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SOME INSIGHTS ON THE OPTIMAL SCHEMES OF TALL GUYED MASTS

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Abstract. The article presents the technique for simultaneous topology, shape and sizing optimisation of tall guyed masts under wind loadings and self-weight using simulated annealing. The objective function is the mass of the mast structure including guys, while the set of design parameters may consist of up to 10 parameters of different nature. The constraints are assessed according to Eurocodes and include the local and global stability constraints, limitations on the slenderness in mast elements, and strength constraints. The proposed optimisation technique covers three independent parts: the optimisation algorithm, meshing pre-processor that yields computational scheme of mast depending on the design parameters, and finite element program evaluating the objective function and constraints via penalisation technique. As an example the results of optimisation of a typical 60 m tall guyed telecommunication mast with different antenna areas are presented. On the basis of these results, the authors try ascertaining the approximate optimal diapasons of geometry and topology parameters such as the width of the shaft, distance of the guy foundation from the mast axis, heights of the guy attachment levels and so on. The authors hope, this will be helpful for constructors as an initial design of mast topology, shape and element sizing.

Keywords: tall guyed mast; global optimisation; stochastic algorithms; optimal ranges of geometry; topology parameters.

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Introduction

In the last decade, the amounts of design and construction of tall erections increased significantly in Lithuania. The main reason behind this development is the expansion of the telecommunications business and, consequently, the development of telecommunications networks, which stimulates research and innovations of tall structures and steel guyed masts among them.

It should be noted that those non-linear prestressed structures were analysed in a number of research papers (Melnikov 1969; Gantes *et al.* 1993; Juozaitis, Šapalas 1998; Smith 2007). Different analytical and computational methods for evaluation of strain-stress behaviour of tall masts are suggested (Voevodin 1989; Wahba *et al.* 1998; Yan-li *et al.* 2003; Gioffrè *et al.* 2004; Juozapaitis *et al.* 2008). Considerable part of these papers deals with dynamic analysis of masts (Melbourne 1997; Peil *et al.* 1996; Gioffrè *et al.* 2004). Several investigations pursue refinements of steel masts seeking for the least possible weight (or, in other terms, cost) of structure (Melnikov 1969; Gantes *et al.* 1993; Jasim, Galeb 2002;). In many cases, the refinement of structure is understood exclusively as the selection of geometrical scheme of mast's shaft elements, that is, leg, bracing and stiffener members, and the dimensioning of cross-sections (Voevodin 1981, 1989; Jatulis *et al.* 2007). However, the maximum effectiveness of pre-tensioned slender structures can be achieved simultaneously aligning all their geometric and physical parameters (Abdulrazzag, Chaseb 2002).

Tall masts can be categorised into two main groups depending on mast-foundation connection scheme: pinned at the foundation and fixed. In case of pinned masts, stresses in the leg are distributed more evenly. In case of fixed masts, horizontal displacements of a shaft cause significant bending

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moments at the support, and the maximum stresses develop in the lowest sections of mast. Such uneven distribution of stresses is irrational and determines substantially more heavy structure compared with pinned masts. However, pinned masts have their inherent shortages. Firstly, the shaft must be strutted at the assemblage stage of a mast. Secondly, the hinged connection at the support does not provide the torsional stiffness of the mast; therefore, either the anti-twist tackle ('mounting star') or sophisticated support construction that do not transfer the bending moment but assure the needed torsional stiffness, must be set up. Due to these drawbacks of a pinned scheme, the majority of masts constructed in Lithuania are fixed at their foundation.

Usually, the mast structures are produced and constructed in certain quantities as typical structures depending on the type of a terrain and area of antennas. Therefore, optimisation of such structures is a relevant engineering problem.

In case of pinned masts, the rational diagram of bending moments in the shaft (and consequently, the even distribution of stresses in the legs) can be obtained by tuning first of all, the geometrical and physical parameters of guys. The problem of optimal design of pinned masts is dealt with in Jatulis and Juozapaitis (2009). The same solution is not possible in case of fixed masts, where the bending stiffness of a shaft has a greater influence on bending moments at the support. Obviously, the lower values of shaft bending stiffness would produce lower bending moments. However, the low stiffness of the shaft implies small leg's second moments of inertia and larger slenderness of structure; and, finally, the lower lifting capacity of the whole mast. Undoubtedly, guys have a significant influence on the behaviour of a mast, foremost on the magnitude of horizontal displacements, too. This implies the increase of the cross-sections of guys, but this is not acceptable due to at least two reasons. Firstly, guys are one of the most expensive elements of the mast structure. Secondly, in order to ensure the appropriate function of guys, which are absolutely flexible, they must be appropriately pre-stressed what leads to additional and unnecessary loads to the mast shaft. Thus, the optimal design of fixed masts is a complex problem that must be resolved simultaneously considering a number of design parameters of different nature.

In mathematical terms, optimisation of masts is a global optimisation problem. Since the number of design parameters is ten, only the stochastic optimisation algorithms seem promising and have been successfully employed for optimisation of slender structures. Thus, Uys *et al.* (2007) proposed a procedure for optimisation of steel towers under dynamic wind loading after the Eurocode 1 (2005). Paper of Venanzi and Materazzi (2007) deals with multiobjective optimisation of wind-excited structures based on the simulated annealing (SA) algorithm. The objective function involves the sum of squares of nodal displacements (i.e. a convenient alternative form of structure stiffness), and the in-plan width of the structure, however, the set of design parameters consists of only three variables.

Evidently, this complex optimisation problem also inspired the development of efficient problem-oriented stochastic algorithms. Zhang and Li (2011) combine shape and size optimisation of an electricity supply tower in two level algorithms, based on the Ant Colony algorithm. Luh and Lin (2011) employ modified binary Particle Swarm optimisation first for the topology optimisation of truss structures. Subsequently, the size and shape of members were optimised utilising the attractive and repulsive Particle Swarm optimisation. Deng *et al.* (2011) and Guo and Li (2011) proposed several successful modifications of genetic algorithms (GA) for optimisation of tapered masts and transmission towers.

In the present paper, the authors propose the simultaneous topology, shape and sizing optimisation of guyed mast using SA. Our aim is to obtain the minimum weight design with a set of design parameters containing up to ten variables of different nature. The SA and GA were found to be one of the most efficient stochastic algorithms for engineering optimisation problems (Belevičius *et al.* 2011). Among other factors, the SA was chosen due to the easiness of implementation and the need to align as few as two parameters to the problem: the initial temperature and annealing rate. Another advantage of SA (as well as GA) is its stochastic character: the optimisation problem has to be solved for a sufficient number of times, each time starting with a random solution in order to exclude the deviation of results. This usually leads to several optimum points with close objective function values, but corresponding to different topologies of the mast and different physical parameters of members' cross-sections, pre-tensions and so on; now, a designer can choose a relevant variant of a mast.

Then, on the basis of obtained optimisation results, the authors try ascertaining the approximate optimal parameters of typical telecommunications mast, such as ratios $l_1/l_2/l_c$, l_x/H, etc. (Fig. 1). Hopefully, this will be helpful for constructors as an initial design of mast topology, shape and element sizing.

1. Problem description

The authors choose to optimise a typical guyed broadcasting antenna for mobile-phone networks. The mast of a triangular cross-section is 59.6 m high and is supported by two clusters of guys (Fig. 1) fixed in conjoint foundations. The scheme of bracing and stiffeners is shown in Fig. 2; stiffeners are included between legs only at the levels of guy attachments. The

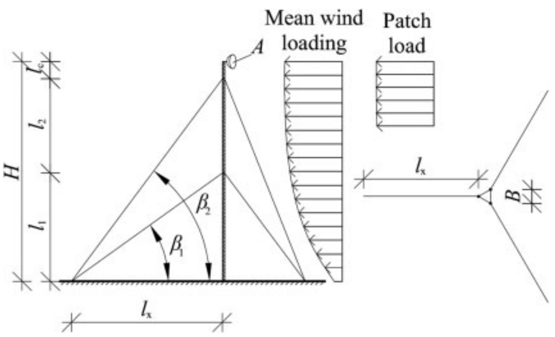

Fig. 1. Geometrical parameters of the mast and loadings

mast was optimised for different antenna areas: 0 m^2; 2 m^2; 4 m^2; 6 m^2; 8 m^2; and 10 m^2. The width of auxiliary equipment (Fig. 2) is constant for all cases and is equal to 0.1 m. The shape of the mast is determined by the coordinate of guys foundation l_x that conditions the angles of guys to the horizontal β_1 and β_2 (Fig. 1), the distances between clusters of guys l_1, l_2, l_c, the width of shaft B, and the number of typical sections along the height of the mast, which in turn conditions the angle between bracing and stiffener elements α.

The in-plane dimensions of mast are constant along the whole height.

The set of physical parameters of mast consists of the cross-sections of guys, legs, and bracing and stiffener elements, the A_g, A_L, A_B, correspondingly, and of pre-tension stresses in the guys of the first cluster σ_{01}, and in the second cluster $-\sigma_{02}$.

The mast scheme was optimised for one loading case. According to the Eurocode 3, Part 3–1 (2006), the most critical loading case consists of two loadings: the mean wind loading spread over the whole height of the mast as shown in Figure 1, and patch loading on the mast console-part plus half of distance between clusters of guys.

2. Idealisations and optimisation problem

The structural behaviour of guyed masts is extremely complicated. Especially, as guys exhibit a nonlinear behaviour, more at low pre-tensioning levels. Increasing pre-tension forces decrease the nonlinearity and enhance lateral stiffness; however, at the cost of increased compressive loads, and therefore, of a higher buckling probability of the mast. The mast itself can be also geometrically nonlinear due its slenderness and due to the substantial wind loading. In addition to wind loads, the loads of self-weight of the tower with all auxiliary equipment, and possible icing should be considered.

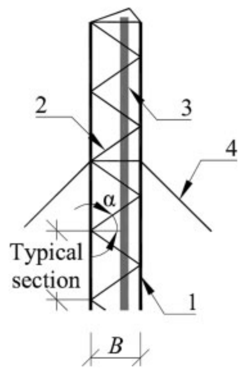

Fig. 2. Structure of the shaft: 1 – leg; 2 – bracing; 3 – auxiliary equipment; 4 – guy

The use of global optimisation algorithms inevitably requires analysing the computational scheme of the structure for thousands and millions of times; therefore, the very fast and reliable analysis tool that is able to solve the direct problem in less than a second, is a pure necessity. Consequently, the authors restrict the analysis to the linear stage, substituting guys by springs of equivalent horizontal stiffness and corresponding vertical compressive forces (Gantes *et al.* 1993). Also, despite the fact that wind forces are of a dynamic nature, and consideration of equivalent statical loads is not always adequate, according to the patch load method (Eurocode 1, Part 1–4 2005 and Eurocode 3, Part 3–1 2006) the authors only evaluate the statical wind loads, multiply them by coefficients of turbulent loading, and solve the statical problem. The structure of the mast is optimised for the most critical case of wind loading, when the direction of wind is at the right angle to one side of the mast, and when the load constituent due to turbulent wind is added only to the top zone of the mast. The loads of the self-weight of structure and equipment are accounted for, but not the ice loads; in Lithuania, heavy icing and extreme winds do not tend to occur at the same time (however, if one wants, inclusion of icing loads is straightforward). Therefore, the presented optimisation technique can be useful during the preliminary design stage of a mast, supplying the designer with hints regarding the topology and shape of the mast and the sizing of mast elements. Later, the chosen design should be verified by more accurate nonlinear analysis.

A finite element method (FEM) program is used as a 'black-box' routine to the optimisation program for solution of direct problem to find the stress/displacements fields in the structure, to verify all constraints, and to yield the value of the objective function. Here, the leg, bracing and stiffener elements are idealised as bending beam elements with 2 nodes and 6 typical degrees of freedom at each. Instead of guys, equivalent mixed stiffness/force boundary conditions are applied to guy attachment nodes. All the distributed loadings are amassed to the concentrated forces at nodes of the computational scheme. Fast problem-oriented original FORTRAN programs with a special mesh pre-processor have been developed and used.

Initial data for the mast optimisation problem are the following:

- Height of the mast;
- The in-plan geometrical scheme of the mast;
- The geometrical scheme of bracing;
- The geometrical dimensions of auxiliary equipment and antennas;
- Material data of beams and guys (Young's moduli, specific weights, material is treated as isotropic);
- Maximum allowable stresses in beams and guys;
- Maximum allowable deflection at the top of mast;
- Loading data;
- Lower and upper limits for radii of leg, bracing, stiffener members and guys.

Given all these data, the pre-processor of optimisation program guesses all design parameters (10 design variables and their feasible ranges are listed in Appendix 1). Then, the second pre-processor program prepares the complete computational scheme for finite element program.

The results of optimisation are the geometrical scheme of the mast including the distance of guy foundations from the axis of mast, all geometrical dimensions of structure members, and pre-tension forces in all clusters of guys.

Hereunder, the authors describe the optimisation problem formulation, principal software scheme, the simulated annealing algorithm used, and present the numerical results of optimisation of one typical mast.

3. Problem formulation

The optimisation problem is formulated as follows:

$$f^* = \min_{x \in D} f(x), \tag{1}$$

subject to:

- Constraints on overall stability of structure;
- Strength constraints in guy elements;
- Local stability constraints in all leg and bracing members;
- Global stability constraints between clusters of guys and between the lower cluster and mast foundation;
- Slenderness constraints in leg and bracing members;
- Lateral stability constraint of the mast top.

$f(x)$ in Eqn (1) is a nonlinear objective function of continuous variables $f{:}\mathrm{R}^n \to \mathrm{R}$; n is the number of design parameters x; $D \subset \mathrm{R}^n$ is a feasible region of design parameters. Besides the global minimum f^*, one or all global minimisers $x^*{:}f(x^*) = f^*$ should be found. No assumptions on unimodality are included into formulation of the problem, that is, many local minima may exist.

In this paper, the total mass of the mast including the mass of guys is considered as the objective function. Since the material of the guys is more expensive, the mass of guys is pre-multiplied by a given factor (in our numerical experiments, by 3). All strength, stability and slenderness constraints are assessed according to Eurocode 3, Part 1–1 (2005) and Eurocode 3, Part 3–1 (2006).

The overall stability of the mast is checked solving the statical problem. Particular computational scheme of the mast corresponding to the set of design parameters x is analysed using the 'black-box' finite element program. The main statics equation is:

$$[K]^{\mathrm{a}}\{u\}^{\mathrm{a}} = \{F\}^{\mathrm{a}}, \tag{2}$$

where: [K] is the stiffness matrix; {u} the nodal displacements; and {F} the active forces; a stands for the ensemble of elements. Expressions of element stiffness matrix can be found in many textbooks (e.g. Zienkiewicz, Taylor 2005).

The influence of guys on the behaviour of mast is modelled by linear springs that are attached to the nodes in the direction of wind. The total stiffness of guy cluster is (Gantes *et al.* 1993):

$$k = n\left\{T_p + \frac{\frac{1}{2}EA_g\left(\frac{l_x}{c}\right)^2}{1 + \left(\frac{mgl_x}{T_p}\frac{EA_g}{12T_p}\right)}\right\}\frac{1}{c}, \tag{3}$$

where: n is the number of guys in one set of guys; T_p is the pre-tension force in guy; E is Young's modulus of guy material; A_g is the guy cross-section area; l_x is the distance of guy foundation from the axis of mast; c is the length of guy; and mg is the dead weight of the guy per unit length. The compressive effects of one set of guys are idealised by the vertical compressive forces applied to the guy attachment nodes:

$$p = nT_p\frac{H}{c}, \tag{4}$$

where H is the height of the mast.

The first of inequality constraints, the strength constraints are checked in the guys, taking into account the axial force N for the allowable stress $\bar{\sigma}$:

$$\sigma = \left|\frac{N}{A_g}\right| \leq \bar{\sigma}. \tag{5}$$

The stability requirements for the leg and bracing members are posed according to the Eurocode 3, Part 3–1 (2006):

$$|\mathrm{N}| \leq \frac{\chi A f_y}{\gamma_{M1}}, \tag{6}$$

where: A is the cross-section area of the member; f_y is the steel yield point (dependent on the diameter of the member). The partial factor of resistance of members to member buckling γ_{M1} is taken to be 1.0 according to the Eurocode 3, Part 3–1 (2006). The reduction factor coefficient is evaluated according to:

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}_{eff}^2}}; \quad (7)$$

$$\Phi = 0.5\left[1 + 0.49\left(\bar{\lambda}_{eff} - 0.2\right) + \bar{\lambda}_{eff}^2\right]. \quad (8)$$

The effective non-dimensional slenderness is:

$$\bar{\lambda}_{eff} = \mathrm{k}\frac{\lambda}{\lambda_1}, \quad (9)$$

where $k = 1.0$ for leg members, and 0.7 for bracing elements. Here:

$$\lambda_1 = \pi\sqrt{\frac{E}{f_y}}, \quad (10)$$

If the length and radius of circular cross-section of the member are L and r, the slenderness is:

$$\lambda = 2L/r \quad (11)$$

The global stability requirements between adjacent clusters of guys according to the Eurocode 3, Part 3–1 (2006) are expressed in the form of mast segment buckling condition due to the equivalent compression force N_{Ed} and the equivalent bending moment M_{Ed} in the cross-section of the mast:

$$\frac{N_{Ed}}{\frac{\chi_y N_{Rk}}{\gamma_{M1}}} + \frac{M_{Ed}}{\chi_{Lt}\frac{M_{y,Rk}}{\gamma_{M1}}} \leq 1, \quad (12)$$

where: χ_y is the reduction factor for the relevant buckling mode; γ_{M1} is the partial factor of resistance of members to member buckling; N_{Rk} is the cross-section axial resistance; and the $M_{y,Rk}$ is the cross-section moment resistance (based on either the plastic, elastic or effective section modulus, depending on classification). The details on the evaluation of these coefficients may be found in Eurocode 3, Part 1–1 (2005).

The slenderness constraints for the mast segments between clusters of guys and slenderness constraints for bracing members, correspondingly, are:

$$\begin{matrix} \lambda \leq 120 \text{ and} \\ \lambda \leq 180 \end{matrix}. \quad (13)$$

The calculation of the buckling length of a mast segment needed for assessment of the first slenderness constraint takes significant numerical effort. Here, the authors use an approximate value of the buckling length that is equal to the segment length. In a successive non-linear design stage, the buckling length should be specified precisely.

Finally, the lateral displacement d of the mast top is constrained to:

$$d \leq H/100. \quad (14)$$

The complete set of design variables is listed in Appendix 1.

4. Optimisation technique and algorithm

The typical Simulated Annealing algorithm was chosen for optimisation. The best mast structure found by the random search in 300 evaluations is taken as the initial solution for the algorithm. At this stage, the authors equally treat all obtained solutions without respect to their viability; the mast structures that violate constraints are penalised. Then, the authors modify the current solution by changing values of the design variables. If better solution is found, the authors exchange the current solution with probability $p = 1$. Otherwise, the current solution is exchanged with probability:

$$p = e^{\frac{\Delta f \ln(1 + jx_2)}{x_1}}, \quad (15)$$

where: Δf is the difference between existing and permuted values of fitness function; j – iteration number; x_1 – initial temperature; x_2 – annealing rate. The following numerical values of parameters $x_1 = 800$, $x_2 = 2.0$ were chosen for our problem on the basis of numerical experiments. The algorithm is terminated after 1700 iterations; this is the minimal number of iterations to obtain the converged solution. Thus, one numerical optimisation experiment involves 2000 evaluations of the objective function.

5. Numerical results and discussion

The mast structure was optimised six times, at the antenna area of 0 m^2, 2 m^2, 4 m^2, 6 m^2, 8 m^2, and 10 m^2. Each time, 30 independent numerical experiments were executed starting from a random solution in order to exclude the deviation of results. The previous experience of authors with stochastic algorithms (Belevičius *et al.* 2011) shows that, for the number of design parameters till 20, 30 independent experiments yield at least a rational solution. One run of the optimisation algorithm takes on average six minutes using the PC Intel(R) Xeon(R) CPU E5420 @ 2.50 GHz, 3069 MB RAM, 32-bit Operating System, while full calculations (30 runs) takes about three hours.

The best results of mast optimisation at all variants of antenna areas are presented in Table A1. Despite the fact that several design variables, such as the radii of mast members, and so on, can take only values from some assortment, they are presented in

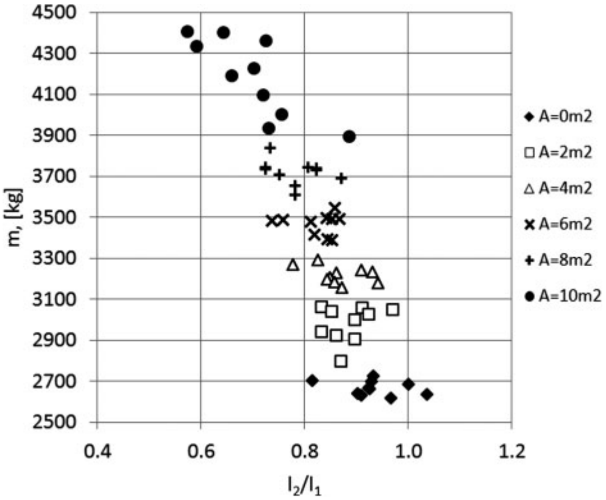

Fig. 3. Optimal values of ratio l_2/l_1

the format of real numbers. The authors do not employ the step-wise character of variable alternation since the algorithm is intended for the preliminary design of the mast. Later, these values can be rounded to the desirable in-stock values. Consequently, the modified mast structure will be slightly heavier. However, if compared to the corresponding designs of the mast obtained after the designing guides of tall steel masts (Kuznetzov *et al.* 1999; Steel Designers' Manual 2008), the optimised structures demonstrate significant material savings. The characteristics of technical designs in corresponding format are presented in Table A2; both optimised and technical designs pass all the specifications of Eurocodes.

On the basis of these six optimisation experiments, the authors try ascertaining the advantageous ratios between optimisation parameters at which the mast design achieves the lowest possible mass.

In Figure 3, the distribution of solutions in the space mast mass / ratio between the height coordinates

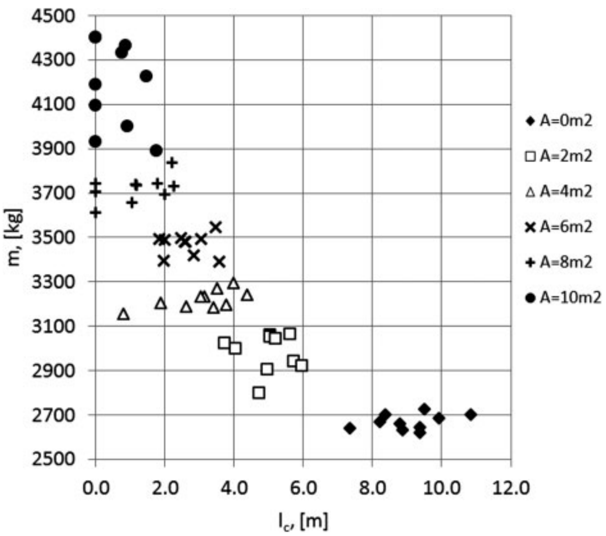

Fig. 4. The optimal length l_c

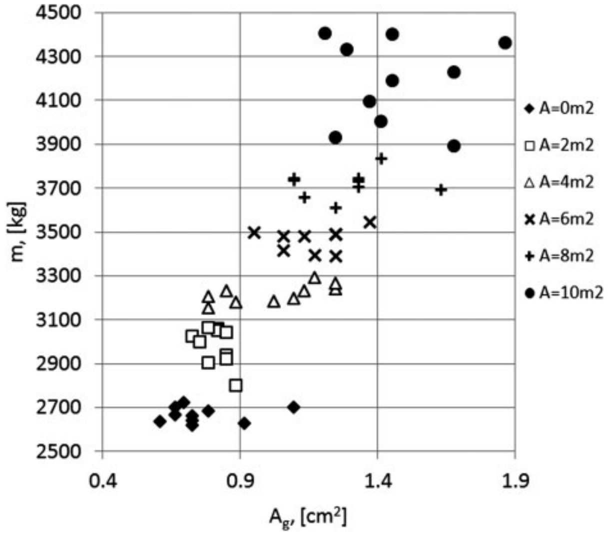

Fig. 5. Optimal area of guy cross-section A_g (all 6 guys have the same cross-section)

of guy attachment levels is shown. In order to have a more definite view, only ten best solutions are shown for each antenna area. A closer analysis of the results revealed that the first segment length l_1 should always be longer than the second one. The ratio seems to be universal for all antenna area values, the favourable value of ratio being $l_2/l_1 \approx 0.85$. Only for the antenna area value 0 m^2, three best solutions exhibit the best ratios varying from 0.9 to 1.05.

The results for the length of console part of mast l_c (Fig. 4.) are evident: a larger antenna area produces a greater bending moment, and therefore, the length of the console should be diminished. For areas $\geq 8m^2$, all best solutions have the minimal console part. For the least antenna areas, the height of the console part around 1/6 of the total mast height is beneficial.

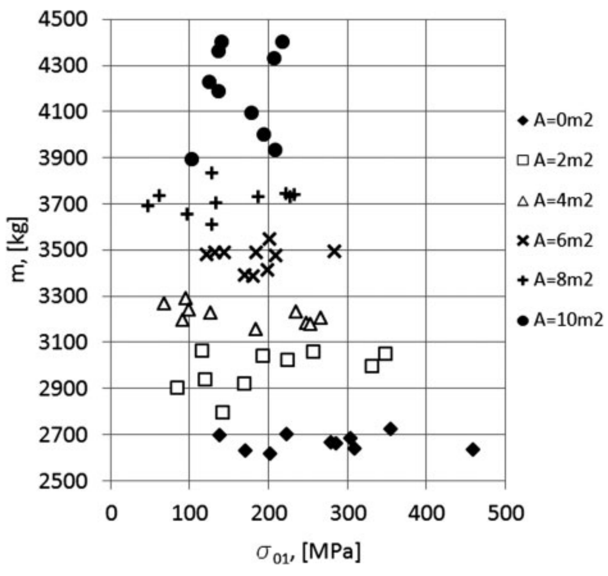

Fig. 6. Optimal pre-stress in guys of the first cluster σ_{01}

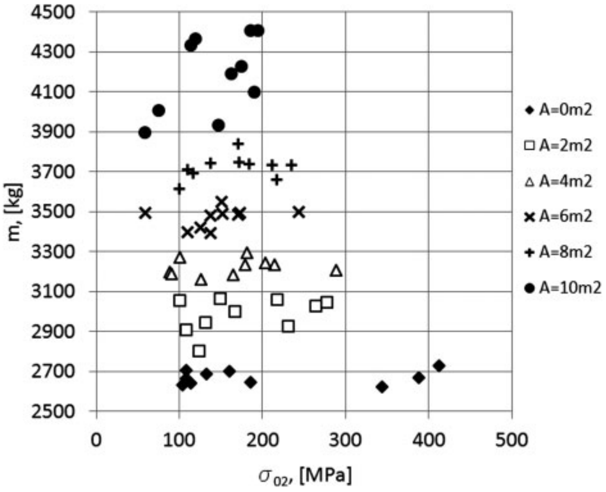

Fig. 7. Optimal pre-stress in guys of the second cluster σ_{02}

The obtained optimal areas of guy cross-section A_g (Fig. 5) show that the factor for the guy mass value being 3 (i.e. assuming the price of guys' material is 3 times higher than one of other materials) tend approaching the least values of the feasible range. For the antenna areas 0 m^2, 2 m^2 and 4 m^2, the optimal $A_g = 0.9$ cm^2.

The optimal pre-stress levels in guys of the first and second cluster (Figs 6 and 7) show, that the recommended value of pre-stress in the second cluster is lower and is approximately 100–150 MPa. The dissipation of results for the first cluster is higher; however, the pre-stress should not exceed 200 MPa.

Optimal values for the distance of guys foundation from the mast (Fig. 8) scattered in a wide diapason L = 35–57 m that corresponds to approximately ½–1 of the total mast height H. From this and ratio l_2/l_1, the optimal values for angles between guys and horizontal follow. Thus, the angles $\beta_1 = 30–35°$ are recommended for guys of the first level (Fig. 9), and angles $\beta_2 = 45–55°$ for the second-level guys (Fig. 10).

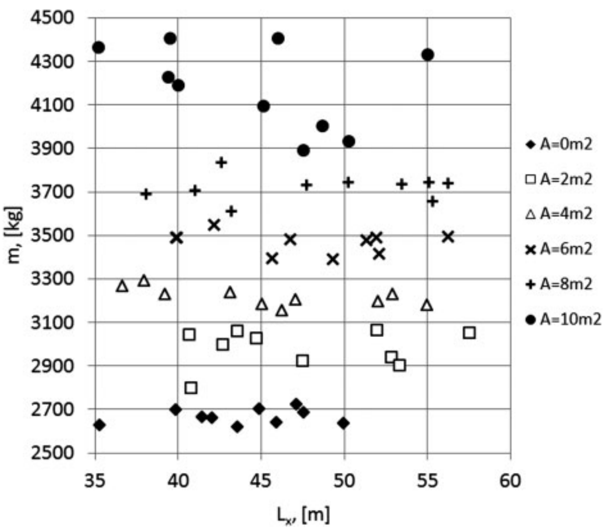

Fig. 8. Optimal values of guy foundation distance from the mast L_x

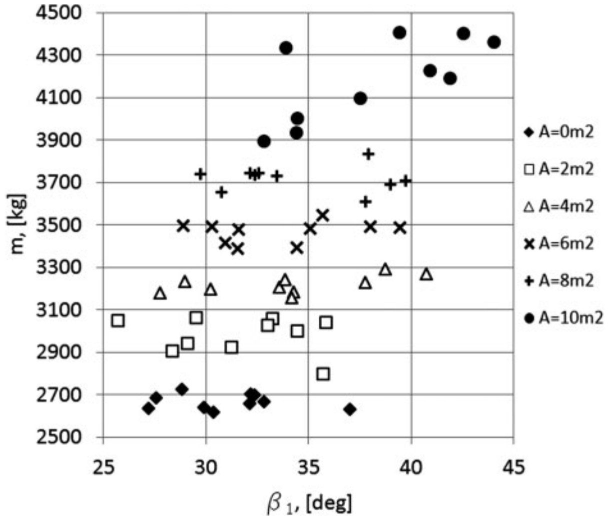

Fig. 9. Optimal angles between first-level guys and horizontal β_1

Contrary to the wide distribution of distances l_x, the rational values of shaft width B are concentrated in a narrow interval (Fig. 11) around the value 0.75 m, the optimal vales being in $B = 0.725–0.775$ m; this corresponds to a 1/80–1/75 of the total mast height.

One of the most important design parameters is the angle between bracing element and horizontal, on which the buckling length of leg depends. In terms of our set of design variables, it is derivative parameter of the width B and the number of typical section along the height of the mast. Dense deployment of bracing elements diminishes the buckling length of legs, and herewith the mass of legs. However, the total length of bracing elements increases together with the bracing mass. The optimisation results show (Fig. 12) that the

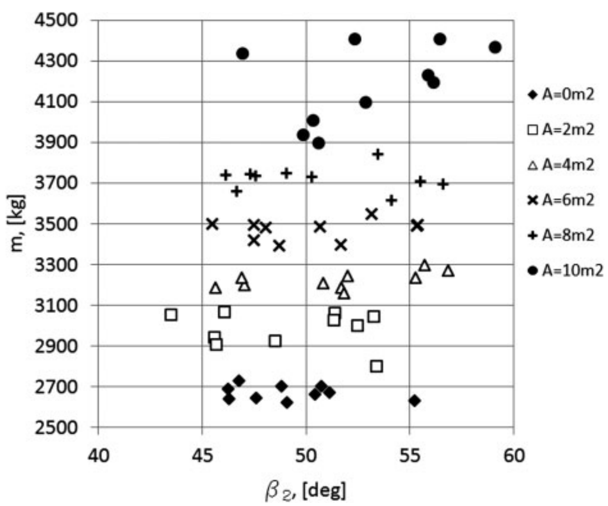

Fig. 10. Optimal angles between first-level guys and horizontal β_2

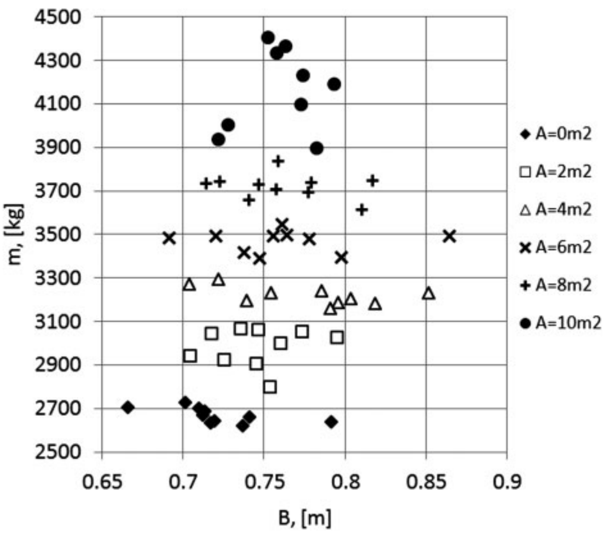

Fig. 11. Optimal width of shaft *B*

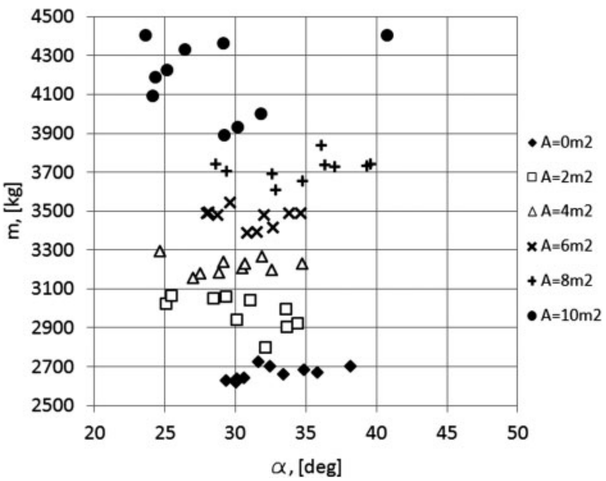

Fig. 12. Optimal angle between bracing element and horizontal α

optimal angle is in the narrow range of 27–33° despite the antenna area.

Conclusions

Computer hardware that is common to a typical civil engineering design bureau and a reasonable computation time does not allow precise, exhaustive global optimisation of tall guyed masts. However, one run of global optimisation of masts using simplified linear statical analysis program and stochastic optimisation algorithm is feasible in less than one hour on a common PC. Provided a several-core PC is available, the whole optimisation process (i.e. several tens of numerical experiments) can be executed per night. The delivered design may serve as a hint for the successive and more precise nonlinear dynamic analysis. Still, there is one advantage of the proposed technique: usually, optimisation renders a number of designs of different topology but of close objective function values; the designer may choose the most appropriate design.

Analysis of optimisation results of a typical 60 m tall guyed broadcasting antenna at different antenna areas reveals that the optimal design first of all depends on the shaft width *B*, the angle between bracing element and horizontal α, and ratios of guy attachment levels l_2/l_1 and l_c. Other design parameters exhibit a much lower impact on the optimal scheme of the mast. All these results may help a designer choosing the initial parameters of the mast scheme in a design process.

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Appendix 1. Design parameters and their feasible ranges (length parameters — in m, force parameters — in kN)

- Radius of column; [0.008, 0.040] – *r*1,
- radius of grid and stiffener elements; [0.010, 0.030] – *r*2,
- radius of guys; [0.001, 0.010] – *r*3,
- side of mast; [0.2, 1.6] – sw,
- number of typical sections along the height of mast; [1, 90] – *n*,
- distance of guy foundation from the mast axis; [0.31, 59.31] – d,
- first level of guys' triplets attachment, in sections; [1, 90]* – *n*1,
- second level of guys' triplets attachment, in sections; [1, 90]* – *n*2,
- pre-stress force in the first level guys; [5, 300] – s1,
- pre-stress force in the second level guys: [5, 300] – s2.

*These design variables are interdependent with the number of typical sections along the mast height and may vary from 1 to the number of sections that is chosen by SA.

Table A1. Results of optimisation: the best solutions in 30 independent experiments for each area of antenna

Area of antenna, m^2	Mass, kg	*r*1, m	*r*2, m	*r*3, m	sw, m	*n*	d, m	*n*1	*n*2	s1, kN	s2, kN
0	2620	0.0160	0.0097	0.0048	0.7369	70	43.5	59	30	14.6	24.9
2	2800	0.0163	0.0100	0.0053	0.7536	63	40.7	31	58	12.5	10.9
4	3158	0.0179	0.0099	0.0050	0.7913	74	46.2	73	39	14.4	9.90
6	3394	0.0173	0.0098	0.0063	0.7469	67	49.2	63	34	22.4	17.1
8	3614	0.0180	0.0107	0.0063	0.8103	57	43.2	57	32	15.9	12.3
10	3894	0.0173	0.0100	0.0073	0.7827	68	47.5	66	35	17.1	9.70

Table A2. Results of technical design for each area of antenna

Area of antenna, m^2	Mass, kg	*r*1, m	*r*2, m	*r*3, m	sw, m	*n*	d, m	*n*1	*n*2	s1, kN	s2, kN
0	3463	0.0165	0.0125	0.005	1.03	60	30.28	29	58	20.8	17.2
2	3727	0.0165	0.0125	0.006	1.03	60	30.28	29	58	10.0	14.8
4	4111	0.017	0.0125	0.007	1.03	60	30.28	29	58	5.30	37.8
6	4323	0.017	0.013	0.0075	1.03	60	30.28	29	58	5.47	21.0
8	4661	0.017	0.013	0.008	1.03	60	30.28	29	58	6.71	24.1
10	4965	0.017	0.013	0.009	1.03	60	30.28	29	58	6.98	37.1

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