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COMPARISON OF TESTING RESULTS OF THREE POORLY STREAMLINED ENTERTAINMENT VENUES

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Abstract. The article discusses experimental investigations of wind effects and use of design codes for solving aerodynamic problems. It provides data regarding wind-tunnel tests conducted on three buildings with poorly streamlined shapes, including: methodology and test conditions, aerodynamic properties of the designed structures, features of physical models and research results. All three civil buildings are multi-purpose stadiums of the European level. Despite the identical functional purpose, each building has a unique shape and volume. The paper analyses and compares testing conditions in the wind tunnel and some selective results. The authors propose a criterion for estimating aerodynamic properties of the overhanging roof over spectator stands. The article also considers dependencies of model surface pressures on airflow directions under various test conditions.

Keywords: wind tunnel, poorly streamlined shapes, stadiums, overhanging roof, comparison criteria.

1. Introduction

When designing civil engineering above-ground structures, the wind effect should be taken into account. In this case, a geometric shape of a building is the basic factor. Of course, other factors may be very important as well, namely, building site conditions, volumes of nearest buildings or influence of nearest trussed structures, irregularity of surfaces and etc. Simple geometric objects (a cylinder, prism, sphere and etc.) have classical analytic solutions. The wind effect on widely used structures (towers, masts, bridges and etc.) has been sufficiently studied (Barshtein 1978; Kuznecov 2009; Samofalov, Cvirka 2010) and described in design codes (LST EN 1991 2005; SNiP 2.01.07–85 1987; STR 2.05.04 2003; DBN V.1.2–2: 2006). Nowadays, aerodynamic properties of non-standard shape buildings are poorly investigated. Special attention should be given to poorly streamlined shapes (Geurts, van Bentum 2010). Wind flow, vortices around such buildings and distribution of pressure on their surfaces hard to predict (Holmes 2007; Simiu, Scanlan 1986, 1996). In such cases, during the design stage of a building, the most reliable results are obtained through experiments. In general, such experiments can be conventionally divided into full-scale, laboratory and virtual.

Wind effect experiments on full-scale buildings are extremely expensive. Laboratory investigations in the wind tunnel are widely known and popular (Wu, Hamada 2000). When similarity conditions of a real building are observed in a physical model, final results are reliable enough. This fact has been repeatedly confirmed through monitoring of the existing buildings (Richardson *et al.* 1997). In modern research, much attention is given to computer simulating of airflow (Dubinskij 2010; Maruoka *et al*. 2001; Goudarzi, Sabbagh-Yazdi 2011). Such analysis provides data without the need to manufacture and test the physical model. However, experience accumulated by virtual modelling cannot completely discard laboratory tests. For more precise analysis of aerodynamic properties of an important structure, both laboratory and virtual investigations are recommended. Certainly, the obtained final results should be compared and analysed.

Very often sports venues represent non-standard combination of geometric volumes and shapes. Realisation of some architectural novelties can create problems for precise estimation of wind effects. Use of conventional schemes from design codes (LST EN 1991 2005; SNiP 2.01.07–85 1987) is unreasonable in this case and may lead to incorrect results. An individual study (Samofalov *et al*. 2011) is welcomed by design codes, but no control requirements are specified for final results or investigation methodology. Consequently, all assumptions and hypotheses are set by authors of experiments on the basis of their knowledge and skills in this field of engineering. As distribution of wind loads on buildings of untypical shape has not been sufficiently studied, it is important to accumulate experimental data for future development.

The European Football Championship 2012 will take place in Ukraine. In preparation, new stadiums are built and existing venues are intensively reconstructed, two of which are considered in this paper. These are football stadium Dnepr in Dnepropetrovsk (Lebedich *et al.* 2007) and stadium Metalist in Kharkov. Another object is the national stadium in Vilnius, Lithuania (Samofalov *et al.* 2008), which was planned to be built to commemorate the Millennium since the name of Lithuania was first mentioned in the Annals of Quedlinburg in 1009. Designs of the stadiums provide for multi-purpose use of venues and ensure conformity to relevant international standards for event competitions in Europe.

The presented investigations are based on the results of tests performed from 2006 to 2008 in the wind tunnel at the Laboratory of Aerodynamic Investigations of Aero-Cosmic Institute of Ukrainian National Aviation University in Kyiv, Ukraine.

2. Investigation methodology

To ensure similarity each of the three physical models were made to a defined scale, considering dimensions of the work section of the wind tunnel (Fig. 1, height $h = 2.5$ m, degree of wall permeability 18%, shape of the cross section – octagon). Roughness on model surfaces was selected to mimic real boundary properties of full-scale buildings. Building site conditions around the models were simulated by creation of vortexes in the boundary layer: large size vortexes were produced by jagged ledges on the front edge of the flat plate, small ones – by cube-shaped blocks (about 300 units). Such reproduction of the boundary layer is well studied by authors (Pavlovskij, Kuznecov 2009) and agrees with the foreign test practice (Lawson 2001; Kozmar 2011).

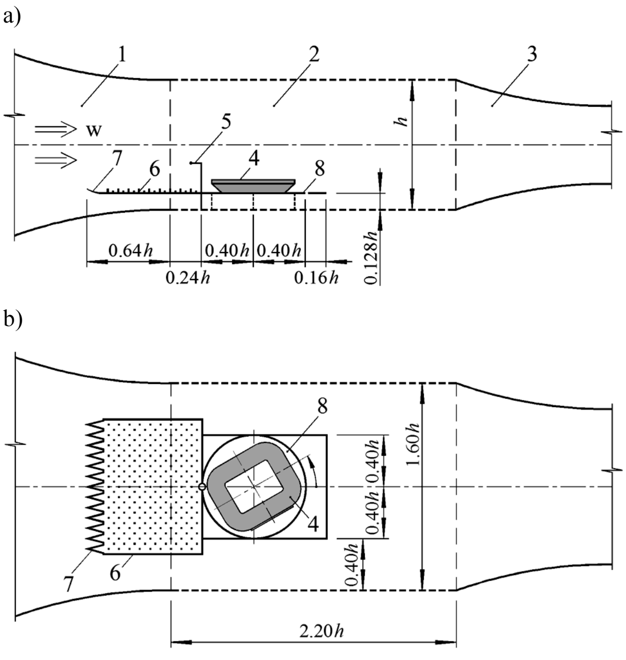


Fig. 1. Layout of the wind tunnel (side view (a), plane view (b)): 1 – nozzle; 2 – working sector; 3 – diffuser; 4 – stadium model; 5 – the pitot-static tube; 6 – small vortex generators; 7 – large vortex generators; 8 – turntable

During the tests, coefficients of airflow pressure were calculated:

$$\mu_q = \frac{\zeta \cdot (P_0 - P_s)}{(P_e - P_a)} \cdot \psi\,, \tag{1}$$

here: ζ is calibration factor of the pitot-static tube; P_0 is the pressure measured in model drainage points; P_s is pressure on the pitot-static tube; P_e is a static pressure in Eiffel chamber of the wind tunnel; P_a is a pressure of atmosphere; ψ is a correction coefficient, which is taken into account in case of individual features of laboratory experiments.

An air velocity has been measured by the pitot-static tube. A velocity coefficient:

$$\mu_v = \sqrt{\mu_q}\,. \tag{2}$$

The turbulence degree, when pulsation is taken into account, is expressed by:

$$\varepsilon = \nu \cdot V^{-1/2}\,, \tag{3}$$

where: ν is an average pulsation component; V is an average flow velocity.

Distribution of the turbulence degree in the vertical direction within the wind tunnel was investigated (Fig. 2) when the turntable was set.

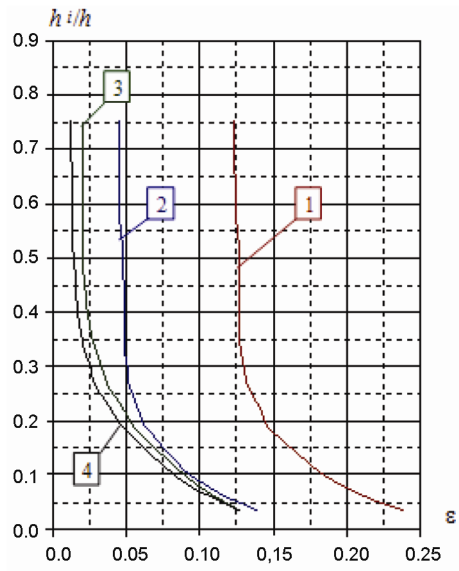


Fig. 2. Distribution of the turbulence degree in the vertical direction within the wind tunnel (distance from the pitot-static tube to the start of working sector of wind tunnel is 0.35 h) while the velocity (m/s): 1 – value 5.7; 2 – value 11.0; 3 – value 19.5; 4 – value 31.3

Because of high intensity of turbulence around physical models the pressure distribution over model surfaces did not actually depend on Reynolds value, i.e. self-similarity was achieved ($1 \cdot 10^3$ is sufficient). Thus, similarity conditions were met.

Airflow pressure coefficients on surfaces were calculated as per expression:

$$\eta = 1 - \frac{1}{\mu_q}. \quad (4)$$

A positive value of the coefficient expresses a compression pressure on a surface local area, while a negative value shows tension pressure, detached from the surface area.

Each of the models was turned on the horizontal turntable at angles from 0 to 360°. At every stop, air pressure values were registered. Once the measured pressure values were averaged, coefficients Eq. (4) were calculated.

Calibration was carried out before the start of each of the tests. During experiments, in the course of each test cycle, an additive correction to check a shift of initial origin data was made. According to the graduation results of transducers, a maximal error value of 0.468 mm water column (4.58 Pa) was defined, it makes up $2.9 \cdot 10^{-3}$ of the transducers measurement range. Thus, the reduced error of the transducers is less than 0.3 (accuracy class 0.3). Consequently, an instrumental error of measurement (Novickij, Zorgaf 1991) is less than 1%.

The pressure values were specified on both surfaces (outer and inner) of the stadium roofs above spectator stands. Design of the aerodynamic coefficient was made with allowance for the pressure direction, i.e. using algebraic signs:

$$c_e = \pm(\eta_{ext} - \eta_{int}) \pm \Delta\eta, \quad (5)$$

where $\Delta\eta$ is the recommended accuracy of the coefficient.

3. Testing the models

3.1. Testing the first model

Some information about experimental investigation of a physical model of the stadium Dnepr in Dnepropetrovsk was presented early by Lebedich *et al.* (2007), only sample data for the comparison was selected.

The contour of the venue in plane is a rectangle with rounded edges (Fig. 3a), but the VIP block disturbs the full symmetry. The slope of the roof is 6.5°. The roof is designed above the stands (Fig. 3b). Cantilever trusses of all 56 transversal frames are of similar shape. A step of frames is approx. 10.5 m. According to the primary design, an opening between stands and the roof on the entire circumference of the stadium was planned. However, subsequent to preliminary aerodynamic tests in a separate sector the opening was closed with a system of wall panels (Lebedich *et al.* 2007). Besides, air penetrates the interior of the arena through pedestrian walkways.

The facility model was made to a scale 1:120 (Fig. 4). Relatively small details and thin beams of the stadium were not modelled, including cantilever trusses and system of braces outside the external contour. The VIP sector was modelled separately.

Taking into account double symmetry of the facility and asymmetric location of the VIP block, the drainage points were located along 9 transversal lines on a half of the model. The points were mounted on both surfaces of the roof (Fig. 3a).

a)

b)

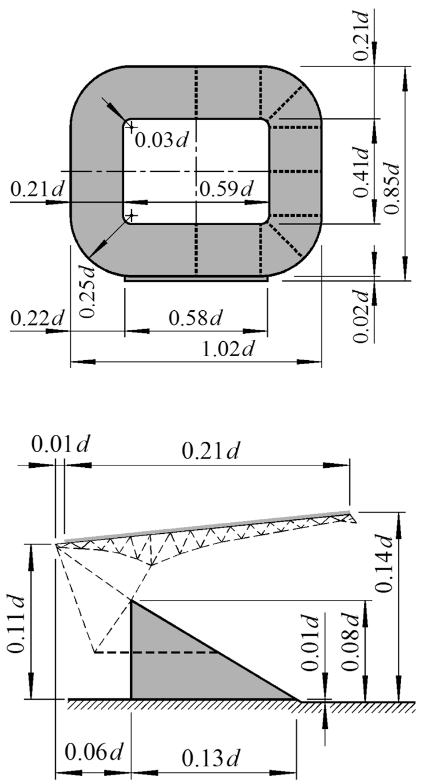


Fig. 3. Principal layout of the stadium in Dnepropetrovsk (relative unit for comparison $d = 200$ m): plane with drainage points on the roof (a) and a side view of the transversal frame (b)

a)

b)

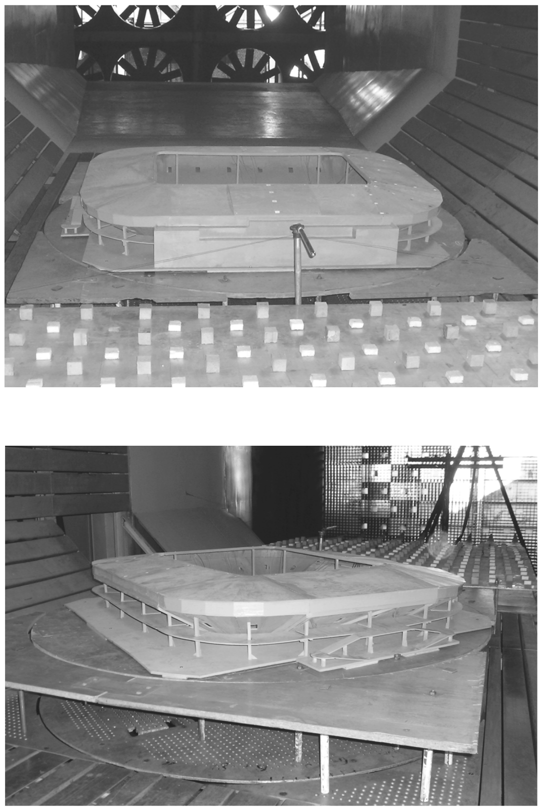


Fig. 4. The 1st model on the turntable within the working sector of the wind tunnel: the view from the side of the VIP block (a) and from one of the edges (b)

The analysis of final results of the experimental tests on the stadium model in the wind tunnel enables making the following conclusion:

- in all drainage points, total (bottom plus top) values of the pressure coefficient are negative, i.e. a lifting force is effected on the roof;
- values of the airflow pressure on the outer surface of the roof are predominantly higher than those on the inner surface;
- any line across the roof is more loaded (the total value of the coefficient can vary from 0 to −1.2) in case of an airflow direction along such line;
- existence of the VIP block reduces extreme aerodynamic coefficients on the nearest local roof zone by values from 0.1 to 0.3.

During experimental tests, values of the airflow pressure on the model surfaces in all drainage points on all considered lines of the stadium roof were registered.

The stadium was designed on the basis of the investigation in the wind tunnel. Reconstruction of the stadium was successfully completed and the venue is already operational.

3.2. Testing the second model

Investigation of distribution of airflow pressures on a physical model of the multi-purpose national stadium in Vilnius has already been discussed (Samofalov *et al.* 2008), thus in this paper will only discuss relevant issues.

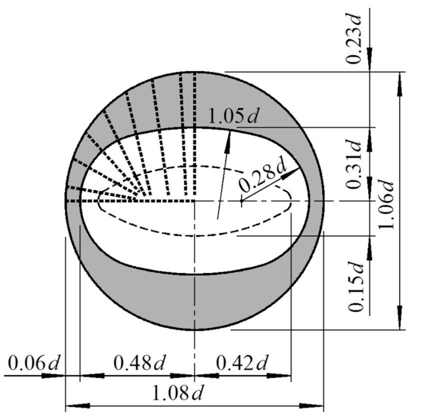
The main above-ground structures of the stadium (Figs 5, 6a) include: roofing over spectator stands, arch, cables with temporary tent and a pedestrian bridge. The venue has a double symmetry with the exception of the VIP lodges on the top of one of the stand sides. Stand and roof structural members are supported on 56 transversal frames. The height of the roof is variable. A steel trussed arch stretches along the arena (Samofalov, Cvirka 2010). It is connected to the roof by 56 cables. In the summer time, the temporary tent can be partially or completely rolled over the arena. Openings were designed between the bottom edge of the roof and external walls. Exits from stands to the outside pedestrian track permit influx of air.

A physical model of the venue was produced to a scale 1:150 (Fig. 6b). Details less than 450 mm in full-scale were not modelled. The flexible tent was manufactured as a stiff structural shell that sags in windless weather. It was made from bottom and top parts. The arch was made as a trussed member of small pipes, and the pedestrian bridge – the plate on short columns.

Taking into account the double symmetry of the venue, the drainage points were distributed on a quarter of the model (Fig. 5a). On other quarters, additional points for symmetry checking were located. It is important for estimating influence of the VIP block. Drainage measurements were made on outer and inner surfaces of the roof and tent.

During the experiment, different configurations of the model (Fig. 7) were tested (Table 1).

a)



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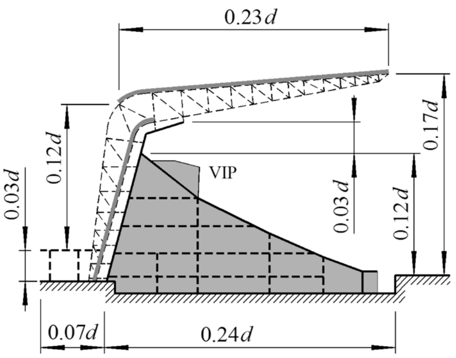


Fig. 5. Principal layout of the stadium in Vilnius (relative unit for comparison $d = 200$ m): plane with drainage points on the roof (a) and a side view of the transversal frame (b)

a)

b)

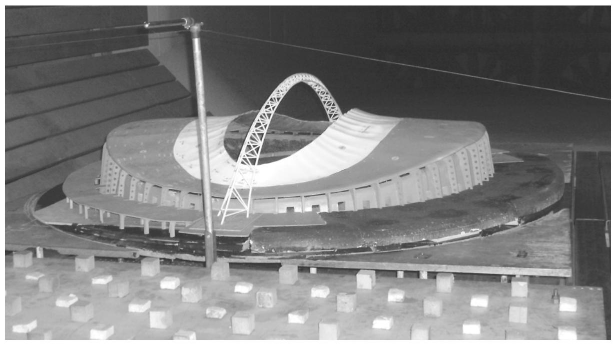
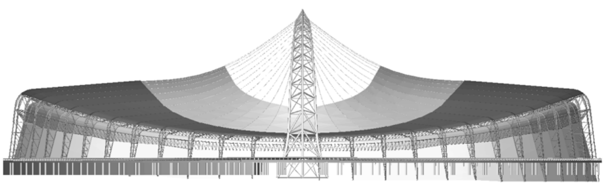


Fig. 6. The stadium in Vilnius: a virtual model of the venue without the tent (a), the physical model (when the tent is stretched on the bottom half of cable length) within the wind tunnel (b)

Table 1. Investigated configurations of the second model

No.	Bottom part of the tent	Top part of the tent	Openings under the roof	Openings for exits
1	taken away	taken away	opened	opened
2	existing	taken away	opened	opened
3	existing	existing	opened	opened
4	existing	existing	closed	opened
5	existing	taken away	closed	opened
6	taken away	taken away	closed	opened
7	taken away	taken away	closed	closed
8	taken away	taken away	opened	closed

a)



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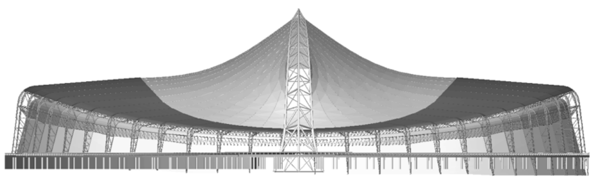


Fig. 7. The tent above the stadium arena rolled on the bottom half of cable length (a) and full length of cables (b)

Analysis of experimental results shows that:

- with airflow directions at angles 0° and 180° (along the arch), the pressure on the roof was less for model with the tent rather than the one without the tent;
- with the airflow along the arch on the model with the completely stretched tent, the air stream was effected with the minimal break;
- opened pedestrian exits are not an important factor for distribution of pressure;
- in case of the model with the half-rolled tent, the shutting of the openings over the stands reduced the pressure from 0.0 to 0.1; and when the tent was completely rolled – from 0.1 to 0.4;
- influence the asymmetric location of the VIP block has on the pressure distribution was not observed;
- on inner surfaces of the roof and tent, wide zones with negative pressure up to –0.3 were detected;
- a zone with significant negative pressure was found on outer surface of the tent;
- differences of pressure for neighbouring points near the top of the tent were explained by the aerodynamic shadow from the trussed arch;
- in case of the air stream direction at the angle of 30° the airflow reached the visitors stands, went up to the inner surfaces of the roof, and then flowed around the space of the arena.

Finally, the distribution of the pressure on the model surfaces was studied.

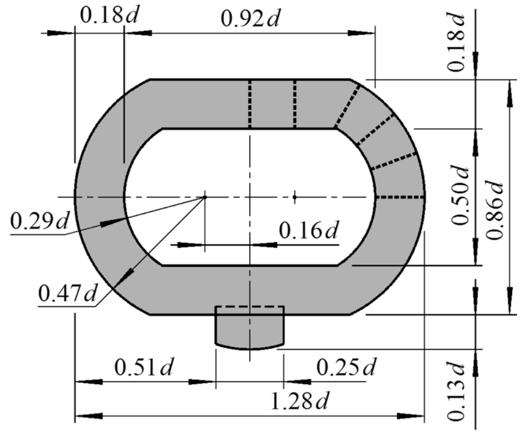
Due to the recent economic downturn, the construction works were stopped in 2009 and it is most likely they will not continue.

3.3. Testing the third model

The contour in the plane of stadium Metalist in Kharkov (tested in 2008) is a rectangle with two round sides (Fig. 8a). All bearing and façade structures are of double symmetry, except for the VIP block. The roof of a constant width is located around the arena. At a distance of a quarter of the width from the inside edge of the roof, the external angle is designed, which resembles a gable (Fig. 8b). The angle of the short part of the roof is 30°, and that of the long part is 15°. The roof is supported by 84 transversal plane trusses, 24 of which are cantilever cabled frame systems. The openings between external walls and the outside edge of the roof remain open.

A physical model of the venue was to a scale 1:130 (Fig. 9). Small details were not modelled – under the internal contour of the roof, the vertical struts were fastened. Drainage points were placed between these columns, an aerodynamic shadow was eliminated. Rooms of

a)



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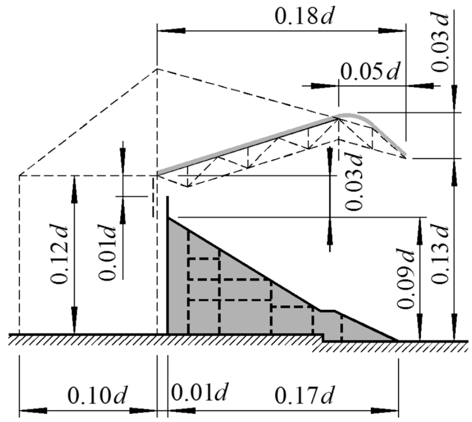


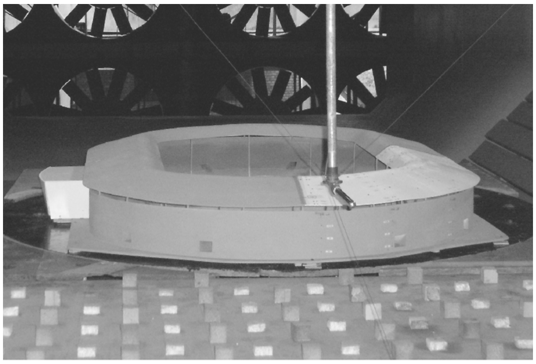
Fig. 8. Principal layout of the stadium in Kharkov (relative unit $d = 200$ m): plane with drainage points on the roof (a), and a side view of the transversal frame (b)

the under-stand space on the model were closed from the arena side (slope surface) and from the outside (vertical surface). Exits for spectators were designed on the football playground level. The VIP block volume, opposite to the external contour was simulated separately. The VIP block was placed from the side of stands as well and occupied some space under the roof.

Taking into account the double symmetry, the main drainage points were mounted on a quarter of the model (Fig. 9). The distribution density of the drainage points over the width of the roof was different due to "jumps" near the top zone and edges. Mainly 6 transversal lines with reducers were placed (Fig. 8a). An additional line with drainage points was set on a symmetric axis near the VIP block. Its task was to estimate influence of the asymmetric VIP volume on the nearest area.

During tests, some configurations of the model (Table 2) were investigated, when different variants with opened or closed openings and various shapes of the roof top were taken into account.

a)



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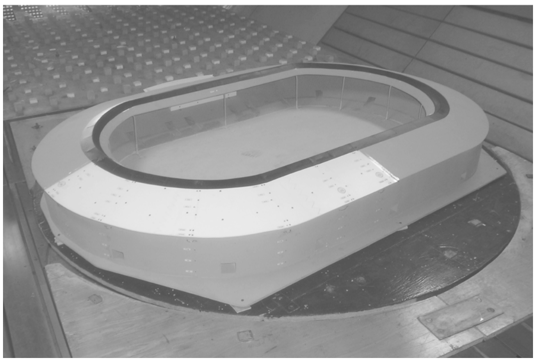


Fig. 9. The third model on the turntable within the working section of the wind tunnel: the model is turned to a short side (a), an additional angle on the roof top is mounted (b)

The operational velocity of airflow in the wind tunnel was assumed to be 30 m/s, corresponding to Reynolds number of $2{\cdot}10^6$.

All drainage points were tested by 1000–fold measurements during 12.8 s on each of 40 stops of the turntable, when the airflow direction angle was changed within the limits of 0° to 360° by a constant step of 9°. In addition, 5 cycles of 1000–fold measurements in the key directions of 0°, 90°, 180° and 270° were made. Such measurements were chosen for a better definition of the pulsation effect of the air stream. The root-mean-square deviation for top points makes up 0.15. This value indicates that there is a considerable pulsation of the airflow in case of the roof of a round-shape top and without any interceptor. For other zones, the deviation does not exceed 0.05. The same value was observed near the top zone in cases of the interceptor or a triangle shape.

Analysis of the received results enables concluding that:

- direction signs of pressure coefficients in case of different angles of the airflow on the main areas of the top and bottom surfaces are negative;
- extreme negative values of the pressure coefficients are in drainage points on the top of the roof in case of the airflow direction along the considered drainage line;
- distribution of airflow pressure along the drainage line showed an extreme value on the external contour of the roof;
- shutting of openings between the roof and walls leads to a decrease in pressure on the top of the roof to an average value from 0.3 to 0.7;
- the installation of a vertical interceptor on the top of the roof reduces the airflow pressure because of a break of an air stream;
- change in shape of the roof top from round to triangle one is similar to usage of a vertical interceptor;
- with different configurations of the model the pressure distribution on the inner (bottom) surface of the roof is smooth enough, it mainly variable within the limits from 0.0 to – 0.5;
- a value of the accuracy $\Delta\eta = \pm 0.10$ is recommended.

During testing with various airflow directions, a distribution of the relative pressure on surfaces of the model in different configurations was analysed.

Table 2. The schedule of experimental investigations of the third model

No.	Roof openings	Openings of the exits	Interceptor	Triangle shape	Features of the investigation
1	closed	opened	taken away	taken away	The most economic variant
2	opened	opened	taken away	taken away	The most common variant
3	opened	opened	existing	taken away	Influence of the interceptor
4	opened	opened	taken away	existing	Influence of the triangle shape

Taking into account this experimental research, technical documentation concerning improvement of a preliminary version of the stadium design was drafted. Recently, reconstruction works were successfully completed and the stadium is in operation.

4. Comparison of test conditions and results

The overall purpose of the three above-described experiments was to determine airflow pressure coefficients on surfaces of the models. All three venues have the same functional application, but each of them is of peculiar character (Biagini *et al*. 2007). According to international requirements of FIFA and other international organisations concerning multifunctional stadiums, spectator stands around arena should be protected from climate effects (van Hooff *et al*. 2011). Thus, availability of a structural roof over the stands and its closed form in plane is a common feature of all three objects of study. Also, common features are:

- dislocation of building sites within urban territories;
- similar dimensions of the facilities in plane and roof height;
- symmetry with respect to two axes in the plane of the facilities;
- round smooth shapes of the contours of roofs in plane of the stadiums;
- large areas of the roofs;
- slopes of the roof surfaces to the external side;
- internal edges of the roofs without supports;
- closed spaces under stands with through passages.

The common feature of the research process: all three models were tested in the same wind tunnel with participation mainly of the same engineering staff. Thus, the technical and organizational conditions of the laboratory experiments were somewhat similar. Differences between venues to be considered according to their design solutions (Table 3) and testing of the models (Table 4) exist as well.

The feature of the second model is a possibility to arrange an indoor space above the arena. This creates two principal new configurations: the stadium with a half-rolled and completely rolled tent. The use of an interceptor on the roof of the third model leads to a qualitatively different configuration as well. The influence of the openings between the roof and walls (as well as of the pedestrian under-stand exits) is insignificant in comparison with the above-mentioned three additional configurations. Therefore, it is appropriate to compare variants (the ones with opened pedestrian exits, for the second and the third models – with opened holes over stands):

A. The first model.
B. The second model without the tent.
C. The second model with the tent rolled to the bottom half of the cable length.
D. The second model with the completely stretched tent.
E. The third model when the top of the roof is round (without an interceptor).
F. The third model when the top of the roof is of a triangular shape.

Variants C, D and F allow to analyse influence of additional activities aimed at changing conditions of airflow through the roof.

Despite the common research task and structural features, it is somewhat difficult to select an unambiguous criterion for comparison of the experimental results. The following approach to perform the comparison is suggested (Fig. 10): on the main axes of the models, two orthogonal drainage lines are denoted (marked by "*vert*" and "*horz*"), on the round edge of the roof in plane – one oblique line (marked as "*diag*"). Lines "*vert*" and "*horz*" are more important for comparison because of different dimensions of the venue in both orthogonal directions. Line "*diag*" is considered as an additional one. On each of the lines "*vert*", "*horz*" and "*diag*" three characteristic points are denoted: "*int*" on the internal contour of the roof, "*cnt*" – at the geometric centre, "*ext*" – on the external contour. The results in endpoints "*int*" and "*ext*" are compared in order to estimate a change at zones with airflow breaks, in midpoint "*cnt*" – to estimate general distribution of the air pressure.

Separate explanation should be given regarding the third model. In this case, the roof is curved (the top is located at a distance of ¾ of the roof width from the external contour) and the main airflow break occurs exactly on this zone. On the internal roof contour, the break is insignificant. Such feature is characteristic to all three shapes of the roof top (round, with a vertical interceptor and triangular). Taking into account such distribution of the pressure, the internal point "*int*" is defined on the top of the roof, midpoint "*cnt*" – at the geometric centre between the newly placed point "*int*" and the point "*ext*" on the external contour.

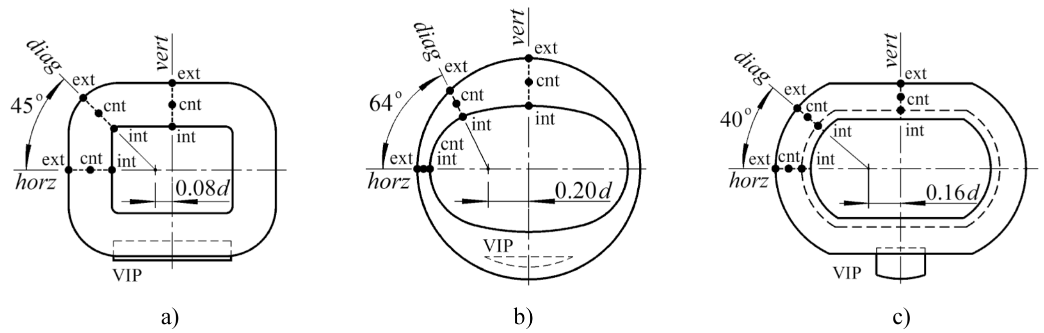


Fig. 10. Drainage lines with characteristic points on roofs of compared models: first (a); second (b); third (c)

Table 3. Data on differences of the investigated venues (which are noted by numbers)

Parameter	Unit	Reference value	Relative value of facilities		
			1st	2nd	3rd
Number of spectators	thous.	30	1	1.00	1.00
Total area , an external contour of roof is taken into account	thous. m^2	33	1	1.09	1.17
The length of the external contour	thous. m	0.66	1	1.02	1.09
The length of the internal contour	thous. m	0.40	1	1.27/0.82	1.24
*The area of an opening over the arena	thous. m^2	10.1	1	1.90/0.67	1.66
*The dimension along an opening of the arena	m	119	1	1.60/1.39	1.54
*The dimension across an opening of the arena	m	82	1	1.40/0.71	1.22
**The height of the roof over the arena	m	26	1	0.52/1.29	1.02
**The width of the roof	m	43	1	0.28/1.05	0.84
***The slope angle of the roof	deg.	6.5	1	0.71	2.3/4.6
The total area of the holes between the external walls and roof	thous. m^2	1.49	0	1	1.24
The total area of the cross section of pedestrian exits	m^2	336	1	1.85	1.31
The angle of a slope of the external walls	deg.	90	1	0.83	1

Comments:
*for the second model without the tent and with the half-stretched tent;
**for the second model min/max is presented;
***for the third model slope values to the external and internal contours are indicated.

Table 4. Differences during testing of the physical models

Parameter	Value for the model No.		
	the first	the second	the third
The scale of the physical model	1:120	1:150	1:130
Operational velocity within the wind tunnel (m/s)	27	30	30
Reynolds number	$4 \cdot 10^5$	$2 \cdot 10^6$	$2 \cdot 10^6$
Calibration factor of the pitot-static tube, ζ	0.997	1.004	1.004
Correction coefficient of an individual testing, ψ	1	1	1
Turn step of the model on the turntable (deg)	18	9	9
Number of the operational stops for measurement	20	40	40
The height of the pitot-static tube point over turntable (mm)	300	690	400
The maximum value of standard deviation	0.17	0.33	0.15
The average value of standard deviation	0.10	0.10	0.05
The recommended accuracy of aerodynamic coefficient, $\Delta\eta$	±0.10	±0.10	±0.10
The basic n-fold measurement	5	5	1000
The control n-fold measurement	20	10	5000
The number of drainage points	62	253	174
The distance on a model from a fixed drainage point to a contour of the roof (mm)	25	30	23

For the variants C and D (the second model with the tent), location of the points "*int*" and "*cnt*" does not change.

It is assumed that investigated lines are independent of influence of VIP blocks.

The distances from the symmetry centre on the venue plane to characteristic points are different in all three cases (Fig. 10). For line "*diag*" with respective characteristic points for each of venues the shift from the general symmetry centre to the additional local centre and appropriate rotation angle are also different.

Dependent comparison of the curves of the aerodynamic coefficient Eq. (5) with $\Delta\eta = 0$ on the angle of the airflow direction in considered points (Figs 11, 12 and 13) enables to note:

- the minimal value –0.946 of the coefficient of curves "*horz*"–"*ext*" is observed for variant A for an angle 0°; the maximal value +0.142 is given for C for the angle 315°;
- the character of all curves for point "*horz*"–"*ext*" is similar enough – negative values are clearly dominated. Transition from positive to negative values is smoother for variants C and D because of the tent;
- for functions "*diag*"–"*cnt*" the minimal value is –0.577 for variant B with the angle 207°; the maximal value of +0.378 is observed for C angle 27°;

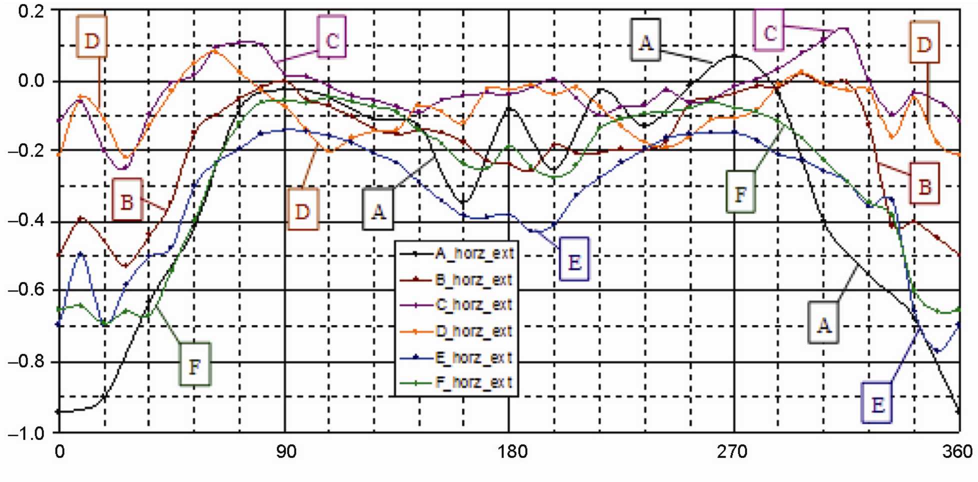


Fig. 11. The dependence of the aerodynamic coefficient at the point "*horz*"–"*ext*" on the turn angle of the model to the airflow

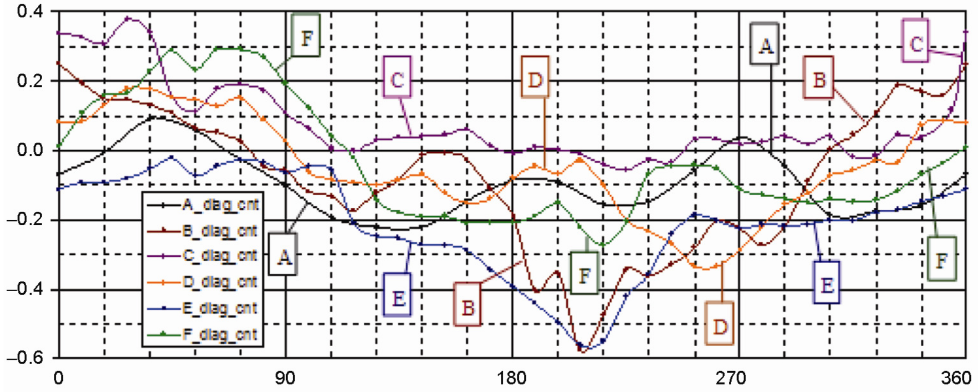


Fig. 12. Dependence of the aerodynamic coefficient at the point "*diag*"–"*cnt*" on the turn angle of the model to the airflow

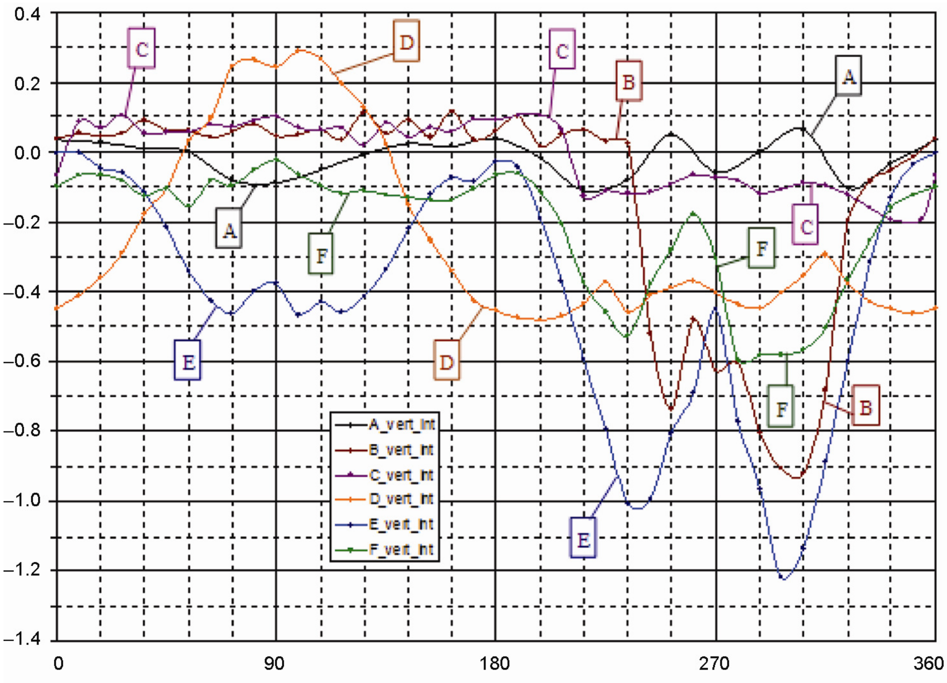


Fig. 13. Dependence of the aerodynamic coefficient at the point "*vert*"–"*int*" on the turn angle of the model to the airflow

- a character of curves for "*diag*"–"*cnt*" is similar, but values are different: for E – negative (due to the significant slope angle); for C – positive (because of increasing the width of the roof); for A, D and F – various (due to a small slope angle in A, closed openings for D, softening effect of the interceptor for F);
- for "*vert*"–"*int*" minimum is −1.217 for E angle 297°; the maximum +0.290 for D angle 99°;
- a character of curves "*vert*"–"*int*" is different, this indicates that pressure distribution depends on the airflow turn angle and the tent;
- comparison of curves (Figs 11, 12 and 13) reveals the symmetry to the relative angle of 180° of the first and the second group and the asymmetrical of the third group. The difference between values is observed as well. It points out that conditions of the internal contour are an essential factor for streamlining of the entire venue.

As it is known, for a flat plate in case when an attack angle of the airflow is small, a non-breaking streamline is observed. Such action causes appearance of breaking away aerodynamic force, which is typical for variants A and B.

Comparison of the values of the aerodynamic coefficient for separate points is of a selective character and does not illustrate a general tendency. For generalisation, the following assumption based on a preliminary review of the pressure distribution through the roof drainage lines is proposed: on a roof of any width $\lambda = 1$ the zone of width 1/6 with the highest non-stationary pressure and zone of width 2/3 with conservative pressure exist (Fig. 14). Therefore, it is appropriate to consider the averaged value of the aerodynamic coefficient, which expresses the entire drainage line:

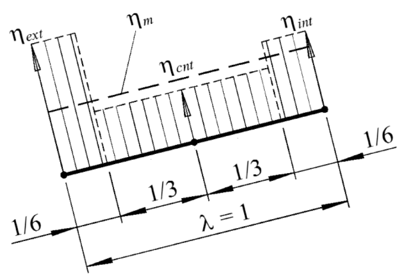
$$\eta_m = \frac{1}{6}\left(\eta_{int} + 4 \cdot \eta_{cnt} + \eta_{ext}\right), \tag{6}$$

Eq. (6) considers the pressure coefficients η together with their algebraic signs.

On the basis of the accepted assumptions in Eq. (6) the corresponding results were obtained (Fig. 15).

The analysis of the dependences of general aerodynamic coefficients η_m on the turn angle of the model to the airflow illustrates the following:

- extreme values of the general aerodynamic coefficient are presented below (Table 5);
- the first and the second dependences (Figs 15a and 15b) are almost symmetrically relative to angle 0° (or 180°), the third one is asymmetrical (Fig. 15c). Such feature shows similarity between general results and the above-analysed results for the individual points (Figs 11, 12 and 13). Obviously, general distribution of the pressure through the lines "*horz*" and "*diag*" is less dependent on the roof slope; the shape of the roof contours in the stadium plane and on airflow break conditions near contours;
- an analysis of general pressure distribution shows: increased negative pressure for variant E – influence of the curved shape of the roof and valuable roof slope in comparison with other variants was observed; positive and small values of the coefficients for variants C and D, which are explained by an increased width of the roof and change of break conditions on the internal contour.



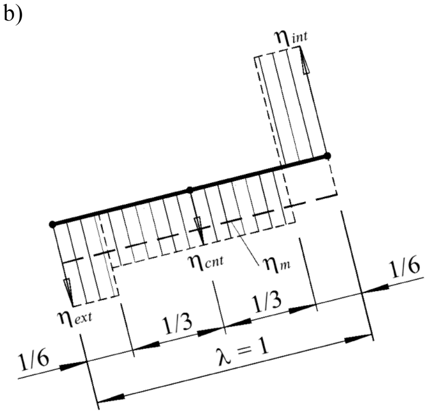
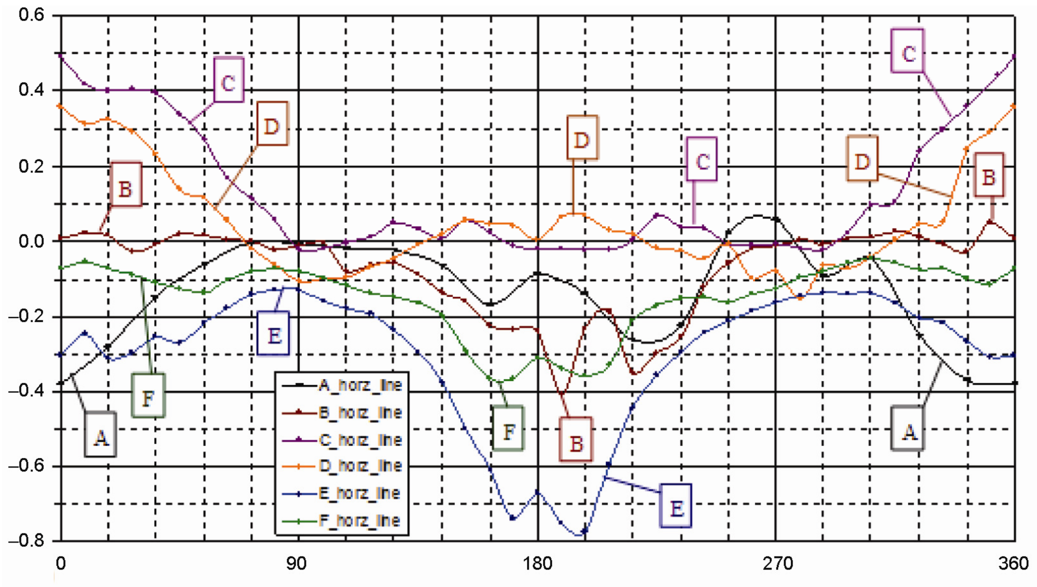


Fig. 14. Distribution of characteristic zones through the drainage line, when pressure is: of the same (a) and different directions (b)

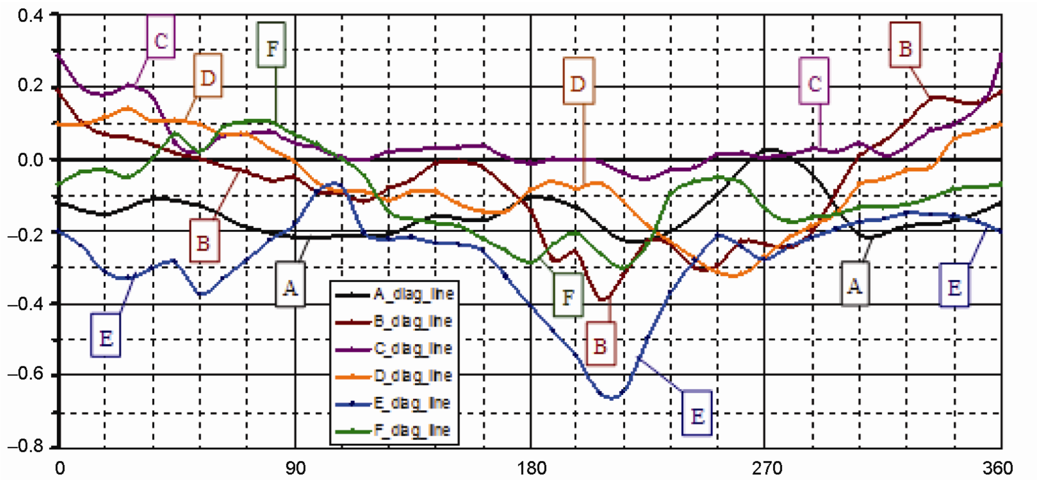
Table 5. Extreme values of general aerodynamic coefficients (see Fig. 15)

Var.	Line *horz*				Line *diag*				Line *vert*			
	deg	min	deg	max	deg	min	deg	max	deg	min	deg	max
A	0	–0.379	270	0.060	216	–0.225	270	0.025	72	–0.472	0	0.047
B	189	–0.406	351	0.051	207	–0.390	0	0.188	306	–0.635	162	0.007
C	207	–0.023	0	0.494	225	–0.053	0	0.284	354	–0.139	63	0.008
D	279	–0.157	0	0.360	261	–0.320	27	0.138	243	–0.431	90	–0.049
E	198	–0.773	81	–0.128	207	–0.649	108	–0.074	234	–0.500	0	0.002
F	162	–0.366	306	–0.044	216	–0.303	81	0.104	297	–0.223	81	0.095

a)



b)



c)

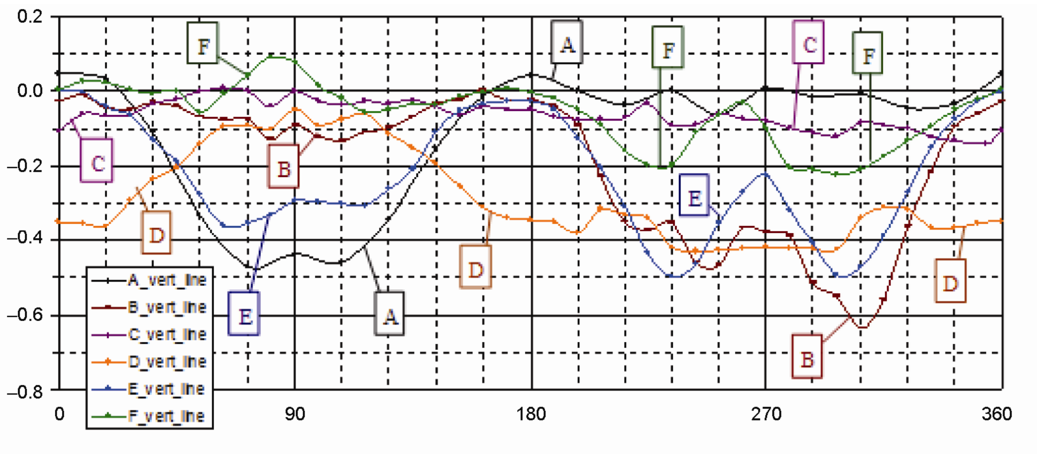


Fig. 15. Dependence of the general aerodynamic coefficient on the roof line "*horz*" (a), "*diag*" (b) and "*vert*" (c) on the turn angle of the model to the airflow

5. Conclusions and discussion

Investigation of aerodynamic properties of three different poorly streamlined models in various configurations during testing in the wind tunnel under many airflow directions allows making the following conclusions:

- for some characteristic points (selection of each could depend on a problem) comparison of the results is performed, the results are analysed, the pressure changes on the model surfaces depending on airflow directions are commented;
- the paper proposes the selection and comparison technique, which is based on the above-presented hypothesis and is suitable only for a certain type of specific venues;
- an exact estimation of the load distribution is significant in many engineering applications (Lazzari *et al*. 2009) as an example for optimisation problems; this allows to use materials taking into account structural reliability and to solve design problems at a higher level by using plastic deformations in case of variable loads (Jankovski, Atkočiūnas 2010, 2011; Atkočiūnas, Venskus 2011).

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TRIJŲ SUDĖTINGO PAVIDALO PRAMOGINIŲ STATINIŲ MAKETŲ BANDYMŲ REZULTATŲ GRETINIMAS

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S a n t r a u k a

Darbe trumpai apžvelgti vėjo poveikių eksperimentiniai tyrimai ir projektavimo normų taikymas aerodinamikos uždaviniams spręsti. Pateikti duomenys apie trijų sudėtingo pavidalo statinių maketų eksperimentinius tyrimus aerodinaminiame vamzdyje: metodika ir bandymų sąlygos, projektuojamų statinių aerodinaminės savybės, ypatingi maketų bruožai, bandymų rezultatai. Visi trys statiniai – europinio lygio universalieji stadionai. Nepaisant bendrosios funkcinės paskirties, kiekvieno statinio pavidalas ir tūrinis sprendinys yra originalūs. Darbe gretinamos bandymų sąlygos ir pasirinktiniai rezultatai, pasiūlytas sportinių ir pramoginių statinių gembinio stogo virš žiūrovų tribūnų aerodinaminių savybių nagrinėjimo kriterijus. Išanalizuotos slėgio ant maketų paviršių priklausomybės nuo oro srauto krypties, esant įvairiems bandymų variantams.

Reikšminiai žodžiai: aerodinaminis vamzdis, eksperimentiniai tyrimai, sudėtingas pavidalas, sporto ir pramogų statiniai, stadionai, gembinis stogas, gretinimo kriterijai.

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