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GRZEGORZ BOSAK*, ANDRZEJ FLAGA*

ANALYSIS OF AERODYNAMIC INTERFERENCE BETWEEN A HIGH-RISE BUILDING AND ITS IMMEDIATE CITY SURROUNDINGS

ANALIZA INTERFERENCJI AERODYNAMICZNEJ POMIĘDZY BUDYNKIEM WYSOKIM A JEGO NAJBLIŻSZYM OTOCZENIEM

Abstract

This paper summarizes results of wind tunnel tests of a high-rise building placed in Warsaw city centre. Aerodynamic laboratory studies were accomplished in a boundary layer wind tunnel. The main objective of the research was to determine the distribution of the mean wind pressure coefficient over the building's external surfaces as affected by the aerodynamic interference between the structure and its immediate city surroundings. Interference coefficients of wind pressure and global wind forces acting upon the surfaces of the building walls and roof were calculated. The aerodynamic studies showed a significant influence of objects located nearby on the wind load that the high-rise building structure surfaces are subjected to.

Keywords: wind tunnel tests, aerodynamic interference, wind action on a building surfaces

Streszczenie

W artykule przedstawiono rezultaty badań modelowych w tunelu aerodynamicznym budynku wysokościowego położonego w centrum Warszawy. Badania zostały wykonane w tunelu aerodynamicznym z warstwą przyścienną. Podstawowym celem analiz było określenie rozkładu wartości współczynnika średniego ciśnienia wiatru na powierzchniach zewnętrznych budynku w warunkach występowania interferencji aerodynamicznej pomiędzy analizowaną konstrukcją a jej najbliższym miejskim otoczeniem. Wyznaczono współczynniki interferencji odnoszące się do ciśnienia wiatru oraz do sumarycznych sił działania wiatru na powierzchnie ścian i dachu budynku. Badania wykazały znaczący wpływ obiektów sąsiadujących na działanie wiatru na konstrukcję budynku wysokiego.

Słowa kluczowe: badania modelowe w tunelu aerodynamicznym, interferencja aerodynamiczna, działanie wiatru na powierzchnie budynku

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* Department of Structural Mechanics, Cracow University of Technology, Poland.

1. Introduction

A high-rise building, the Echo Tower building, the height of which is equal to 155 m, is located in the center of Warsaw in the quarter bordered by Jan Paweł II Avenue, Grzybowska Street and Twarda Street. The distances between the buildings in the immediate surroundings of the Echo Tower building are very small. Along Grzybowska Street and on both sides of Jana Pawła II Avenue, there are 40 m high buildings. The Westin Hotel building, the TP SA Tower and the PZU SA building are all over 100 m tall – these predominate over the immediate surroundings. Additionally, during the wind tunnel tests, two high-rise buildings which are planned to be constructed nearby were taken into consideration. The Gmina Żydowska building is a structure of 170 m in height and will be located at a distance of 220 m from the analyzed building. The height of the Cosmopolitan Tower, the second planned building, is equal to 160 m and is going to be located a similar distance from the analyzed structure as the first planned building. Computer generated images of the Echo Tower building with its immediate surroundings are presented in Fig. 1.

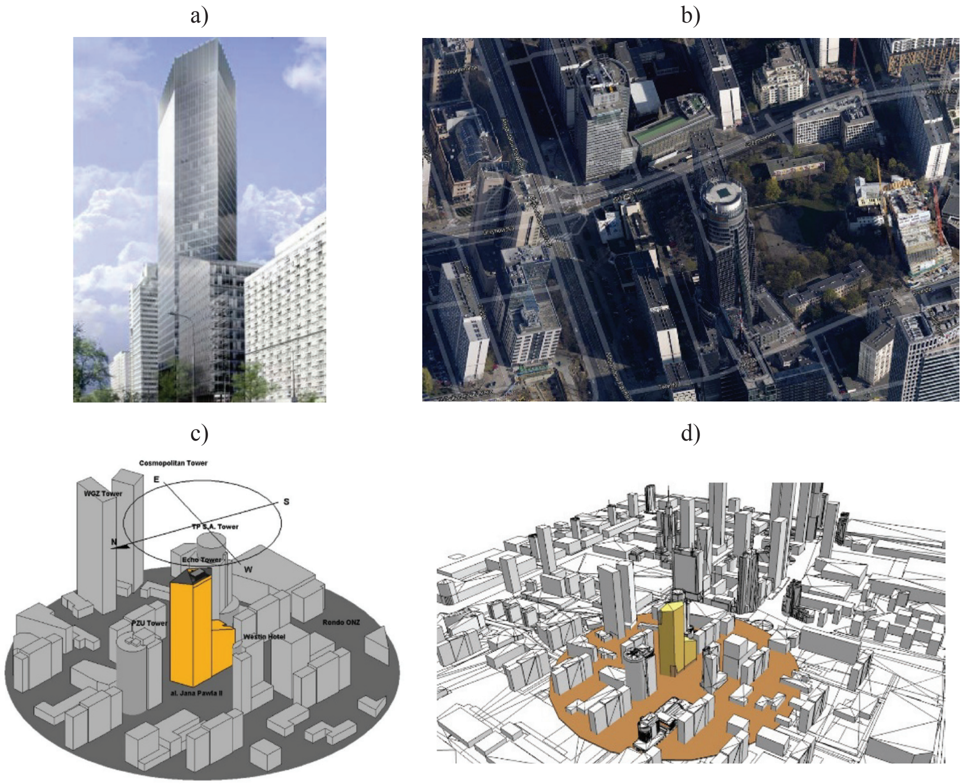

Fig. 1. Computer generated images: a) of the Echo Tower building; b) of the quarter limited by Jan Paweł II Avenue; Grzybowska Street and Twarda Street in Warsaw; c) of the interference configuration analysed during wind tunnel tests, d) of the immediate surroundings of the building on the architectural plan of Warsaw city centre

The subject of this article is to evaluate the influence of aerodynamic interference on the wind action on the building structure. The following circumstances are the reasons for the aerodynamic modelling of the building structure in a wind tunnel. Firstly, the shape of the building is non-standard and very complicated (see Fig. 1a). The building consists of two parts. The lower part, a podium, has a rectangular cross-section and consists of 17 levels. The second part of the building, the tower, has an irregular shape that various along the height a cross-section, narrowing towards the top of the building. The total height of the building is 155 m. The outer surface of the structure consists of 32 planes connected at corners and forming pointed edges. Secondly, the building is located in Warsaw city center where we can expect significant interference influences coming from the immediate surroundings. Even though the majority of buildings in the immediate surroundings have a height of about 40 m, there are 5 structures with a height of over 100 m. In addition, the distances between the highest buildings are very small, from 80 m to 220 m. All the above mentioned reasons motivated an aerodynamic wind tunnel investigation of the building model.

2. Characteristics of the wind tunnel tests

The wind tunnel tests were conducted, using a 1:250 scale model, in the wind tunnel of the wind engineering laboratory of Cracow University of Technology [1]. The building and its immediately surrounding area within a radius of 250 m were modelled.

a) b)

Fig. 2. Measuring configurations: a) a non-interference configuration; b) an interference configuration

The building model and the other model objects in the immediate surroundings were placed on a 200 cm diameter turn-table – this allowed for the simulation of any wind direction in the working section. The measurements were taken for 40 wind directions with increments of 10° each and additionally, for the four characteristic wind direction (45°, 135°, 225°, 315°). The model was instrumented with 219 pressure taps which allowed introducing the pressure taps into all characteristic areas of the external building model surfaces with sufficient density. The mean wind pressure and the standard deviation of wind pressure fluctuations were measured at each tap. On the basis of the measured data, mean pressure coefficients were calculated based on the measured mean dynamic pressure of wind at a height equivalent to 150 m above the ground for the real construction. Two different measurement configurations were examined. In the first configuration, only the building model was placed in the tunnel working section; in the second configuration, the building model with the immediate surroundings was taken into consideration. The views of the tested model in the two different measurement configurations in the wind tunnel are presented in Fig. 2.

The experiments were performed for the following conditions: power law exponent of mean wind velocity profile $\alpha = 0.35$; area-averaged turbulence intensity $I_v = 12\%$ on the reference level (0.6 m in model scale equivalent to 150 m in full scale); reference velocity at a height level to the building roof model $V_{ref} = 15.6$ m/s. All of the wind tunnel properties such as the configuration of an adjustable ceiling, the ejection of floor blocks, the RPM of the fan, the type of circulation, the settings of barrier and spires was optimised due to the model size, its scale, external shape, and roughness of the terrain. The mean wind velocity profile obtained in the wind tunnel working section during the experiments is presented in Fig. 3.

A turbulence intensity profile obtained in the wind tunnel tests is given in Fig. 4.

A profile pressure probe, a pressure electronic scanner, which allows measuring wind pressure in 64 taps simultaneously, and a hot–wire anemometer system were used during the experiments.

A flow chart of the measuring system of wind pressure on the wall and roof surfaces of the building is presented in Fig. 5.

The comparison of the results, namely the values of the wind pressure coefficients and the components of the global wind forces acting on the building structure, was accomplished on the basis of the test results for the two analysed configurations.

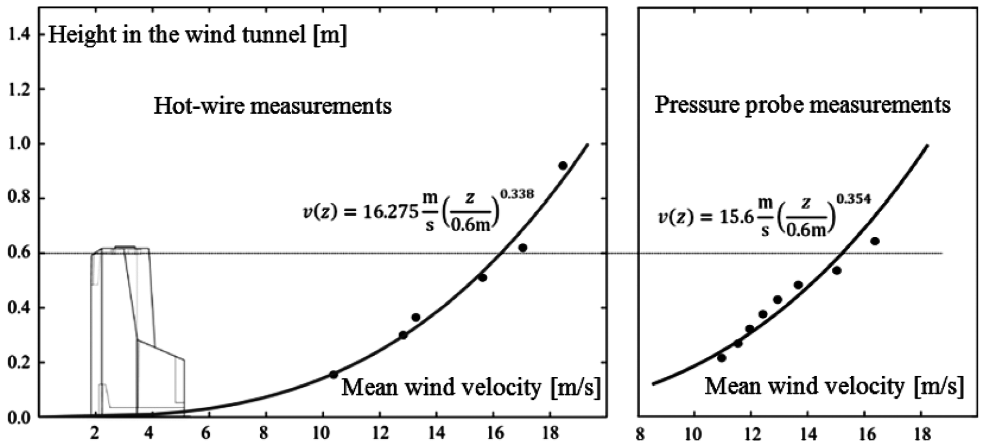

Fig. 3. Mean wind velocity profile obtained in the wind tunnel working section (the horizontal line marks the reference level)

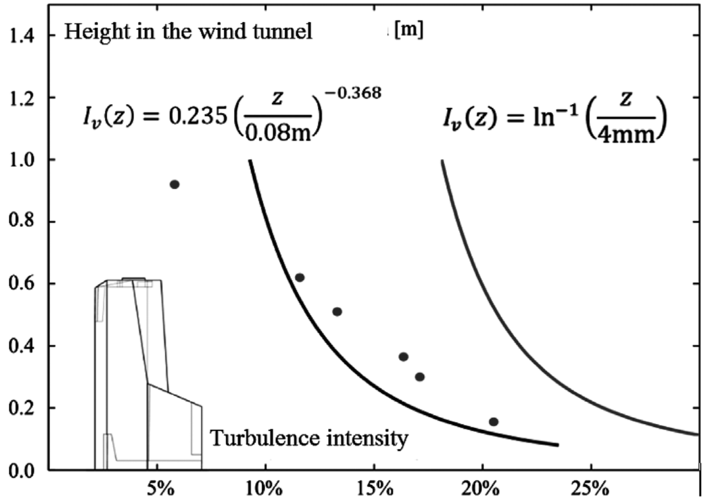

Fig. 4. Turbulence intensity profile obtained in the wind tunnel tests (the left curve) in comparison to the theoretical profile according to [3] (the right curve)

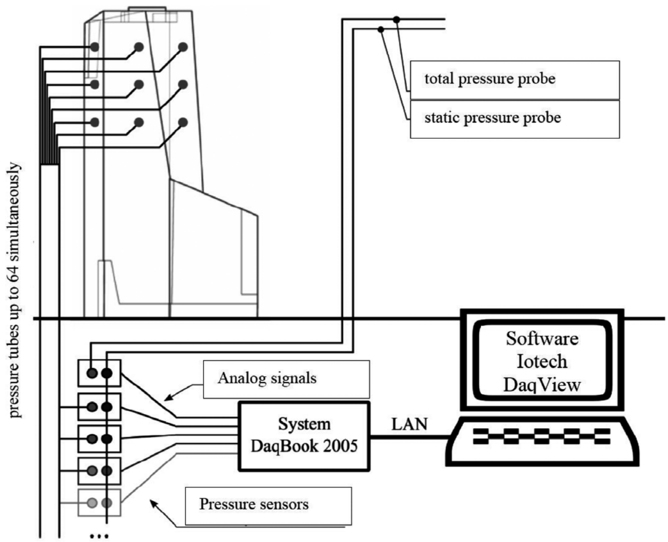

Fig. 5. Flow chart of the measuring system of differential wind pressure on the roof surface

3. Results of the wind tunnel tests

Firstly, the values of the C_{pe} coefficient were determined in the non-interference and the interference configurations according to the formula:

$$C_{pe}\left(x, y, z, \mathrm{dir}\right) = \frac{p_e\left(x, y, z, \mathrm{dir}\right)}{q_{\mathrm{ref}}\left(z_{\mathrm{ref}}\right)} \tag{1}$$

The reference level was at the height of the top level of the building model roof (equivalent to 150 m above the ground at full scale). Positive values of wind pressure act on the external surfaces in line with the inner unit vector perpendicular to the surface. Below, in Fig. 6, exemplary distributions of the C_{pe} coefficient in the non-interference and interference configuration for the chosen wind directions (30°, 70°) are presented. For these two wind directions, the largest changes of wind pressure distributions on the building surfaces are observed.

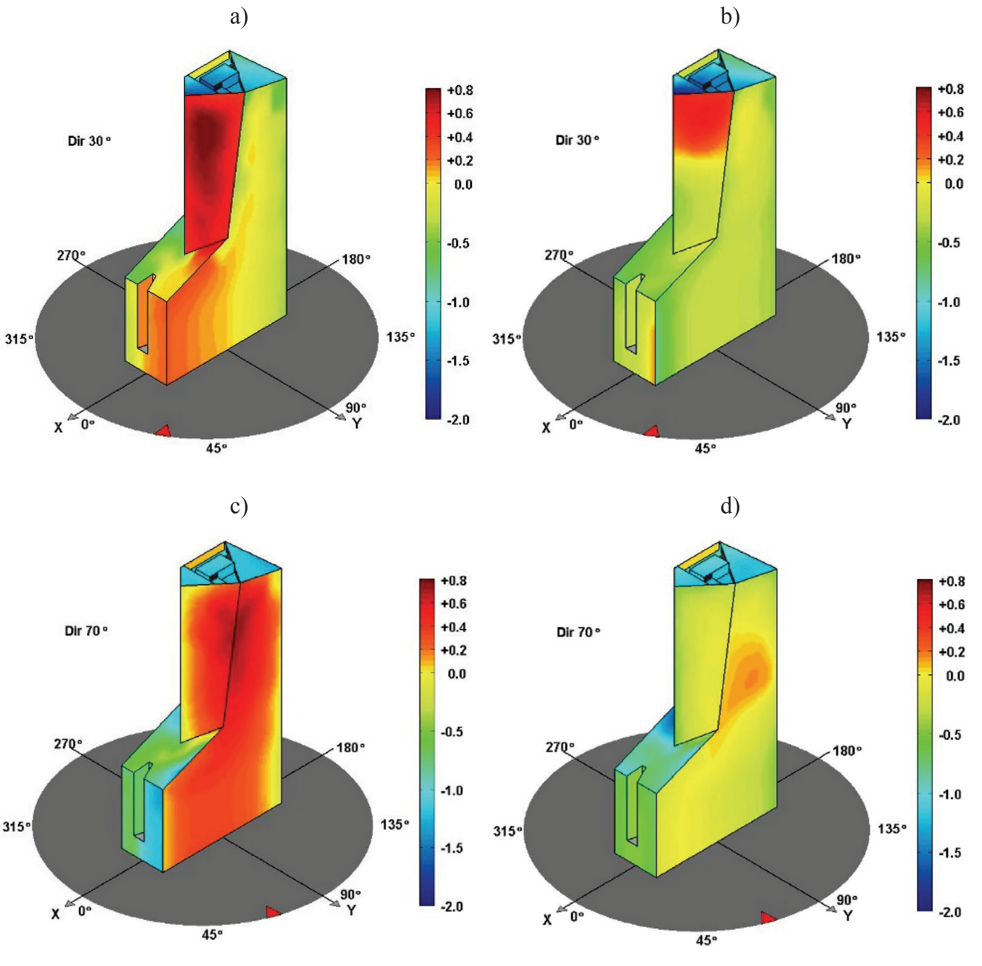

Fig. 6. Distributions of C_{pe} coefficient in the non-interference (a, c cases) and in the interference configurations (b, d cases) respectively for the 30° and 70° wind directions (red arrows indicate wind direction)

The values of the wind pressure coefficients are between +0.8 (positive pressure) and -2.0 (negative pressure [suction]) for both analysed configurations. It is observed that the leeward regions the lower sections of the building were sheltered by the neighbouring structures. This caused an aerodynamic effect which consisted of changing the positive wind pressure over these areas into negative values. At the same time, a negative aerodynamic effect was observed connected with the occurrence of an increase in the negative pressure values mainly over the areas at the edges of the building surfaces. The most significant factor relating to wind pressure distributions over the building surfaces was the existence of the highest structures located nearby. In cases where the building was in the leeward area behind the highest structures, which was the case for the 70°–80° wind directions, the pressure distribution changes occurred not only over the lower parts of the building but also over the rest of the building surfaces including the roof planes. An increase in the positive wind pressure on the building surfaces was not observed.

The significance of the aerodynamic interference for the changing of the wind pressure on the surfaces of the building was determined by the interference coefficient [2] obtained according to the formula:

$$I_c^p\left(x,y,z,\text{dir},\text{type},\text{area}\right)=\frac{\left|\left[C_{p,net}^{I}\left(x,y,z,\text{dir}\right)-C_{p,net}^{S}\left(x,y,z,\text{dir}\right)\right]_{\text{type}}\right|}{\max\left|C_{p,net}^{S}\left(x,y,z,\text{dir}\right)\right|_{\text{area}}} \tag{2}$$

where: dir – wind direction, x,y,z – point coordinates, I – interference configuration, S – non-interference configuration, type – the type of wind pressure variation on the surfaces according to Tab. 1., area – the wall or the roof area of the building.

Table 1

Types of wind pressure coefficients changing on the building surfaces

Type	Change type	Colour mark	$C^I_p(x,y,z,\text{dir})$	$C^S_p(x,y,z,\text{dir})$	$C^I_p(x,y,z,\text{dir})$ - $C^S_p(x,y,z,\text{dir})$
6	pos ↑	red	$C^I_p > 0$	$C^S_p \geq 0$	$C^I_p - C^S_p > 0$
5	pos ↓	orange	$C^I_p \geq 0$	$C^S_p \geq 0$	$C^I_p - C^S_p \leq 0$
4	neg ↑ pos	yellow	$C^I_p \geq 0$	$C^S_p < 0$	$C^I_p - C^S_p > 0$
3	pos ↓ neg	green	$C^I_p \leq 0$	$C^S_p > 0$	$C^I_p - C^S_p < 0$
2	neg ↑	blue	$C^I_p \leq 0$	$C^S_p < 0$	$C^I_p - C^S_p \geq 0$
1	neg ↓	magenta	$C^I_p < 0$	$C^S_p \leq 0$	$C^I_p - C^S_p < 0$

The most significant influence of the aerodynamic interference between the building and the objects in the immediate surroundings was observed for the wind directions of: 30°, 70°–80°, 280° and 340°. The situations for the 30°, 70° wind directions are presented in Fig. 7, where the building was sheltered by the highest structures located nearby (the building was located on the leeward side of the highest surrounding structures).

According to the wind tunnel tests, the largest influence of the aerodynamic interference connected with the existence of the neighbouring buildings, was observed for lower sections of the building walls situated near the neighbouring structure. Mostly, the effect of aerodynamic interference consisted of sheltering these regions which resulted in the changing of positive pressure values to negative pressure (see Fig. 7).

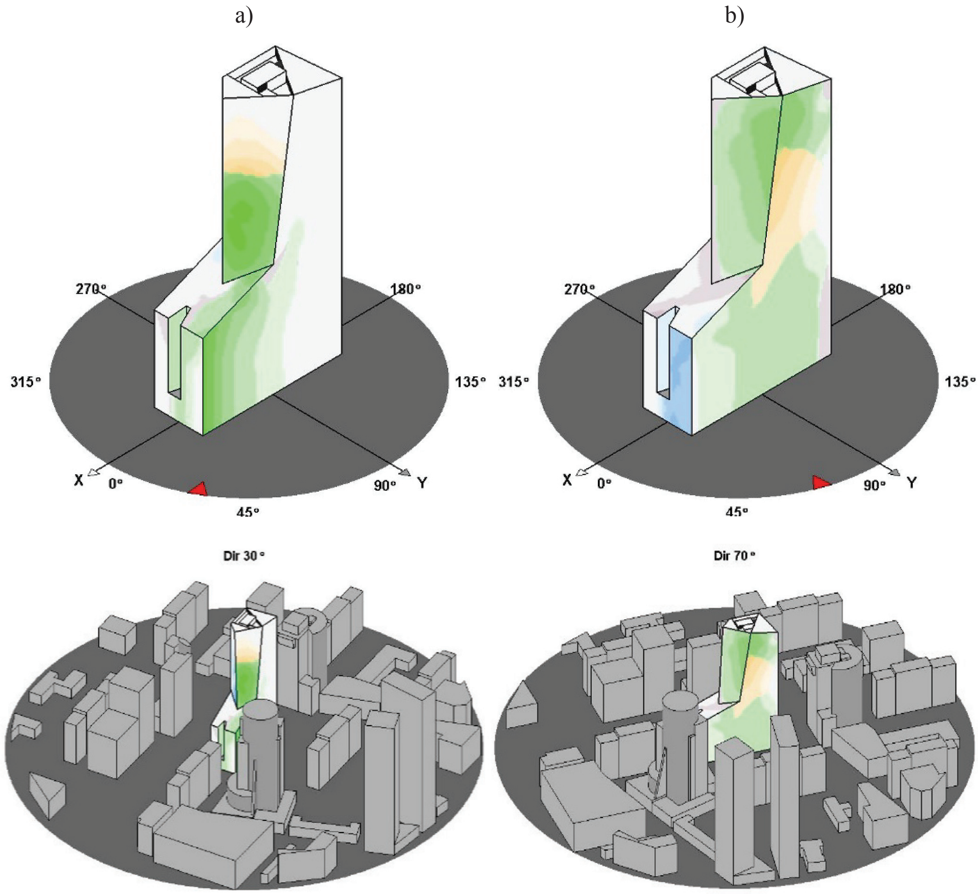

Fig. 7. Distribution of coefficient: a) for the 30° wind direction, b) for the 70° wind direction

At full scale, the global aerodynamic forces, F_k, for the building were separately calculated by using distributions of the C_{pe} coefficient obtained from the measurements according to the formula:

$$F_k(\mathrm{dir}) = q_p(z_{\mathrm{ref}}) \cdot \sum_{p=1}^{32} \sum_{A_p} C_{pe}(x, y, z, \mathrm{dir}) \cdot \Delta A_p(x, y, z) \cdot n_k(p) \tag{3}$$

where: dir – wind direction, $q_p(z_{\mathrm{ref}})$ – peak velocity pressure according to [3], k – coordinates x, y, z, p – the wall or the roof plane region (total number of planes was equal to 32), A_p – the area of the particular plane region, ΔA – a part of the area of the wall or the roof surface, n_k – a coordinate of the unit vector, perpendicular to the surface,

The force components F_x, F_y of the horizontal global wind action acting on the building (at full scale) in the interference configuration (line with square markers) in comparison to the results obtained in the non-interference configuration (dashed line) is presented in Fig. 8. A coordinate system of the global aerodynamic forces for the building is also given in Fig. 8.

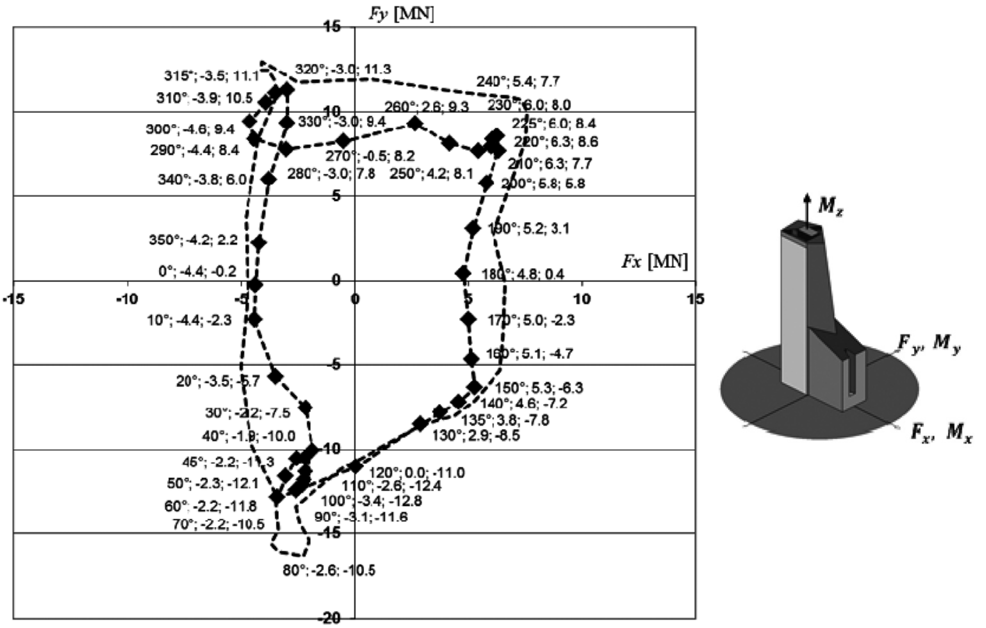

Fig. 8. The force components F_x, F_y of the horizontal global wind acting on the building (in full scale) in the interference configuration (line with square markers) in comparison to the results obtained in the non-interference configuration (dashed line)

A global force interference coefficient was assumed:

$$I_c^F(\text{dir}) = \frac{F_H^I(\text{dir}) - F_H^S(\text{dir})}{\max\left|F_H^S(\text{dir})\right|} \cdot 100\% \tag{4}$$

where: F_H^S, F_H^I – absolute values of a vector of the horizontal global wind action force in the non-interference and in the interference configuration respectively.

A diagram of the interference coefficient as a function of the wind direction obtained using formula (4) is shown in Fig. 9.

The general conclusion referring to the total horizontal wind forces acting on the building structure is that the immediate surroundings play a positive, sheltering role. For all the wind directions, a decrease in the total horizontal wind force is observed.

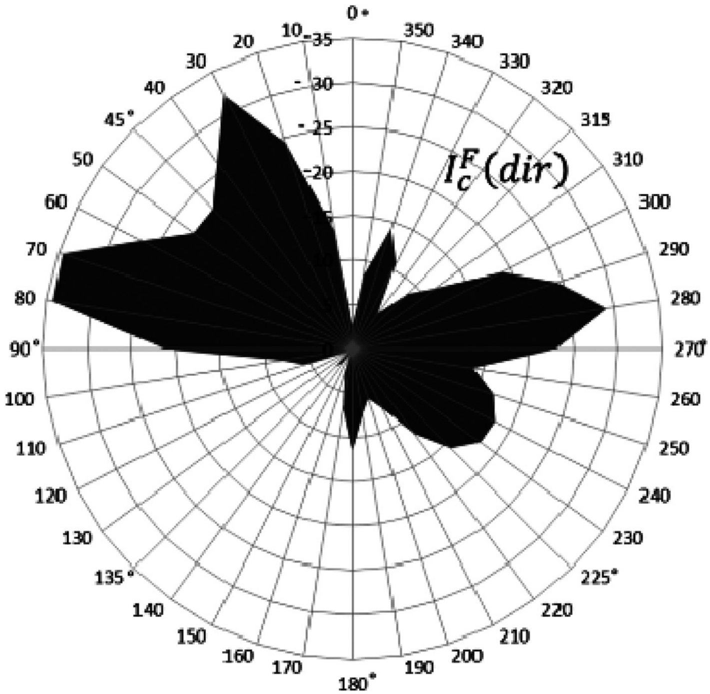

Fig. 9. Diagram of the force interference coefficient as a function of the wind direction

Local extremes, where the reduction of wind forces is significant, occurred for several wind directions. The global extreme took place for the 70°–80° wind directions where the reduction could be evaluated at a level of 35%. An important reduction of about 30% occurred for the 30° and 280° wind directions which was connected with the existence of the TP SA building (30°) and the Westin Hotel building (280°) located nearby.

4. Conclusions

The results of the measurements which were carried out in the wind tunnel allow for the formulation of the following conclusions:

- the building surroundings reduced the wind action on the building in relation to the horizontal global wind force;
- an increase in the positive wind pressure on the building surfaces was not observed;
- a noticeable rise of a suction (negative wind pressures) occurred mainly in areas located at the edges of the building surfaces.

The conclusions cannot be considered as general rules because of the single nature of the measurements. It is necessary to carry out such tests for different interference configurations [4, 5].

References

[1] Flaga A., Bosak G., Kłaput R., Flaga Ł., Kimbar G., *Wind tunnel tests and study analysis of the wind action on the high-rise building placed at the crossroads of Jana Pawła II Avenue and Grzybowska Street in Warsaw*, Research Report, Politechnika Krakowska, Kraków 2012 (in Polish).

[2] Bosak G., *Wind tunnel tests of aerodynamic interference of double-shell tanks*, Czasopismo Techniczne, 3-B/2012*,* Kraków, 3-19.

[3] PN-EN 1991-1-4: Actions on structures. Part 1-4: General actions- Wind actions.

[4] Khanduri A.C., Stathopoulos T., Bédart C., *Wind-induced interference effects on buildings – a review of the state-of-the-art,* Engineering Structures, Vol. 20(7), 1998, 617-630.

[5] Geurts C.P.W., *The use of wind tunnel experiments for wind loads on structures*, TNO Built Environment and Geosciences, Delft, The Netherlands.