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Technical note

A COMPARISON OF THE WIND SPECTRUM ACCORDING TO DIFFERENT METHODS - AN ORIGINAL PROJECT OF A BUILDING ON A CLIFF IN GDYNIA

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The article presents numerical simulations of the dynamic wind loads on the structure of a building designed on a cliff in Gdynia. The results obtained from the two methods: Davenport's and Karman's are compared. The results allowed a comparison of the two methods, and they provided an answer to the question how a construction, designed in such an unusual condition of a cliff behaves under the influence of the gusting wind. The wind spectrum is presented and compared in both directions: of the *X*-axis and of the *Y*-axis. The dynamic calculations are carried out in the Abaqus software. The conducted numerical analyses compare the displacements in two points - at half height of the building and at the top - obtained by the two methods.

Key words: wind spectrum, Davenport, Karman, cliff, dynamic analysis, modal analysis, FEM.

1. Introduction

Completing detailed schemes of a wind load of a building is very complex, for it is dependent on a large number of factors, such as: the geographical location, the climate, the basic wind speed, the height of the building, the shape of the object, the building's exposure in the area, the gusts of the wind, the dynamic characteristics of the building, and the materials used in the construction process. Hence, the influence of the wind on the building requires familiarizing and analyzing the physical phenomenon of the wind, as well as determining a number of characteristics and properties of its influence in order to evaluate the effect the wind has on the obstacle on its way of movement, which is the building. In general, the wind may be defined as a random movement of air masses over the ground. The wind under the influence of its own force and speed exerts a pressure on the individual elements of the construction and generates forces perpendicular to the construction. What is more, large friction forces that act tangentially to the surface are created. Due to the turbulence, the wind speed and direction are constantly changing. It is the so-called gusty wind, that is the chaotic changes of the molecules' movement speed falling within its structure. Modeling of the loads resulting from the fluctuation of the wind causes difficulties and might be complicated, as regards the same methodology of calculation. Furthermore, the process of modeling the spectrum of the wind requires determining a number of parameters and the initial boundary conditions at the precalculation stage. There are many methods that allow the determination of the dynamic interaction caused by the turbulence of the wind. The methods by Davenport and Karman may be perceived as the basic ones.

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2. Cliff in Gdynia

Gdynia is one of the most important cities in northern Poland. Located on the shore of the Gdańsk Bay, it is a part of conurbation along with the city of Sopot and Gdańsk. Among them, this is the youngest, yet the most high-tech city in the Pomeranian Province. Gdynia was built in the Interwar period, during first years of long-awaited country's independence. The city was built following a new architectural ideology – modernism which has significantly left its mark in shaping the doctrines and ideas of both architectural and urban designs. Modernism was a great contribution toward industrial design, which can be stated one of the reasons why Gdynia was constructed in such a style. It has always been one of the most important seaports in the country and the presence of the industrial sector contributed to the development of modernism in the area. The unique architecture of Gdynia can be mostly found within shipyard, downtown and residential districts like St. Maximilian's Hill.

The downtown area was constructed in a very short period of the Thirties and was considered the Polish "window to the world'' as part of both political and economic strategy for the country. Many young architects, urban planners or interior designers came to the city to build modern buildings with a unique avant-garde style, which can be recognised as ''white architecture''. Cubic shapes, marine theme and streamlined frontages helped Gdynia to became the most modern city of that time. Nowadays, Gdynia is the city of young entrepreneurs, designers, artists and engineers. Putting emphasis on the development of technology, it has become one of the most important centres of start-ups and fast-growing businesses.
Gdynia at the beginning of the Thirties was one of the fast-growing port towns in Europe, yet south of there, in Orłowo district many leisure attractions emerged. Orłowo was once a small, seaside fishing village, and later, holiday summer resort, located on land belonging to Kolibki (today housing apartments in Orłowo). The settlement received municipal rights in 1931. Attractive walking areas for holidaymakers, beach and seaside climate, have become major attractions in Orłowo. Architecture in Orłowo is stylistically connected with Gdynia. Although building density is lower, yet the last few years brought to the district a growing number of residential investments. Luxurious apartments are highly desired in this region, mostly because of a good connection with the rest of the Tri-City and developed facilities in the area.

Fig.1. Panoramic view of the Orłowo cliff taken from the pier.

The Orłowo Cliff is a steep, distinctive seashore located on the border of two districts - Redłowo and Orłowo (Fig.1). The Cliff belongs to the Kępa Redłowska reserve park, albeit irregularly and gradually releases its part to the sea. The cliff is shrinking and lowering its height approximately a few centimetres per year. The Cliff extends over to a length of 650 meters. The slopes are covered by a diverse protected species. The Cliff extends picturesque walking routes leading towards the centre of Gdynia. The first is the coastal route, along the beach. The second is the upper forest route – a stroll among the greenery and trees, where nature can be marvelled. From the highest top of the slope, a beautiful panorama of the Hel Peninsula and the Port of Gdynia can be admired. The Cliff due to the heavy leaching caused by the Baltic Sea makes it difficult for the foundation of any architectural structures to stand on the ground.

3. Description of the designed building

The site of the designed building is located on the upper shelf of the Orłowo Cliff in Gdynia (Figs 2, 3). Inspired by the local modernist architecture and proximity to the sea, the house has a two-storey, rectangular form, where the front facade is heading toward Kępa Redłowska forest, and the opposite wall is glazed, giving a panoramic view of the Baltic Sea. Access to the building is through a forest path, which is an extension of the road to the Rehab House. The first floor is situated at the height of 38 meters above the sea level and the second floor is lowered by almost 4 meters.

Fig.2. Visualization of the designed building.

The Cliff has harsh conditions for the foundation of the building. Erosion is affected by rain, which for the cliff is more dangerous than storms and crashing waves on the edge. Cliff walls consist mostly of clay which is impervious to rainwater. This makes land to be simply flushed, creating furrows which further weaken the ground. To prevent the building from being washed and falling with the cliff to the sea, it is necessary to design a strong foundation that will hold the structure in place. For building maintenance, the best solution is to provide eight concrete piles to be drilled into cliff's soil at an angle of 45 degrees. Concrete piles should be about fifteen meters in length and be resistant to water activity. Building construction is made as reinforced concrete walls and columns. Because the house is long and narrow interior spaces can be easily changed so it does not affect the structure.

Elution of bed is not the only threat to the building. One of the strong interactions on the building can be wind blowing from the Baltic Sea. The greatest wind speeds occur in Gdynia from November to March, also accompanied by storms and big waves . In spring and summer, winds from the west are prevailing, also marked by a part of north-eastern and eastern winds.

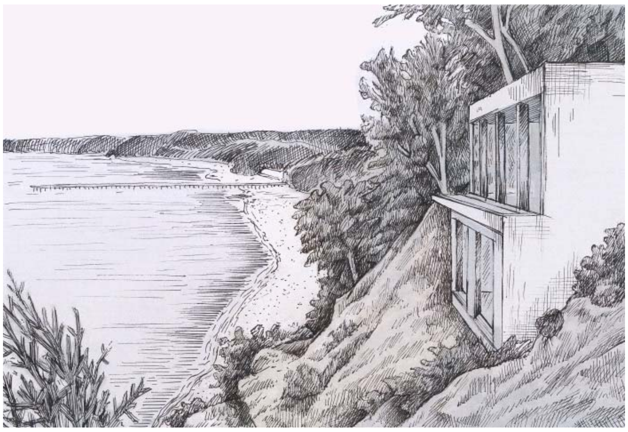


Fig.3. Visualization of the designed building.

4. Spectrum of the wind - methods of Davenport and Karman

The wind emerges as a result of an uneven heating of the earth's surface. Its speed is dependent inter alia on the latitude and the arrangement of water and land. Air masses flow from places with higher pressure to places where the pressure is low. When calculating the influence of the wind on a civil structure, only the direction parallel to the earth's surface is taken into consideration. The influence in the vertical direction is in fact ten times smaller.

Gustiness is a characteristic feature of the wind. This phenomenon involves the occurrence of the chaotic whirls resulting from the speed and the direction of the air particles changes. Because of the obstacles, such as buildings, trees, hills, the air masses are being broken into smaller parts, the so-called turbulent elements. They are characterized by the differentiated values of the momentum's influence, and energy. During their activity, the phenomenon of preserving the individual features is observed, however in certain points in space they change their direction and speed. On the basis of observations, it may be noted that the wind speed is a random vector field. At each point in the field, the instantaneous velocity of the turbulent motion $U(t)$ can be described by using two components: the velocity of the steady flow U and the temporary fluctuation $u(t)$. The velocity of the steady flow is subjected to slow changes, whereas the fluctuations are characterized by the pulsing movement and they constitute a function of time and space along the three axes in the rectangular coordinate system. Fluctuations, otherwise known as turbulence, are described by the Gaussian function with zero mean value. The main feature of the process is the spectral density, defined in the frequency domain, called the spectrum of the wind. It is a dimensionless value that describes the frequency of the wind dispersion with U speed. The basic form of the spectrum is shown in Fig.1 (Żurańska and Gaczek ,2011, Biegus, 2010) The first phase, the so-called production range, consists of the whirls' formation through the movement between the slow airflow and the still air settled by the ground. The second phase of the spectrum is the energy dispersion resulting from the large shear forces arising. Between them, the energy is constantly being transferred from large to smaller whirls, due to their division into smaller volumes. This cascade phase is known as the inertial subrange. For most structures, the values of the spectrum in this phase are the most important. Uematsu and Yamada (1995), Fu *et al*. (2012) The general formula for the distribution of the component's frequency along the speed of the wind can be estimated as follows

$$R_Z(z,n) = nS_u(z,n) \big/ \sigma^2{}_u(z)$$

where:
n – frequency [Hz],
$S_u(z, n)$ – spectral density along the turbulent movement.

The wind influence on the buildings is an extremely complex issue. One of the assumptions that needs to be taken into consideration in determining the influence is the averaging time of the wind speeds. For it should be long enough in comparison to the time scale of the turbulence, and short enough in respect to the slow speed changes that are not considered as the changes resulting from the turbulence of flow. Worldwide, it is assumed that the averaging time should be between 10 minutes to up to 2 hours. In Poland, according to the World Meteorological Organization the averaging time of the wind speed is assumed to be 10 minutes. Biegus (2010)

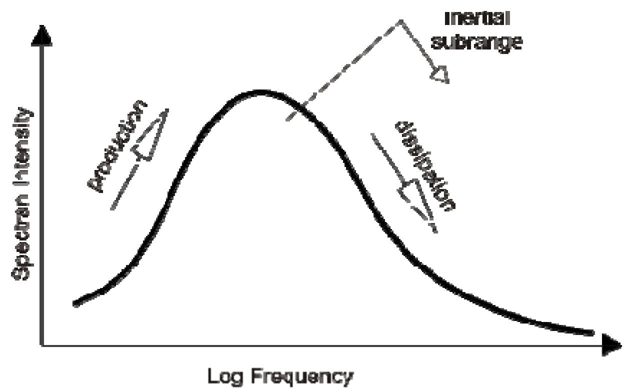

Fig.4. The diagram of the turbulent motion.

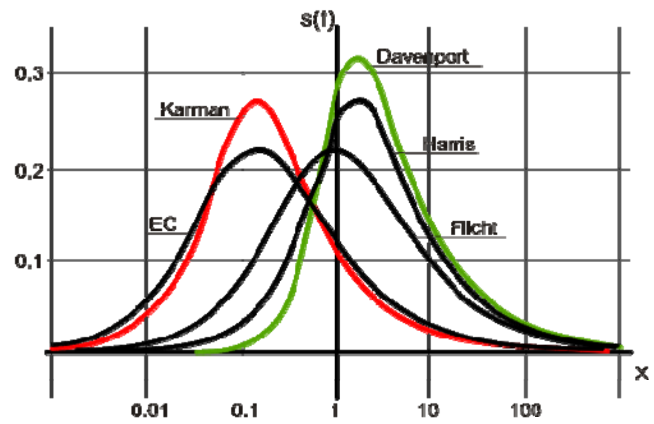

Fig.5. The comparison of the spectrum of wind according to different methods.

The functions of the wind spectrum are approximately described by the empirical formulas based on the analysis of results. In order to determine the spectrum of the wind, numerous methods, such as Karman's (1948), Davenport's (1967), Harris' (1968), Panovski's (1964), Flicht's (1970), Kaimal's (1972), Simiu's (1974.1975) ESDU's (1976, 1985), Naito's (1978, 1983), Kareem's (1985), Solari's (1987.1993) methods may be used. On the basis of the two of them - methods elaborated by Davenport and Karman - a comparative analysis of the wind influence on the building situated on a cliff in Gdynia was made. In Fig.2 the methods of Davenport and Karman in comparison with other exemplary methods of determining the wind spectrum along the frequency axis are presented. The maximum deviation in the methods of Davenport, Harris and Flicht in combination with the method of Karman is caused by the difference of the scale (Davenport, 1961, Simiu, 1974).

One of the basic models of the wind influence on structures is the method worked out by Davenport. It involves the coupling of 5 factors affecting the value of the wind influence. Among them one can distinguish the climatic and terrain conditions, the aerodynamic and mechanical response, as well as the design criteria (Fig.1). According to Davenport's assumptions, the design value of the wind load may be determined from Eq.(4.1)(Żurański, 1978), Żurański and Gaczek ,2011, Biegus, 2010).

$$w = q_k \, x \, C_{exp} \, x \, C_p \, x \, C_{dyn} \, x \, \gamma_f \tag{4.1}$$

where

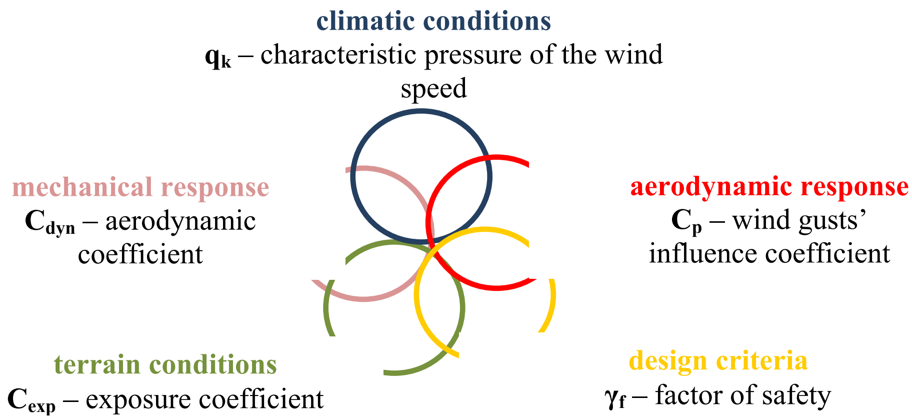

Fig.6. The factors of the wind influence on the structure according to Davenport's method.

Davenport's spectrum is the powe spectral density, that does not depend on the height. Creating a wind history for this method consists of two stages. The first stage is the production of the energy spectrum of all components of the turbulence in all nodal points of the structure. The second stage is preparing a separate history of the wind through Fourier- retransformation (Uematsu and Yamada ,1995, Fu *et al.*, 2012) According to Davenport's method, the spectral density function along the frequency axis can expressed with the formula

$$R_Z(z,n) = 2 f_L{}^2 \Big/ 3\left(1 + f_L{}^2\right)^{4/3} .$$

This function is based on the expression

$$f_L = \frac{nL}{U(z)}, \qquad \text{where} \qquad L \approx 1200m.$$

According to Karman's theory the spectrum of the wind along the frequency axis can be described according to the formula

$$R_Z(z,n) = 4 f_L \Big/ \left(1 + 70.8 f_L{}^2\right)^{5/6}$$

or

$$\frac{f \cdot S}{\sigma^2} = \frac{a_1 \cdot X \cdot a_2 \cdot X^2 \cdot a_3 \cdot X^3}{\left(1 + b_1 + X + b_2 + X^2\right)},$$

$$X = \frac{f}{f_0} = \frac{f \cdot L}{V}$$

where:
L- the effective wavelength dependent on the wind profile,
f_0 – the effective frequency of the turbulence.

The shape of the wind spectrum according to Karman's method differs depending on the direction. There are six coefficients $a_1, a_2, a_3, b_1, b_2, c$ defined by three components. In the literature other deviations that need to be considered depending on the type of the wind spectrum can be found. The most important ones are provided in the table and can be directly used for the purpose of the analysis.

Method	a_1	a_2	a_3	b_1	b_2	c
Karman – Longitudinal	*4.000*	*0.0*	*0.0*	*0.0*	*70.8*	*0.8333*
Karman - lateral	*4.000*	*0.0*	*3021*	*0.0*	*283.0*	*1.8333*
Davenport*	*0.0*	*0.6667*	*0.0*	*0.0*	*1.0*	*1.3333*

* $f_0 = V(10)/1200$

The coefficients for the longitudinal or lateral direction in Karman's method were determined empirically. Davenport's method is a simplification with a small deviation in relation to Karman's method. Nevertheless, it is widespread in Europe. Despite the fact that the shape of Davenport's method has been changing over the years, it is still used in its initial version.

5. Numerical analysis of the wind spectrum influence on the object located on the cliff

The designed building is located on the cliff in Gdynia Orłowo. According to the norm, it is situated in the wind load zone II. The basic wind speed in this zone is equal to *26*[*m/s*] what corresponds to the speed pressure equal $0.42 kN/m^2$. Increasing the speed at the coastline results from implementing the appropriate terrain category. In the case of the 0 category terrain (open sea) along with the orography coefficient, the wind speed is equal to *38m/s* was obtained. The height of the object is equal to *12m*. The climatic and terrain conditions, the influence of the wind gusts, the drag coefficient and other data necessary to perform the analysis were selected according to the actual parameters of the designed object. Eurocode 1

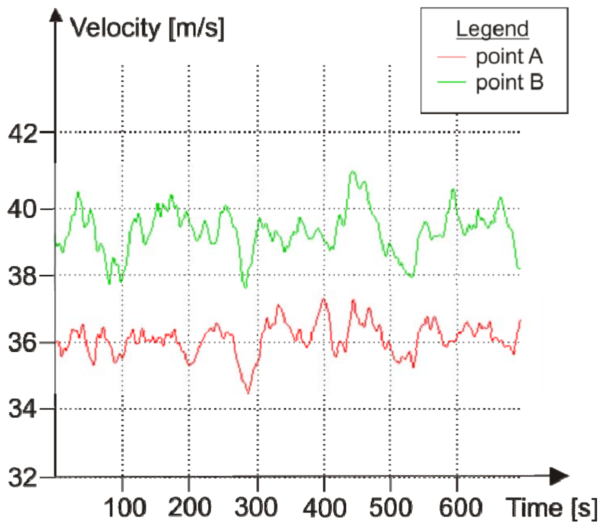

Fig.7. The graph of the wind spectrum history in the *Y* direction according to Davenport's method.

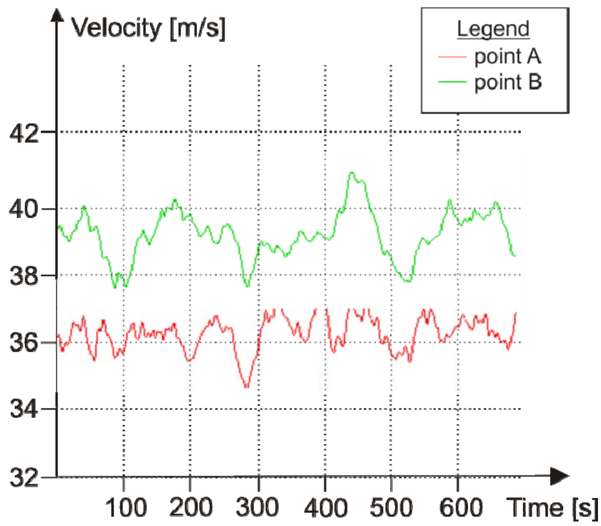

Fig.8. The graph of the wind spectrum history in the *Y* direction according to Karman's method.

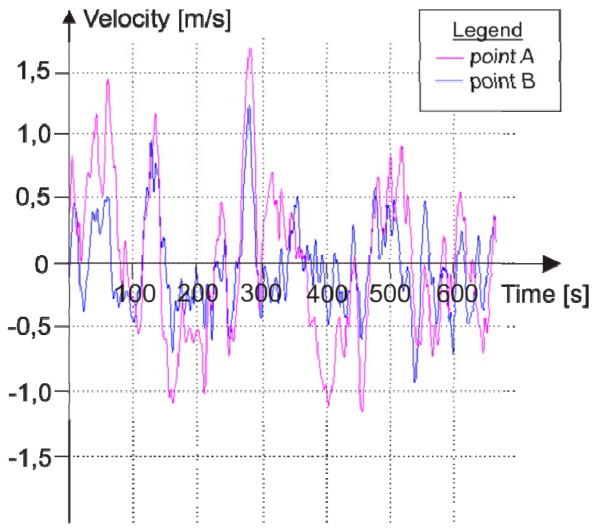

Fig.9. The graph of the wind spectrum history in the *X* direction according to Davenport's method.

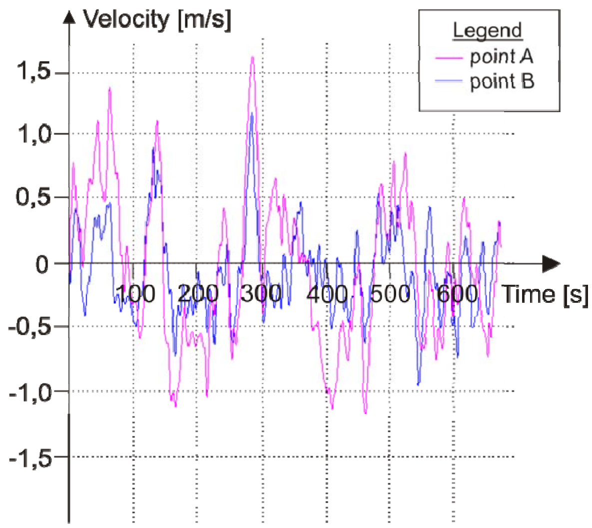

Fig.10. The graph of the wind spectrum history in the *X* direction according to Karman's method.

The dynamic calculations were carried out in the Abaqus software. The numerical model was made of the solid elements C3D8R and coating elements S4R. The numerical simulations were carried out according to the two methods of the wind activity: the method of Davenport and of Karman. The object's construction designed on the cliff in Gdynia was subjected to the wind activity for a period of 10 minutes. The graphs 4-7 show the influence of the spectrum of wind on the basis of the two methods. For the purpose of the analysis two points were selected, point A - at half height of the building (*6m*) and point B - at the top (*12m*). The wind spectrum was presented in both directions: of the *X*-axis and of the *Y*-axis. The influence of the wind along the *X*-axis has had a negligible impact on an object what can be observed by comparing the wind spectrum history, hence this direction was omitted in the numerical simulations.

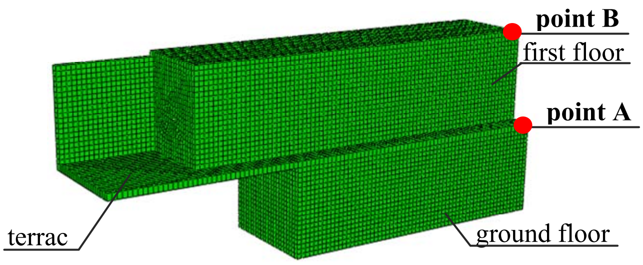

Fig.11. Model of the numerical analysis.

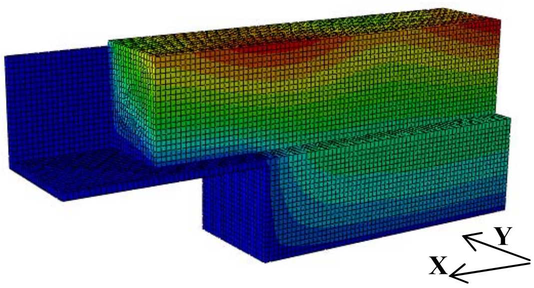

Fig.12. The map of acceleration obtained by Davenport's method in the fifth minute.

Displacement maps obtained from the dynamic analysis are shown in the Fig.9. The results were presented for Davenport's method in the fifth minute of the wind activity. Furthermore, the A point displacements (half the height) were compared to the point B (top of the building). The obtained results are summarized in the graphs (Figs 13, 14).

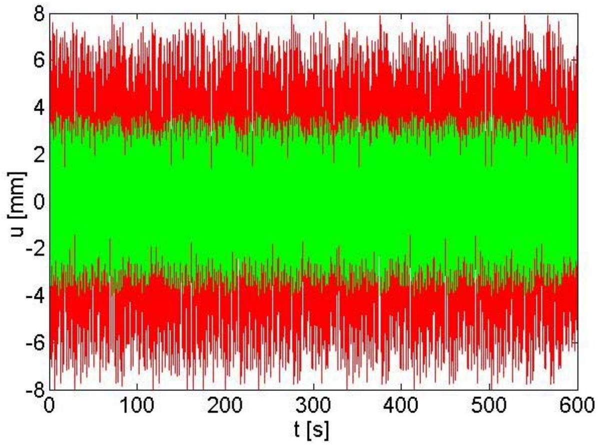

Fig.13. The graphs of horizontal displacements in the *Y* direction in 10 minutes time according to Davenport's method.

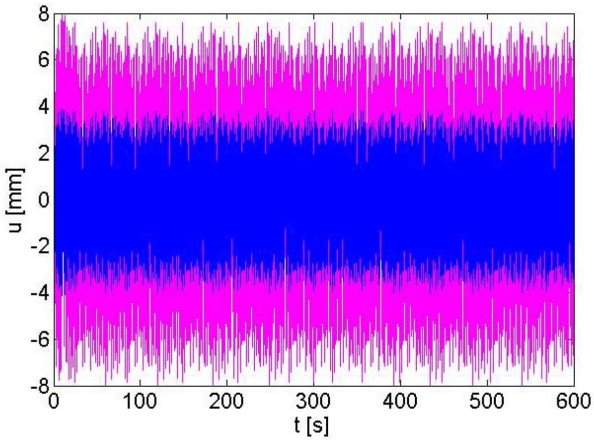

Fig.14. The graphs of horizontal displacements in the *Y* direction in 10 minutes time according to Karman's method.

The maximum displacements at the point A were equal to 4.1 and *4.2*[*mm*] and in the point B - *7.8* and *8*[*mm*] for the method of Davenport and Karman, respectively. Davenport's method is a simplified method that requires providing less input parameters, and its application gives the results similar to those obtained by a more complex method (Karman's method).The obtained results differ only by approx. *3*%, which proves that both methods can be used equally.

6. Conclusions

The objective of this paper was to solve the dynamic issues of the wind spectrum influence using the methods of Davenport and by Karman in the case of the building designed on the cliff in Orłowo. The conducted analyses aimed at comparing the displacements obtained by the two methods. The results were read at the two points of the object, at half height, and on top of it.

On the basis of the results it was proved that the object's aerodynamics is well-shaped in respect with the wind that blows in the given climatic conditions. On the basis of the results obtained from the comparison of Karman's and Davenport's methods it was also shown that the difference in the application of both methods is small and remains within the *3* [%] limit. Thus, in the analysis of the dynamic wind loads both Karman's and the Davenport's method can be used, depending on the available parameters, data and boundary conditions. The load and the analysis of the wind influence by Davenport is a simplification in relation to the method of Karman, hence by using the easier method comparable or even identical simulation results and calculations can be obtained.

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