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Model tests of global stability of two types of lightning protection masts under wind action

Modelowe testy globalnej stateczności masztów przy silnym wietrze

Abstract

The paper presents results of wind tunnel experiments of wind action on two free-standing lighting protection masts: cantilevered and tripod. Own similarity criteria concerning phenomenon of global stability loss were used in these tests. It was determined whether masts fulfill the requirements of overturning and shift global stability in range of base wind velocities adequate for Poland and different categories of terrain roughness according to the Eurocode [13]. Two possible forms of the loss of the global stability of lighting protection masts in strong wind were considered: overturning a mast and shifting of mast as a whole structures. The measurements were conducted for eight directions of wind attack, five positions of masts on the roof, two settings of the mast for tripod mast and one for cantilevered mast, two categories of terrain roughness. Conducted tests allowed to determine whether it is safe to locate tripod mast in all wind zones in Poland. Cantilevered mast can be located safely in I and II wind zone in Poland.

Keywords: wind tunnel test, masts, similarity criteria, global stability

Streszczenie

W artykule przedstawione zostały wyniki badań oddziaływania wiatru na dwa wolnostojące maszty odgromowe: pojedynczy i na trójnogu. W badaniach tych zastosowano własne kryteria podobieństwa dotyczące zjawiska globalnej utraty stateczności. Określono, czy maszty spełniają warunki stateczności globalnej na obrót i przesuw w zakresie prędkości bazowych wiatru adekwatnych dla Polski i różnych kategorii chropowatości terenu według Eurokodu [13]. Rozpatrywano dwie możliwe formy utraty globalnej stateczności masztów przy silnym wietrze: wywrócenie masztu (jako całości) i przesunięcie masztu (jako całości). Pomiary przeprowadzono dla ośmiu kierunków natarcia wiatru, pięciu położeń masztu na dachu, dwóch ustawień masztu na trójnogu i jednego ustawienia masztu pojedynczego, dwóch kategorii chropowatości terenu. Przeprowadzone badania pozwoliły na stwierdzenie, czy bezpiecznie jest ustawić maszt na trójnogu we wszystkich strefach wiatrowych w Polsce. Wykazano, że maszt pojedynczy może być ustawiony w I i II strefie wiatrowej w Polsce.

Słowa kluczowe: badania modelowe, maszty, kryteria podobieństwa, globalna stateczność

1. Introduction

Lightning protection plays an important role in protection against direct lightning strikes in buildings. The lightning protection mast is an ideal and low-cost solution to protect all types of objects from the destructive influence of atmospheric discharges. The free standing lightning protection mast is intended for lightning protection of devices on the roofs of buildings. It can find particular application on large surfaces – where we cannot afford on anchoring the structure to the roof. The self-supporting structure of the mast allows to avoid the perforation of the roofing material, so these masts can be used on flat roofs. In wind zones, it is necessary to predict increased load of the construction and apply appropriate measures to ensure its stability.

Wind action is one of the most important action in designing of free-standing lightning protection masts. Two types of lightning protection masts, i.e. cantilevered and tripod masts, were considered in this paper. Two possible forms of global stability loss of lightning protection masts in strong winds were tested and analysed: overturning and shifting of the masts as a whole structure. Investigations were conducted on models of the masts, so it had mainly practical aspect.

Problems of aerodynamics of such type of structures were considered in many publications e.g. [1–7] in the case of free-standing towers; and [8–12] in the case of guyed masts. Completely different aerodynamic and stability problems take place in the case of light small free-standing lightning protection towers placed on the building roofs, together with additional supporting ballast [13]. Taking it into account it is necessary to analyse this type of construction in the aspect of wind zones.

2. Considered research arrangements

Wind tunnel tests of the cantilevered and tripod free-standing masts of 4.0 m and 6.0m height (comp. Fig. 1) were carried out in a boundary layer wind tunnel of the Wind Engineering Laboratory at the Cracow University of Technology.

The basic dimensions of the wind tunnel working section are: 2.20 m (width), 1.40 m (height), 10.00m (length). Formation of the mean wind velocity profile and atmospheric turbulence takes place in the first part of the working section at the length of 6 m by use of respective turbulence elements: barriers, spires and blocks of respective geometry and mechanically controlled height. In the working section of the tunnel, there is a round rotational table of 2 m diameter which enables the change of a wind inflow direction on the examined model.

The masts models used in wind tunnel tests were made in a scale of 1:6.

The measurements were realized at the following measuring conditions and situations:

- Two terrain roughness category: suburban (III) and city (IV) according to Eurocode [13];
- Kind of roof: flat, covered with asphalt, rectangular (2:1), 15 meters height;

- Placement of masts on the roof according to Fig. 2.2; a distance between the building edge and mast vertical axis is 0.25 m in model scale (i.e. 1.5 meter in natural scale);
- Different arrangement of tripod mast on the roof with respect to wind direction as in Fig. 2.3(b);
- Eight directions of wind attack: N, NE, E, SE, S, SW, W, WN;
- Range of wind velocities: 22–36.2 m/s (I–III wind zones according to Eurocode [13]).

It gives 160 measuring cases for tripod mast and 80 for cantilevered mast.

Fig. 1. View of cantilevered mast MA4-4m (a) and tripod mast MAT6-6m (b)

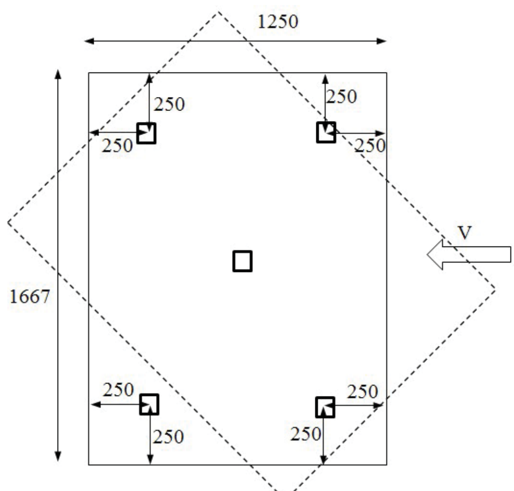


Fig. 2. Placement of masts on the roof in the model scale (dimensions in mm)

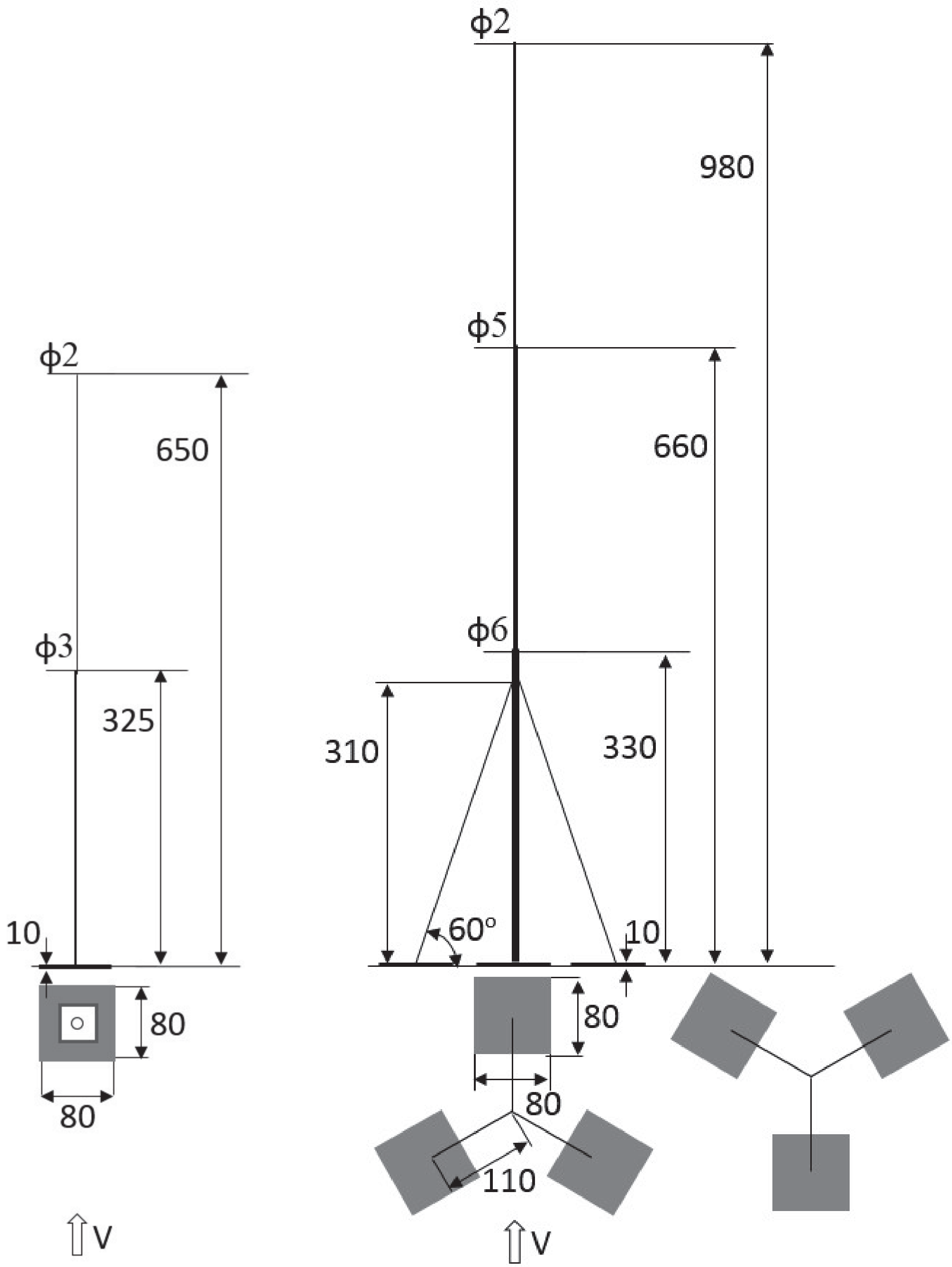


Fig. 3. Schematic drawing of masts settings of cantilevered MA4-4m (a) and tripod MAT6-6m (b) analyzed in the paper (dimensions in mm)

A view of the tested models in the wind tunnel working section is presented in Fig. 4.

Fig. 4.Models of the masts: cantilevered (a) and tripod (b)
in the wind tunnel working section

3. Simulation of boundary layer

During the ivestigations the wind profile was formed with use of barrier, spires and blocks. Thermo-anemometers were used to measure mean as well as fluctuation part of wind velocity in 6 points located in the working section of the wind tunnel on the height from 10 cm to 100 cm above the floor level in front of the model. Using power-low form of wind profile and data obtained from measurements, the following wind profile parameters were obtained:

$$V(z)=V_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{1}$$

$$z_{ref}=1\text{m},\ V_{ref}=11.9\frac{m}{s},\ \alpha=0.20$$

$$z_{ref}=1\text{m},\ V_{ref}=12.3\frac{m}{s},\ \alpha=0.24$$

where:
z_{ref} – reference height [m], α – exponent depend on terrain roughness, V_{ref} reference wind velocity.

Turbulence intensities were calculated according to the formula:

$$l_v(z)=\frac{\sigma(z)}{V(z)} \tag{2}$$

Obtained wind profile and turbulence intensity profile are shown in Fig. 5 (a) and (b). Red points mark values from wind tunnel tests and black line marks function determined by least-square regression. The turbulence intensity I_v on the reference level (z_{ref} = 1 m) was 13% for III and 29% for IV category of terrain roughness.

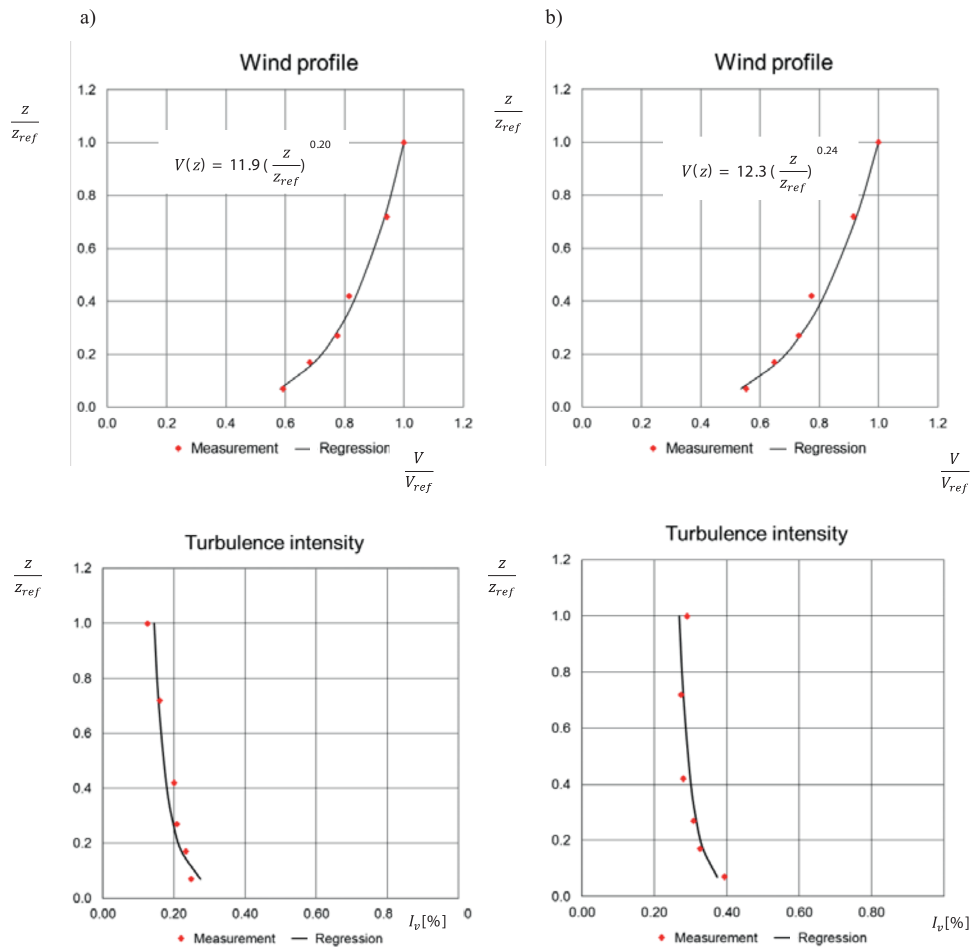


Fig. 5. Measurements results of wind characteristics: wind velocity profiles and turbulence intensity profiles for two categories of terrain roughness III (a) and IV (b)

4. Similarity criteria of global stability loss of lighting protection masts in strong wind

4.1. The definition of global stability loss

There are considered two possible forms of global stability loss of lighting protection masts in strong wind:

- Overturning a mast (as a whole structure);
- Shifting a mast (as a whole astructure).

Critical velocities of wind when these phenomena occur will be designated respectively as: V^{roll} and V^{shift}.

4.2. Variable quantities and parameters affecting for the loss of global stability of lighting protection masts

- Parameters characterizing the incoming air

$$\{W\}=\{\rho,\nu,V_{ref},V_H,V_b,\Theta,I_v\} \tag{3}$$

where:

ρ – air mass density.
ν – kinematic viscosity of atmospheric air,
V_{ref} – reference wind velocity,
V_H – wind velocity at the top of the model,
V_b – basic wind velocity for the given localization according to Eurocode [13],
Θ – angle of wind attack,
I_v – turbulence intensity (fluctuation) of wind velocity.

Geometrical quantities characterizing the particular structural element of the mast and the spatial relationships between them

$$\{G\}=\{\{x_e,y_e,z_e;\alpha_e,\beta_e,\gamma_e;c_e;D_e,L_e\};\{x,y,z;X,Y,Z\};\{d_e,h_e\},H,A\} \tag{4}$$

where:

x_e, y_e, z_e – local Cartesian coordinates of the structural element,
$\alpha_e, \beta_e, \gamma_e$ – angles defining spatial relationships between local system x_e, y_e, z_e and global system X, Y, Z,
c_e – curved contour coordinate of the cross-sectional element,
D_e, L_e – characteristic transverse dimension and length of the structural element,
x, y, z – coordinates of wind system which specifies the characteristics of air flow velocities,
d_e, h_e – diameter and height of the mast foundation,
H – height of the mast,
A – projection area of the mast in the vertical plane.

- Mechanical quantities characterizing the mast

$$\{O\}=\{\rho_{me},f,g,E\} \tag{5}$$

where:

ρ_{me} – material density of the structural element.
f – friction coefficient between the base of mast foundation and the upper surface of the roof.
g – gravity acceleration.
E – structure modulus of elasticity.

- Parameters characterizing wind effects on the mast system:

$$\{F\}=\{M_A, M_S, F_A, F_S\} \tag{6}$$

where:
M_A – aerodynamic rolling moment,
M_S – stabilizing moment due to mast weight,
F_A – aerodynamic sliding force,
F_S – aerodynamic stabilizing force due to friction.

4.3. The basic functional dependencies of the analyzed issue

Taking into account above sets of parameters, there can be determined functional relationships of the analyzed problem. Parameters of investigations depend on the following quantities sets:

$$M_A = f_{MA}(\{W\},\{G\}) \tag{7}$$

$$M_S = f_{FA}(\{G\},\{O\}) \tag{8}$$

$$F_A = f_{FA}(\{W\},\{G\}) \tag{9}$$

$$F_S = f_{FR}(\{G\},\{O\}) \tag{10}$$

In critical situation, which is the subject of these measurements, the global stability loss can appear in two cases:

(1) Aerodynamic rolling moment is equal to stabilizing moment, hence the starting point of the mast overturning:

$$V^{roll} = V_H\big|_{M_A = M_S; V_{ref} \leq V_b}; \qquad V^{roll} = f_{V^{roll}}(\{W\},\{G\},\{O\}) \tag{11}$$

(2) Aerodynamic sliding force equals drag force, so the starting point of the mast shifting:

$$V^{shift} = V_H\big|_{F_A = F_S; V_{ref} \leq V_b}; \qquad V^{shift} = f_{V^{shift}}(\{W\},\{G\},\{O\}) \tag{12}$$

4.4. Dimensional base of the issue and dimensionless quantities

Next step in dimensional analysis is to assume a dimensional base of the issue:

$$\{B\} = \{\rho, V_{ref}, H\} \tag{13}$$

Using above base and $\Pi\omega$ theorem (Buckingham's), the following dimensionless parameters can be obtained:

Dimensionless critical roll-over/ shift wind velocity	$\breve{V}^{roll} = \frac{V^{roll}}{V_{ref}}, \breve{V}^{shift} = \frac{V^{shift}}{V_{ref}}$
Reynolds numer	$Re = \frac{V_{ref}H}{\nu}$
Dimensionless wind velocities	$\breve{V}_b = \frac{V_b}{V_{ref}}, \breve{V}_H = \frac{V_H}{V_{ref}}$
Dimensioless geometrical quantities	$\{\breve{G}\} = \left\{\frac{x_e}{H}, \frac{y_e}{H}, \frac{z_e}{H}; \frac{c_e}{H}, \frac{D_e}{H}, \frac{L_e}{H}\right\}; \left\{\frac{x}{H}, \frac{y}{H}, \frac{z}{H}; \frac{X}{H}, \frac{Y}{H}, \frac{Z}{H}\right\};$ $\left\{\frac{b_e}{H}, \frac{h_e}{H}\right\}; \left\{\frac{A}{H^2}\right\}$
Dimensionless mass density	$\breve{\rho}_{me} = \frac{\rho_{me}}{\rho}$
The Froude number (dimensioless acceleration):	$Fr = \frac{V_{ref}^2}{gH}$
The Cauchy number	$Ca = \frac{\rho V_{ref}^2}{E}$

4.5. The Π theorem of dimensional analysis and similarity criteria

The following dimensionless relationships can be presented on the base of theorem of dimensional analysis:

$$\breve{V}^{roll} = \breve{f}_{V^{roll}}\left(Re, \breve{V}_b, \breve{V}_H, \Theta, I_v, \left(\breve{G}\right), \breve{\rho}_{me}, Fr, Ca\right) \tag{14}$$

$$\breve{V}^{shift} = \breve{f}_{V^{shift}}\left(Re, \breve{V}_b, \breve{V}_H, \Theta, I_v, \left(\breve{G}\right), \breve{\rho}_{me}, f, Fr, Ca\right) \tag{15}$$

All dimensionless quantities appearing in these functional relationships are the similarity criteria of the analyzed issue.

4.6. Similarity scales in the model tests

The following denotations were adopted in further analysis: superscripts M and P relates to model and prototype (object in natural scale), respectively.

The assumptions assumed in model tests are as follows:

(3) It is assumed one geometric scale k_H for all geometric quantities;

(4) A model will be made of the same materials as the prototype, hence a scale of material similarity will be fulfilled (k_{ρ_m} =1.0);

(5) It is assumed one velocity scale k_V for all velocities;

(6) Directions of the wind attack and turbulence intensity will be the same in model tests and in the nature;

(7) The friction coefficient f in model tests will be similar with the coefficient in nature ;

(8) Gravity acceleration in model tests and in nature is the same i.e. k_H = 1.0 ;

(9) The fulfilment of similarity criteria for Froude number can be written as:

$$Fr^M = Fr^P; \left(\frac{V_{ref}^2}{H}\right)^M = \left(\frac{V_{ref}^2}{H}\right)^P \tag{16}$$

On the base of above, it can be defined wind velocity scale:

$$k_V = \sqrt{k_H} \tag{17}$$

The fulfilment of similarity criterion for Reynolds number can be presented as:

$$Re^M = Re^P; \left(\frac{V_{ref}H}{\nu}\right)^M = \left(\frac{V_{ref}H}{\nu}\right)^P \tag{18}$$

hence:

$$k_V = k_D \tag{19}$$

This criterion is inconsistent with the criterion of Froude number, but the range of wind velocity for both models and prototypes will be at a subcritical range of *Re* number. Hence, unfulfillment of Reynolds criterion does not result in essential mistakes in outcomes of tests in model and natural scales.

Fulfilment of Cauchy number similarity criterion leads to the relationships:

$$Ca^M = Ca^P; \left(\frac{\rho V_{ref}^2}{E}\right)^M = \left(\frac{\rho V_{ref}^2}{E}\right)^P \tag{20}$$

hence:

$$k_V = 1 \tag{21}$$

This criterion would be fulfilled only if k_D = 1 (with respect to Eq. (15)). In model tests a geometrical scale was assumed as $k_H = \frac{1}{6}$ = 0.17. So, assuming Froude number as a basic similarity criterion, the velocity scale is: k_V = 0.41. It is impossible to fulfill criteria of Froude and Cauchy numbers simultaneously with adopted assumptions.

In problem of stability loss of such type of structures the most meaningful are structure gravity forces, so fulfillment of Froude number is essential. Vibrations of mast have secondary role in stability loss, hence unfulfillment of Cauchy number is not significant negligence in practical assessment of investigated phenomena.

Hence, respective basic velocities in model scale for I-st and III-rd wind zones can be determined:

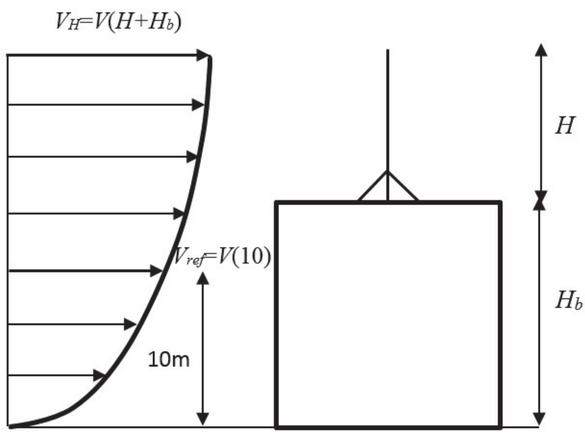
$$V_I^P = 22.0 \text{ m/s} \quad V_I^M = 8.98 \text{ m/s} \tag{22}$$

$$V_{III}^P = 36.2 \text{ m/s} \quad V_{III}^M = 14.78 \text{ m/s} \tag{23}$$

5. Quantities characterizing wind velocity field

5.1. Initial information

Relations for 10-minutes mean wind velocities are shown in Fig. 6.



H_b=15m (height of the building), H=4m/6m (height of cantilevered mast/tripod mast)

Fig. 6. Relations for mean 10-minutes mean wind velocities

According to Eurocode [13] vertical profile of mean wind velocity is described by:

$$V(z) = c_r(z) \cdot c_o(z) \cdot V_b \tag{24}$$

where:

$c_r(z)$ – terrain roughness coefficient dependent on terrain category roughness,
$c_o(z)$ – orography coefficient (assumed as 1.0),
V_b – base wind velocity dependent on the wind zone.

For two categories of terrain roughness (III, IV) the coefficient $c_r(z)$ can be given by:

Terrain category	$c_r(z)$
III	$0.81\cdot\left(\frac{z}{10}\right)^{0.19}$; for $z=10\text{m}$ $c_r=0.81$
IV	$0.62\cdot\left(\frac{z}{10}\right)^{0.24}$; for $z=10\text{m}$ $c_r=0.62$

Reference wind velocity is defined as follows:

Terrain category	$V_{ref}=V(z=10m)$
III	$0.81V_b$
IV	$0.62V_b$

Base velocities for I–III wind zones are assumed as:

$$V_{b,I}=22.0\text{m/s};\ V_{b,III}=36.1\text{m/s}\ (30\text{m/s})$$

Therefore, in the natural scale there will be following velocities for respective masts:

Terrain category	$V(15+4)=V(19)$ – cantilevered mast
III	20.13 m/s
IV	15.91 m/s

Terrain category	$V(15+6)=V(21)$ – tripod mast
III	33.67 m/s
IV	26.74 m/s

5.2. Relations for stream velocity in model scale

Reference wind velocity in model scale can be written as follows:

Terrain category	$V_{ref}^M=V^M\left(z\cdot k_H=1.67m\right)$
III	$0.81V_b^M$
IV	$0.62V_b^M$

Taking into consideration the velocity scale, one may obtain model base velocity:

$$V_b^M=k_V\cdot V_b=0.408V_b=\begin{cases}8.98\dfrac{\text{m}}{\text{s}}-\text{I wind zone}\\ 14.73\dfrac{\text{m}}{\text{s}}-\text{III wind zone}\end{cases} \tag{25}$$

Velocities in model scale for both masts and different terrain categories are summarized below:

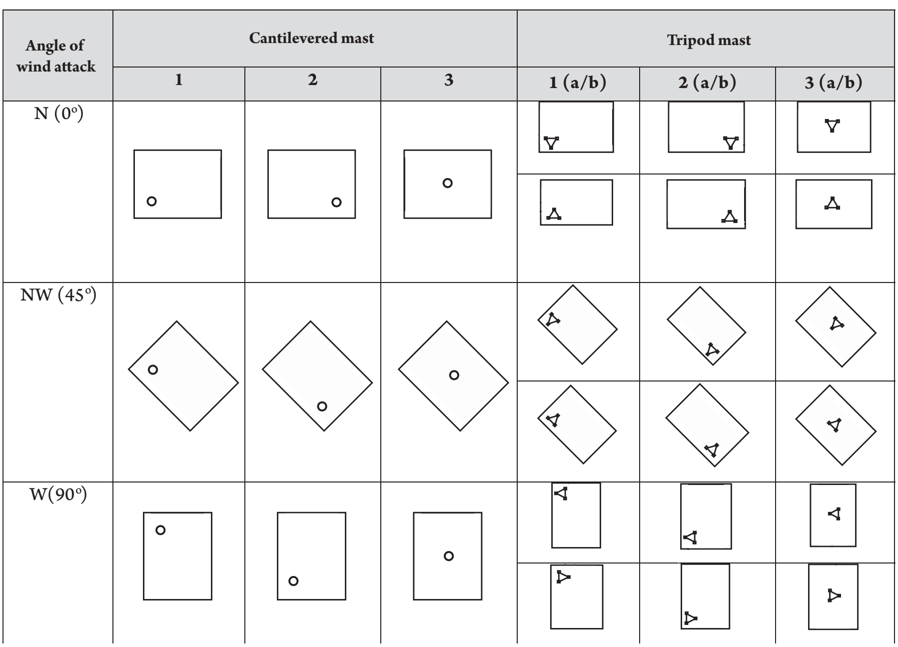
Terrain category	I wind zone	
	$H = 4m$	$H = 6m$
III	8.21 m/s	8.37 m/s
IV	6.49 m/s	6.65 m/s

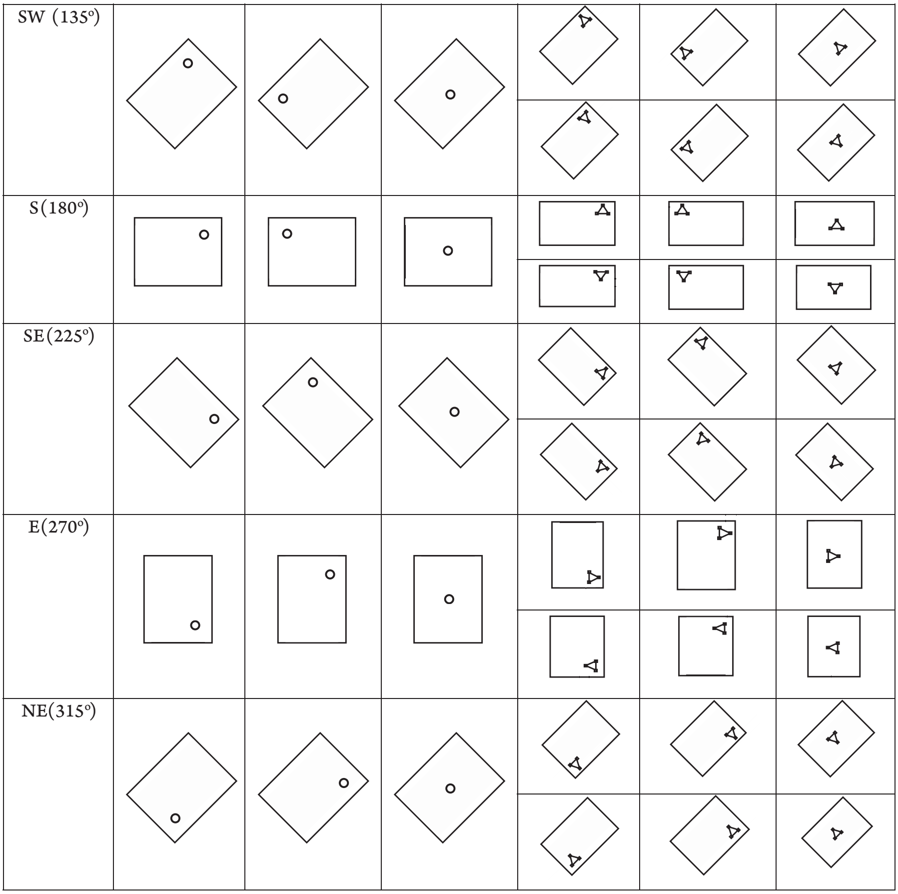
Terrain category	III wind zone	
	$H = 4m$	$H = 6m$
III	13.48 m/s	13.74 m/s
IV	10.65 m/s	10.91 m/s

6. Results of experiments

A set of arrangements for cantilevered and tripod masts for different angles of wind attack is given in Tab. 1. In further analysis, the respective masts arrangements are identified by the prescribed numbers given in Fig. 7–12. These figures show wind velocity at which masts started losing its stability because of foundation one-side-lifting. It can be interpreted as V^{roll}. There are also marked dash lines of basic wind velocity for I and III wind zones. All presented velocities are in model scale.

Table 1. Set of arrangements for cantilevered and tripod masts





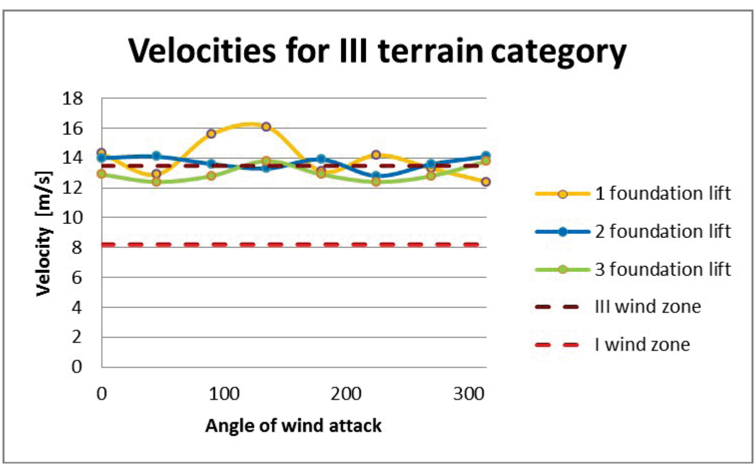


Fig. 7. The velocities of the windward foundations lift for cantilevered mast and III terrain category

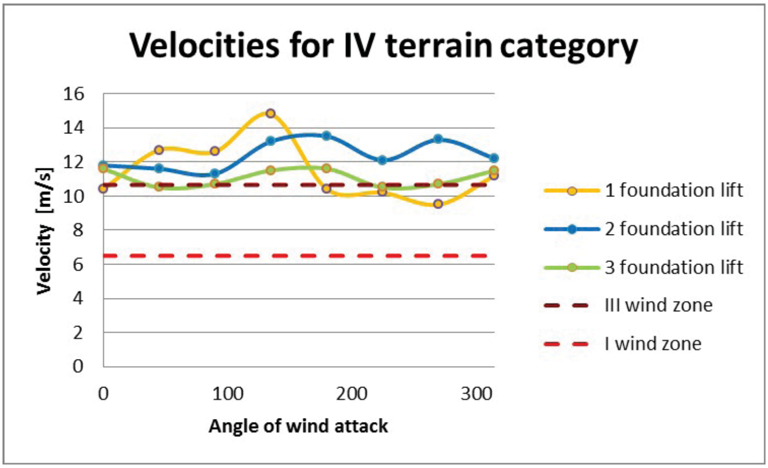


Fig. 8. The velocities of the windward foundations lift for cantilevered mast and IV terrain category

Two states of masts arrangements were distinguished from results of measurements: favourable and unfavourable. As favourable for cantilevered mast are considered these cases when wind velocity which caused one-side foundation lift was high, say generally greater than basic wind velocity in III wind zone . The opposition to them were unfavourable arrangements when stability loss appeared at wind velocities lower than basic wind velocity in III wind zone.

On the base of results given in Fig. 7, 8, the following conclusions concerning cantilevered mast can be drown:

- The most unfavorable angles of wind attack for both terrain categories appear in the situations when mast is localized in the middle of the building roof;
- The most favorable angles of wind attack for both terrain categories appear in the situations when mast is localized on the leeward side of the building;
- The most unfavorable mast arrangement:
  - Terrain III: 3rd ;
  - Terrain IV: 3rd (but for the angles of wind attack above 180 1st arrangements is the most unfavorable);
- The most favorable mast arrangement:
  - Terrain III: 1st;
  - Terrain IV: 1st (only for the angles of wind attack below 180), 2nd (whole range of the angles of wind attack);
- Windward foundations lift: for IV terrain category it appears much faster ($10 - 14\frac{m}{s}$) than for III ($12 - 16\frac{m}{s}$). In most cases foundation lift for III terrain category starts at the wind velocity below the velocity for III-rd wind zone. Regarding to IV terrain category, foundation lift starts generally at the velocity above the velocity for III-rd wind zone.

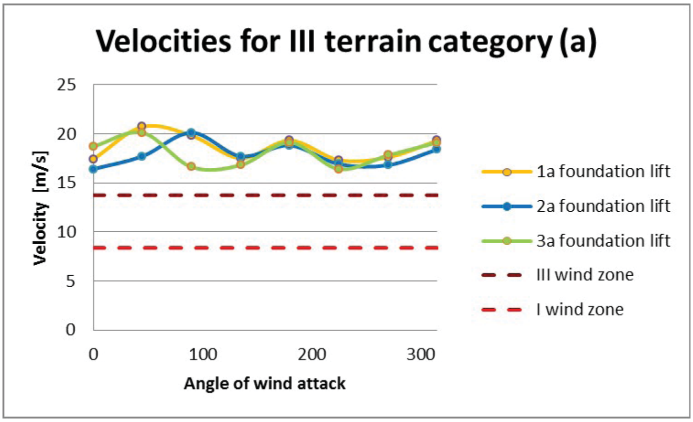


Fig. 9. The velocities of the windward foundations lift for tripod mast and III terrain category for arrangements 1a–3a

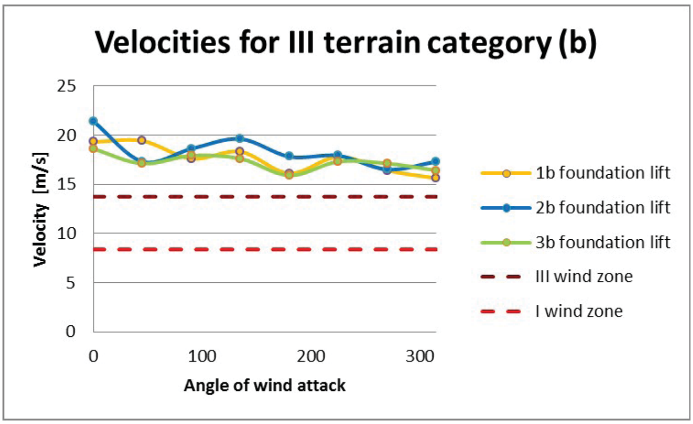


Fig. 10. The velocities of the windward foundations lift for tripod mast and IV terrain category for arrangements 1a–3a

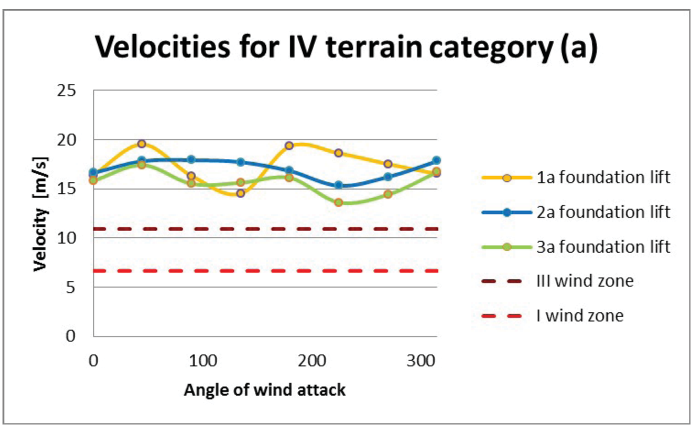


Fig. 11. The velocities of the windward foundations lift for tripod mast and III terrain category for arrangements 1b–3b

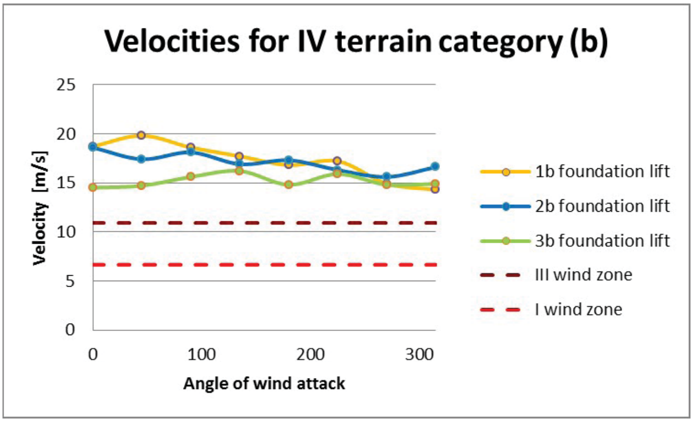


Fig. 12. The velocities of the windward foundations lift for tripod mast and IV terrain category for arrangements 1b–3b

As favourable for tripod mast are considered these cases when wind velocity which caused one-side foundation lift was greater than 1.22 basic wind velocity in III wind zone (16.7 m/s). The opposition to them were unfavourable arrangements when stability loss appeared at lower wind velocities. It was decided to use coefficient of 1.22 because the mass of tripod mast is higher, so consequences of its overturning would be greater than in the case of cantilevered mast.

On the base of results given in Fig. 9–12, the following conclusions concerning tripod mast can be formulated:

- The most unfavorable angles of wind attack for both terrain categories appear in the situations when one mast leg is on the windward side and two legs are on the leeward side of the mast; the most favorable are the opposite situations;
- The most unfavorable mast arrangement:
  - Terrain III: 3rd (a and b) ;
  - Terrain IV: 3rd (a and b);
- The most favorable mast arrangement:
  - Terrain III: 1st (a), 2nd (b);
  - Terrain IV: 1st (a) (beside the range of the angles of wind attack between 45–180° (a)), 2nd (a) in the range of the angles of wind attack 45–180°;
- Windward foundations lift: for IV terrain category it appears a little earlier (14–20$\frac{m}{s}$) than for III (16–21$\frac{m}{s}$). Phenomenon occurs above wind velocity for I-st and III-rd wind zone for both terrain categories. It starts at the wind velocity greater than the velocity for III-rd wind zone of for III terrain category and of 3$\frac{m}{s}$ for IV terrain category.

The results of particular wind velocities obtained in these investigations are summarized in Tab. 2.

Table 2. Particular wind velocities obtained in wind tunnel tests for different mast arrangements and terrain categories for both types of masts

Type of mast	Terrain category	Masts arrangement		Velocity of windward foundations lift Vroll[m/s]	Velocity for I-st wind zone [m/s]	Velocity for III-rd wind zone [m/s]
Cantilevered mast	B	1		12–16	8.2	13.5
		2		13–14		
		3		12–14		
	C	1		9.5–15	6.5	10.7
		2		11–14		
		3		10–12		
Tripod mast	B	1	a	17–20.5	8.4	13.7
			b	15–20		
		2	a	16–20		
			b	17–21		
		3	a	16–20		
			b	16–19		
	C	1	a	14.5–20	6.7	10.9
			b	14.5–20		
		2	a	15–18		
			b	15.5–19		
		3	a	13.5–17		
			b	15–16		

7. Final conclusions and remarks

7.1. General conclusions

Basing upon results of obtained velocities which cause windward foundations lift, the following two general conclusions can be drawn:

1. The cantilevered mast is safe with respect to global stability loss in the range of the base wind velocities up to 30 m/s.
2. The tripod mast is safe with respect to global stability loss in the range of the base wind velocities up to 36.2 m/s.

These conclusions concern nature scale. On the base of them one can state that it is safe to locate tripod mast in all wind zones in Poland. Cantilevered mast can be located safely in I and II wind zone in Poland. It should be pointed out that even if free-standing mast are located in appropriate wind zone, there will be still need to check local features of their localization place. One must take care of any circumstances which could increase wind action on masts and, in such cases, examine this instance separately.

7.2. Factor of safety for lightening protection masts design

During design of lightening protection masts there should be taken into consideration uncertainty of input data, mainly as: wind velocity field, location of the mast on the roof, geometry of the building or the roof, computational model of global stability loss of roll-over or shift type, possible measuring errors during wind tunnel tests, etc.

On the base of included in Eurocodes procedures and taking into account the fact that wind action on buildings depends, with enough assessment, on wind velocity square, it is recommended in this study to introduce safety factor for lighting protection masts design, defined as follows:

$$\gamma_m = \left(\frac{V_{H,\min}^{model,roll}}{V_{H,b}^{model}} \right)^2 \geq 1.5 \qquad (26)$$

so:

$$\frac{V_{H,\min}^{model,roll}}{V_{H,b}^{model}} \geq 1.22$$

where:

$V_{H,\min}^{model,roll}$ – the smallest velocity of lightening mast roll-over in model tests measured at the top height of the mast;

$V_{H,b}^{model}$ – base wind velocity in model tests measured at the top height of the mast.

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