Taking Into Account Disturbing Factors

The geometric axis of tower-like buildings deviates from the local (centre) vertical under the action of environmental factors (wind, non-uniform sunlight), the deviation exceeding sometimes even the design margins of the centre. The design of the centre of the building should ensure the vertical position of the structure in conditions of lacking external excitations, including the influence of the centrifugal force, of the difference between the axis of the local vertical and the normal to the ellipsoid for the latitude of the placement area. There should be computed the deviations determined by the influence of the environment and they should be compensated. In order to analyse the basic laws of deviations and their computational method, the main factors that determine the deviations from the vertical of the axes of towers are considered to be: the horizontal strains at the action of the wind and at the non-uniform warming under the action of sunlight. The parameters of each factor can be classified into the following groups:

1.  $K_C$  parameter, characterized by the physical-mechanical characteristics of materials and constructive characteristics of the given building;
2.  $K_{CE}$  parameter, which characterizes the situation of external conditions;
3.  $K_S$  parameter, which determines the position in space of the given point.

If at the beginning, the coordinates coincide with the central point of the building at the given horizon, then the projection of the deviation of the central point of the building can be presented under the following form:

$$\begin{cases} x_i = f_x(K_c, K_{CE}, K_S) \\ y_i = f_y(K_c, K_{CE}, K_S) \end{cases} \quad (1)$$

A first approximation of the dependency between the parameters  $K_C$ ,  $K_{CE}$ ,  $K_S$ , under the influence of sunlight, shows that one side of the tower gets warmer than the others. The propagation of the temperature on the body of the building is not immediate, but on the sunny side there will be a larger linear dilatation, and the axis of the tower in the upper section will deviate.

## 4. Topographic Technologies Used for the Execution and Exploitation of Tall Buildings, Synthetic Analysis, Precision Improvement Proposals

Along time, starting from the classical plumb-bob wire and ending with laser scanners, there have been developed many methods for tracing, verifying, monitoring and surveying the behaviour of tall buildings, from among which I mention: the methods of the “plumb-bob wire”, “tangents”, “inclined projection”, “perpendiculars”, “fix stations and aims at fix marks”, “optical vertical”, “pendulum installation”, “direct intersection on central circle”, “electro-optical”, total topographic stations, the study of verticality by determining the settlements, V.I.Raikin method used to monitor the Ostankino television tower, photogrammetric

method with recording on a plate or film, using He-Ne lasers, for directing the execution of tall structures, video-graphic method, using laser scanners.

### 5. Spatial Intersection Accomplished Using Two Total Topographic Stations From Two Perpendicular Bases, for Measuring the Declivity of Cone-Like Structures (Chimneystacks), the Case of the Chimneystack From Baia Mare

In what follows, there will be analysed the precision expected as result of using the method of spatial intersection with two total topographic stations, in concrete conditions – with two bases (12 and 34) fixed in the field, thus imposing distances and horizontal angles (figure 1).

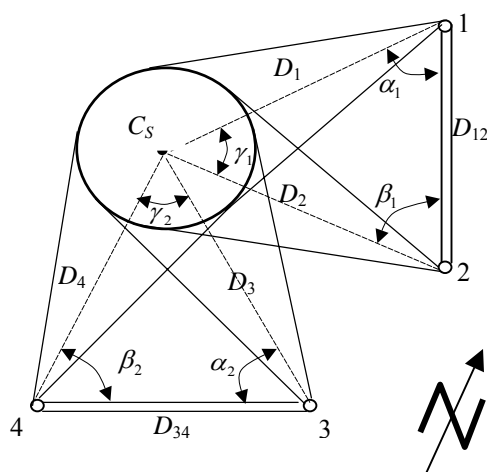


Figure 1: The Position of Devices With Respect to the Studied Structure, Horizontal Elements

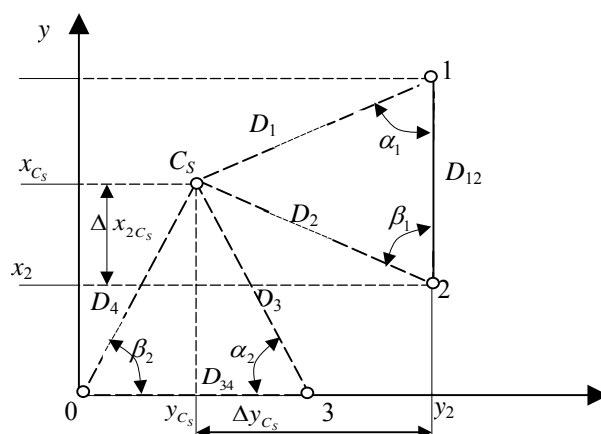


Figure 2: The Computation of the Coordinates of the Structure Axis From the Measurement Bases

$$\Delta X_{2C_s} = D_2 \cos \beta_1 = \frac{D_{12} \sin \alpha_1 \cos \beta_1}{\sin(\alpha_1 + \beta_1)} \quad (2)$$

$$\Delta Y_{2C_s} = D_2 \sin \beta_1 = \frac{D_{12} \sin \alpha_1 \sin \beta_1}{\sin(\alpha_1 + \beta_1)} \quad (3)$$

$$X'_{C_s} = X_2 + \Delta X_{2C_s} \quad (4)$$

$$Y'_{C_s} = Y_2 + \Delta Y_{2C_s} \quad (5)$$

Computing the coordinates of the centre  $C_s$  in the chosen system, the following relations are obtained:

$$\Delta X_{1C_s} = D_1 \cos \alpha_1 = \frac{D_{12} \cos \alpha_1 \cos \beta_1}{\sin(\alpha_1 + \beta_1)} \quad (6)$$

$$\Delta Y_{1C_s} = D_1 \sin \alpha_1 = \frac{D_{12} \cos \alpha_1 \sin \beta_1}{\sin(\alpha_1 + \beta_1)} \quad (7)$$

respectively:

$$X''_{C_s} = X_1 - \Delta X_{1C_s} \quad (8)$$

$$Y''_{C_s} = Y_1 - \Delta Y_{1C_s} \quad (9)$$

The measurements being compatible, the most likely values of the coordinates of the  $C_s$  axis can be obtained by computing the mean of the two values obtained on  $X$ , and  $Y$ , respectively. The measured elements are the angles  $\alpha_1, \beta_1$  and the distance  $D_{12}$ , therefore the precision of determining the coordinates of the  $C_s$  axis will depend on the precision of measuring these values. Taking into consideration that:

$$X_{C_s} = f_1(D_{12}, \alpha_1, \beta_1) \quad (10)$$

$$Y_{C_s} = f_2(D_{12}, \alpha_1, \beta_1) \quad (11)$$

and differentiating, we obtain:

$$dX_{C_s} = \frac{\partial f_1}{\partial D_{12}} dD_{12} + \frac{\partial f_1}{\partial \alpha_1} d\alpha_1 + \frac{\partial f_1}{\partial \beta_1} d\beta_1 \quad (12)$$

$$dY_{C_s} = \frac{\partial f_2}{\partial D_{12}} dD_{12} + \frac{\partial f_2}{\partial \alpha_1} d\alpha_1 + \frac{\partial f_2}{\partial \beta_1} d\beta_1 \quad (13)$$

Continuing processing the relations and taking into consideration that:

$$A = \left[ \frac{\sin \alpha_1 \cos \beta_1}{\sin(\alpha_1 + \beta_1)} \right]^2 \quad (14)$$

$$B = \left\{ \sin^2 \alpha_1 [\sin \beta_1 \sin(\alpha_1 + \beta_1) + \cos \beta_1 (\cos \alpha_1 \cos \beta_1 - \sin \alpha_1 \sin \beta_1)]^2 + \right. \\ \left. + \cos^2 \beta_1 [\cos \alpha_1 \sin(\alpha_1 + \beta_1) - \sin \alpha_1 (\cos \alpha_1 \cos \beta_1 - \sin \alpha_1 \sin \beta_1)]^2 \right\} \cdot \\ \cdot \frac{1}{\sin^4(\alpha_1 + \beta_1)} \quad (15)$$

$$C = \left[ \frac{\sin \alpha_1 \sin \beta_1}{\sin(\alpha_1 + \beta_1)} \right]^2 \quad (16)$$

$$D = \left\{ \sin^2 \alpha_1 [\cos \beta_1 \sin(\alpha_1 + \beta_1) - \sin \beta_1 (\cos \alpha_1 \cos \beta_1 - \sin \alpha_1 \sin \beta_1)]^2 + \right. \\ \left. + \sin^2 \beta_1 [\cos \alpha_1 \sin(\alpha_1 + \beta_1) - \sin \alpha_1 (\cos \alpha_1 \cos \beta_1 - \sin \alpha_1 \sin \beta_1)]^2 \right\} \cdot \\ \cdot \frac{1}{\sin^4(\alpha_1 + \beta_1)} \quad (17)$$

and  $m_{\alpha\beta} \cong m_\alpha \cong m_\beta$ , it results that the mean square errors of the computed elements can be:

$$m_X = C m_{D_{12}}^2 + D \left[ \frac{D_{12} m_{\alpha\beta}}{\rho} \right]^2 \quad (18)$$

$$m_Y = Am_{D_{12}}^2 + B \left[ \frac{D_{12} m_{\alpha\beta}}{\rho} \right]^2 \quad (19)$$

The total mean square error of the position of the section of the measured axis will be:

$$m_{C_s} = \sqrt{m_X^2 + m_Y^2} \quad (20)$$

In order to assess the precision of the results of recording the vertical deviation of the top of a tall structure, the mean square errors of the components of the partial declivity vector are computed, using the formula of the error of a function, resulting the following expressions:

$$m_{\delta x_i}^2 = \delta x_i^2 \left( \frac{m_b}{b} \right)^2 + (\delta x_i \operatorname{ctg} \gamma + L_1 \delta \beta_i)^2 \left( \frac{m_\alpha}{\rho} \right)^2 + (\delta x_i \operatorname{ctg} \gamma + K_1 \delta \alpha_i)^2 \left( \frac{m_\beta}{\rho} \right)^2 + K_2^2 m_{\delta \alpha_i}^2 + L_2^2 m_{m_{\delta \beta_i}}^2 \quad (21)$$

$$m_{\delta y_i}^2 = \delta y_i^2 \left( \frac{m_b}{b} \right)^2 + \left[ \delta y_i \operatorname{ctg} \gamma + \left( \frac{G}{2} - L_2 \right) \delta \beta_i \right]^2 \left( \frac{m_\alpha}{\rho} \right)^2 + \left[ \delta y_i \operatorname{ctg} \gamma - \left( \frac{G}{2} - K_2 \right) \delta \alpha_i \right]^2 \left( \frac{m_\beta}{\rho} \right)^2 + K_1^2 m_{\delta \alpha_i}^2 + L_1^2 m_{\delta \beta_i}^2 \quad (22)$$

where:  $m_b$  – is the mean square error of measuring the fix base;  $m_\alpha$  and  $m_\beta$  – are the mean square errors of the horizontal angle differences and are expressed by the formulas:

$$m_{\delta \alpha_i} = \sqrt{m_{\alpha_{i+1}}^2 + m_{\alpha_i}^2}, \quad m_{\delta \beta_i} = \sqrt{m_{\beta_{i+1}}^2 + m_{\beta_i}^2} \quad (23)$$

In both cases a mathematical point is assumed to be aimed, on the side exposed towards the measuring base, which is possible only if these marks have been planted during the execution process, taking into account the position of the measuring bases with respect to the structure. In reality, the measurements are performed using tangent aims to the envelop of the structure, and the confidence degree concerning the results of plan deviation is unquestionably greater in the case of emphasizing the deviations on a direction parallel to the measuring base, if the base 12 is parallel to the NS direction, and the base 34 is parallel to the WE direction, the deviations on these directions will be considered only in the value determined from the two bases. Therefore using two perpendicular bases is appropriate, and not only two points placed on perpendicular directions.

## 6. The Analysis of the Environment in which the Structure is Performed

The choice of methods and instruments for studying the verticality of tall structures assumes a good understanding of the environmental factors from the placement area and its surroundings, all monitoring actions of these buildings beginning with the analysis of the wind distribution and the temperature evolution in the area. Based on the values recorded by the meteorological stations from Dura hill, Baia Mare and the one belonging to the Environment Protection Agency from Maramures, it can be seen that: the climate of the studied region is a cool summer continental climate and the relief is characterised mainly by depressions (Baia Mare depression). The average annual temperature of the air slightly

exceeds 9°C. The real distribution of the temperature on vertical is necessary, characterised by the temperature gradient of the environment. **The height inversion** is produced at some height from the surface of the ground, in the studied case, at around 300 m. Until 300 m the temperature decreases with height. In the inversion layer (300-400 m) the temperature increases with height, and above this layer, the temperature again decreases with the height. The inversion layer stops vertical movements, acting as a barrier.

The stability of the atmosphere in the first few hundred meters suffers a quite pronounced diurnal variation, stable conditions alternating instable ones, depending on the hour. Temperature recording during measurements was performed using electronic thermometers, the sensors of the device being placed during measurements at about 2 meters above the ground, in the four cardinal points.

## 7. Programs for Interpreting Results

The following programs have been used:

1. **TABLECURVE**, which the equations of the movement lines of the top of the structure can be defined by, in the mentioned period.
2. **MATHCAD PROFESSIONAL 2000**, which the daily, mean, maximal and minimal trajectories are computed and traced with, parsed from the centre of the top of the chimneystack, also deducing the course, from the not measured period, limited by lack of visibility.

Both software programs are based on the principle of the method of least square approximation of the functions by regression curves, beginning with a range of results of some measurements performed on the same study objective.

For the studied case, formed of data recorded in ten consecutive days in June 2003, 11 daily measurements have been performed, between 7 and 21 hours, as follows: RECORDING no.1 ... 7 o'clock, no.2 ... 8 o'clock, nr.3 ... 9 o'clock, nr.4 ... 12 o'clock, nr.5 ... 13 o'clock, nr.6 ... 14 o'clock, nr.7 ... 15 o'clock, nr.8 ... 16 o'clock, nr.9 ... 17 o'clock, nr.10 ... 20 o'clock, nr.11 ... 21 o'clock.

$$\min(X) = -132.7 \quad \max(X) = 146 \quad \min(Y) = -214.1 \quad \max(Y) = -16.9$$

### Trajectoriile varfului cosului pentru 10 zile de masi

N:=11    i:=1..N

X1:=	Y1:=	X2:=	Y2:=	X3:=	Y3:=	X4:=	Y4:=	X5:=	Y5:=
-135	-41	-140	-43	-127	-39	-141	-42	-136	-54
-108	-46	-111	-48	-110	-45	-117	-53	-112	-48
-92	-84	-96	-87	-87	-82	-92	-78	-96	-77
-48	-173	-51	-175	-32	-171	-37	-181	-29	-164
-14	-201	-16	-203	-16	-194	-30	-204	-24	-202
-9	-222	-12	-225	-8	-217	-12	-224	-14	-216
13	-200	11	-201	12	-198	16	-187	10	-188
40	-186	38	-188	37	-184	42	-173	46	-168
64	-140	61	-146	62	-138	68	-126	66	-112
154	-48	151	-51	151	-46	143	-36	136	-29
139	-23	141	-25	138	-21	112	-14	110	-12

X6:=	Y6:=	X7:=	Y7:=	X8:=	Y8:=	X9:=	Y9:=	X10:=	Y10:=
-132	-47	-129	-43	-131	-46	-129	-43	-127	-39
-108	-46	-116	-42	-112	-46	-102	-41	-99	-36
-96	-78	-98	-77	-100	-68	-87	-86	-85	-78
-27	-173	-29	-181	-36	-178	-46	-186	-45	-169
-22	-194	-20	-188	-20	-170	-11	-201	-9	-194
-14	-212	-14	-200	-10	-191	-7	-223	-5	-211
8	-191	12	-188	11	-178	12	-198	11	-187
41	-178	38	-164	36	-162	36	-186	32	-175
68	-118	63	-114	58	-110	61	-145	58	-131
141	-24	143	-22	147	-26	151	-48	143	-41
114	-14	116	-12	116	-8	137	-23	131	-17

$$X_i := \frac{(X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8 + X_9 + X_{10})}{10}$$

$$Y_i := \frac{(Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 + Y_8 + Y_9 + Y_{10})}{10}$$

X <sup>T</sup>	1	2	3	4	5	6	7	8	9	10	11
1	-132.7	-109.5	-92.9	-38	-18.2	-10.5	11.6	38.6	62.9	146	125.4
Y <sup>T</sup>	1	2	3	4	5	6	7	8	9	10	11
1	-43.7	-45.1	-79.5	-175.1	-195.1	-214.1	-191.6	-176.4	-128	-37.1	-16.9

Figure 3: The Trajectory of the Top of the Monitored Structure for Ten Days of Measurement

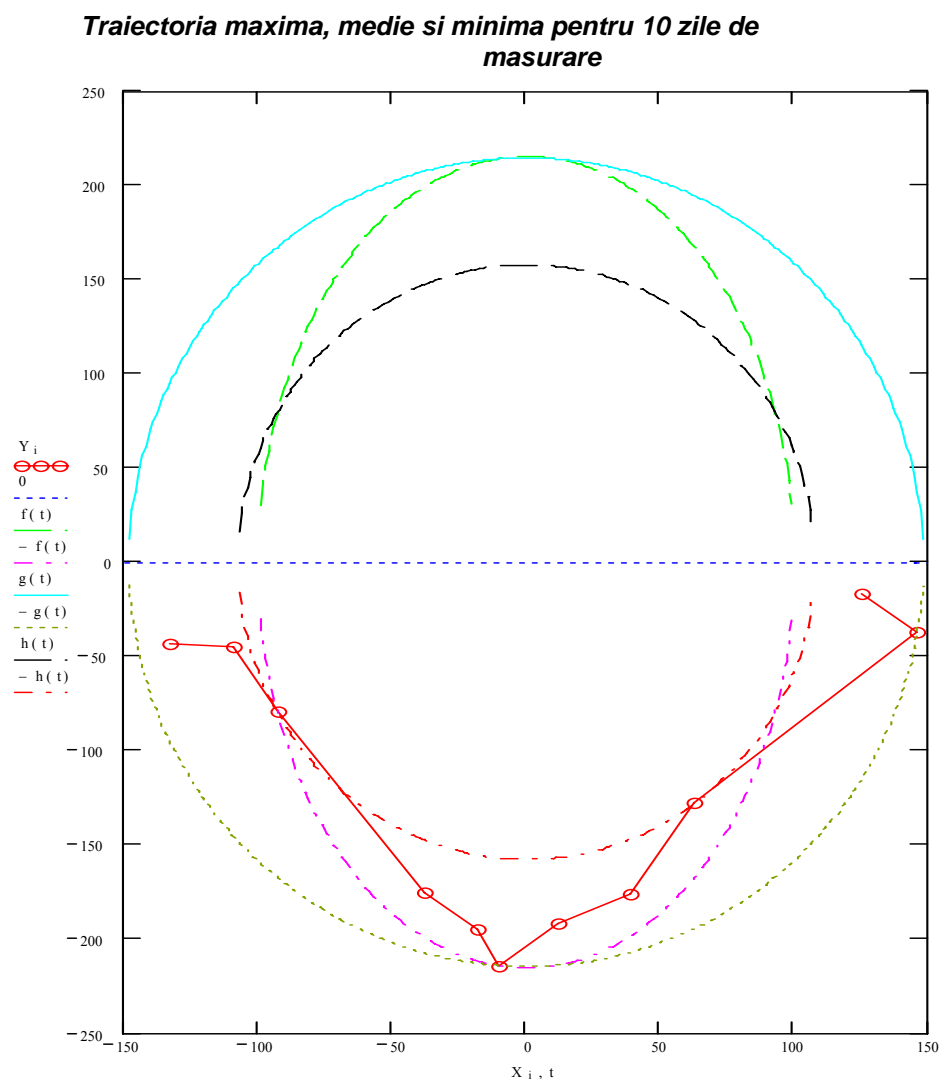


Figure 4: The Maximal, Minimal and Mean Trajectories for Ten Days of Measurement

## 8. The Variation of the Vertical Axis of Buildings – High Column at Non-Uniform Sun Warming

The buildings – the closed section column (cylindrical or conical) suffer a parabolic deviation of the central vertical axis, at unilateral warming by solar exposure. Repeated measurements on some various height buildings (chimneystacks and antenna-towers), correlated with the existing data, have shown that the angular deviation rarely exceeds  $0.2^\circ$  in the case of chimneystacks and  $0.4^\circ$  in the case of antennas.

### 8.1. Measurement Results

Evolving throughout a day on an ellipse, whose axis can reach the maximal values of 28 cm (WE) and 18 cm (NS), respectively (figure 5), the positions taken by the top of the structure on different days at the same hour correspond also to some ellipses, with the long axis parallel to the common tangent of the two ellipses.



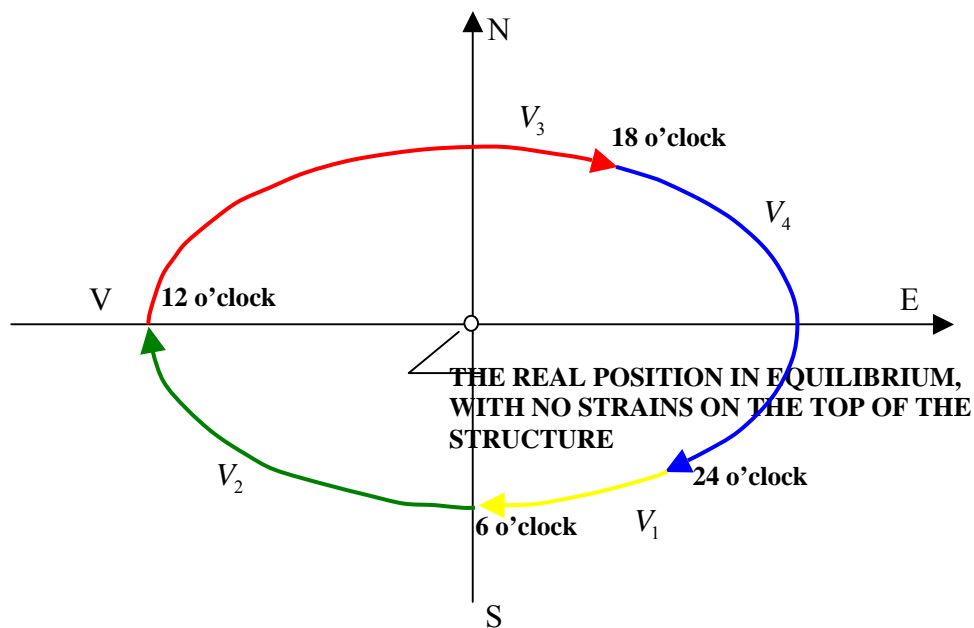


Figure 5: The Variation of the Displacement Speed of the Top of the Building. The Mean Displacement Speed of the Centre of the Top of the Structure Is:  $V_1=33\text{mm/h}$ ;  $V_2=67\text{mm/h}$ ;  $V_3=85\text{mm/h}$ ;  $V_4=68\text{mm/h}$

## 8.2. The Comparative Study of Variations Determined by Non-Uniform Sunlight for Various Tall Buildings

Analysing the deviations of the vertical axis determined by solar radiation, throughout one-two days, for many television towers and chimneystacks, it can be seen that though they were recorded using different means, on different dates, in different conditions and geographic regions (but all buildings are situated in the N-NE of Europe), the data presents common characteristics that allow establishing some rules and variation limits.

Therefore:

- The size of the deviation of the real longitudinal axis of a reinforced concrete tower, with circular section and large height, is proportional to the temperature difference between the tower wall on the sunny side and the wall on opposite side,
- The maximal values are recorded between 8-12 o'clock, that is in the morning, when the warming of the structure side exposed to sunlight is produced,
- There can be determined some correlations between the size of deviations (cm) and the solar radiation ( $\text{kJ/cm}^2$ ) – but these are valid only for atmospheric temperatures with close values,
- The declivity angle of the vertical axis with respect to solar exposure can have significant influences, the deviation having maximal values for a perpendicular exposure,
- The speed of reaction of the structure to such strain depends on the size of the transversal section, and on the slimness of the building, respectively,
- It is considered that at large altitudes (or in mountain regions) there take place larger deformations of the structure than at small altitudes (or in hill-plain regions),

- The clouds change the magnitude of deviations, but they less influence the characteristics of the deviation curve,
- Reporting the displacement to the WE-NS directions that pass through the vertical axis of the tower base, it can be seen that in all the recorded situations, the ellipse is parsed in the interval 0<sup>h</sup> - 24<sup>h</sup> on the following trajectory: **SE - S - SW - W - WN - N - NE - E – SE**,
- Denoting with  $V_1$  the displacement speed in the interval 0-6, with  $V_2$  that in the interval 6-12,  $V_3$  in 12-18, and  $V_4$  in 18-24, it can be said that  $V_3 > V_4 > V_2 > V_1$ . This statement can be explained as follows: at sunrise, the temperature of the tower wall is approximately the same on the entire circumference; after some warming of the exposed wall of the tower, a sudden increase of the displacement speed takes place ( $V_2 \rightarrow V_3$ ),
- The subsequent warming of the tower determines the warming of the air in the area of the structure and therefore the temperature of the shadowed wall increases, the temperature difference decreases and therefore the speed decreases, too ( $V_3 \rightarrow V_4$ ),
- In the evening, the air gets cooler, the exposure becomes almost perpendicular, the temperature difference increases (but less than during the morning hours), and therefore the speed increases ( $V_4$ ),
- During the night, because of the decrease of temperature of the surrounding air, the temperature difference and obviously the speed ( $V_1$ ) will tend towards minimal values, which will gradually increase with sunrise ( $V_1 \rightarrow V_2$ ).

In closing we can notice that cold or warm wind can change both the amplitude and the characteristics of the deviation curve. During night, especially a cold wind, which operates on one side of the tower wall, can determine deviations because of the temperature difference in the building section. Because of that, measurements that aim the behaviour of structures at temperature differences are performed simultaneously with studies concerning the action of the wind, or at least, the characteristics of wind are recorded during the entire measurement period.

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