Tower structure optimization through finite element analyses

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Abstract. In this study the objective is to obtain an optimal configuration for an antenna lattice tower which has an imposed height of 30 m. For this purpose, a variable geometric model which considers specific working parameters is created, and a 3D finite element (FE) model is generated by using beam and shell elements for an optimization study. The 3D FE analysis is updated automatically for each variant of the geometric model. The response surface methodology (RSM) is used together with the central composite design (CCD) approach as to optimize the response of the lattice tower. The model of the tower is subject to static and dynamic loadings, including earthquake analysis. A response spectrum analysis based on Rosenblueth's Double Sum Combination (ROSE) is performed because the natural frequencies resulting from the modal analysis have close values. The optimization solution algorithm used for the tower optimization is the nonlinear programming by quadratic Lagrangean (NLPQL), which is based on the gradient algorithm for models with only one objective function and several optimization restrictions. Out of three final candidate design solutions the one which gives the minimum mass is proposed.

1. Introduction

The response surface methodology (RSM) is a method based on a group of mathematical and statistical techniques that explores the relationship between the independent variables and the response variable, in order to optimize the desired response of the investigated system, and to explore the optimal operating conditions. The term response surface is used to describe the surface that represents the response of a process or system when the values of the input parameters vary in the specified fields.

The first step for applying RSM is to determine an appropriate function that represents the relationship between the output response variable and the input variables, a function that is generally unknown. It provides the empirical models that could describe the effect of variables on the response and select the optimized response region from the response surface described by the models. Central composite design (CCD) is the most widely used response surface design. Since introduced by Box and Wilson [1], the CCD has been studied and used by many researchers. CCD design has the advantages of a smaller number of tests, high precision, and good predictability. For many RSM studies, the central composite experiment is used, as is the case with the present study. As an alternative to the CCD numerical experiment, the Box-Behnken experiment [2] can be chosen. The latter requires lower costs but should only be used if the experiment's borders are assumed to be known.
Textbooks and monographies [3-5] have been dedicated to optimization using designed experiments. Optimal designs are experimental designs that are generated based on an optimality criterion and are generally optimal only for a specific statistical model. Optimal design methods use a single criterion to construct designs for RSM; this is especially relevant when fitting second order models. An optimality criterion is a criterion which summarizes how good a design is, and it is maximized or minimized by an optimal design. Design of Experiments (DoE) have been widely used to understand the effects of multidimensional and interactions of input factors on the output responses of pharmaceutical products and analytical methods [6], preparation of hydroxyapatite from catfish bones at optimized conditions by employing CCD [7], optimization and characterization of micelles [8], optimization by CCD of nanostructured lipid carriers [9].

For large scale structures various approaches were taken. A dedicated global-local modelling approach for the multi-scale optimisation strategy for composite structures was performed through parametric finite element (FE) models [10]. A gradient based optimization approach was taken to reduce the mass of a composite material tower for an offshore wind turbine structure [11]. For the design and analysis of a composite flexible wing the support vector regression method is applied for optimization, as to reduce the time of computation. For this multi-objective design optimization problem, numerical results show that several useful Pareto optimal designs exist for the flexible wing [12]. DoE and FE modelling was employed to limit the number of simulations required to arrive at a diagnostic for the study of a collapse of an older communications antenna [13]. Topology optimization of planar structures considering induced actual and artificial earthquake seismic loads was investigated in [14] and vibration modal experiments and the modal interactions for a large space deployable antenna with a ring-truss structure were presented in [15]. Therefore, FE simulations proved to be efficiently used for the optimization of large-scale structures for both static and dynamic loadings.

The communication industry has seen a significant increase nowadays and therefore many towers are used to increase the coverage area and network performance. In the wireless domain these lattice towers play a particularly important role, hence the failure of such a large structure is of a major concern. Thus, a proper importance should be given in considering extreme conditions in the specific optimization process of this type of metallic structure. In this study, a four-legged lattice tower is analyzed and optimized for static and seismic loads. The optimization process is based on a parametric FE model done in Ansys Workbench 2019 R3 and uses CCD to obtain a lightweight topology of the tower. Two geometrical working parameters are defined between imposed limits and CCD is used to establish 9 preliminary design variants. RSM of genetic aggregation type made possible the visualization of three response surfaces as to better understand the influence of the working parameters on the main outputs, total maximum displacement and maximum von Mises stress. The nonlinear programming by quadratic Lagrangean (NLPQL) was used as an optimization solution algorithm for the reduction of the tower mass. Three candidate design solutions are analyzed at the end and the best lightweight design is suggested to be used.

2. Problem description, geometry, and material properties definition

To perform the topological optimization for a lattice tower which is fixed at the base, free at the top end and is subjected to gravity, wind loads and seismic loads, the following categories of optimization parameters and restrictions were considered.

The fixed dimensions of the tubular structure made from trusses are presented in View 1 from figure 1. The total height of the antenna H is divided into five characteristic sections of fixed lengths, four of them notated as S1, S2, S3, S4 having a truncated cone shape with square bases. The last section (at the top of the tower) has a constant square section of size T both top and bottom. Width at the square base of the antenna is B; a perspective view of the tower is also shown, together with Detail views (Fig. 1) in which are specified the sections of the trusses. The principal vertical columns are made from circular hollow section steel trusses. Four platforms are reinforcing the tower structure, being made from aluminum, and framed by horizontal aluminum trusses, also with a hollow circular section, but of smaller diameter. The rigidity of the tower is increased by using inclined and
horizontal trusses with equal length angles section. These trusses are rigidly fixed to the circular ones as shown in figure 2.

**Figure 1.** The fixed dimensions of the tower in View 1 and the variable elements in Detail views.

**Figure 2.** Fixture of trusses with equal length angles section.

The diameter of the columns decreases with the height of the tower and for this reason several diameters are defined. The diameter $D_1$ is used as outer dimension for the columns from the ground to the level of 10.5 m ($S_1+S_2$) and $D_2$ is the outer diameter of the columns from the level of 10.5 m up to the level of 24 m ($S_3+S_4$). $D_3$ is the outer diameter of the horizontal trusses which border the four platforms and is also the diameter of the columns from the level of 24 m up to the top of the tower at a level of 30 m. These platforms have constant thickness and will be modelled later with shell elements. The diameter $D_1$ will be defined as a working parameter and diameters $D_2$ and $D_3$ will be a function of $D_1$. The equal length angles dimension is $L_1$; second working parameter will be the angle length $L_1$. The thickness of the angle sections is kept constant as 5 mm.

Therefore, the main input parameters $D_1$ and $L_1$ will define the geometry of the truss sections. The output parameters are the equivalent von Mises stress $\sigma_{eq}$ and the total deformation $u_{total}$. The objective function is the mass minimization.

The following dimensions are used in the preliminary finite element analysis:
- fixed dimensions of the tower: $B = 4$ m – base square dimension, $T = 1.2$ m – top square dimension, $H = 30$ m – tower total height, $S_1 = 6$ m, $S_2 = 4.5$ m, $S_3 = 6.5$ m, $S_4 = 7$ m – height of characteristic sections as defined in figure 1; the top section of the tower is of
constant cross section and a height of 6 m. Platforms thickness (four as shown in figure 1) was considered fixed as being 20 mm;

- variable hollow sections dimensions (input parameters) are the outer diameters of the hollow sections with initial dimensions: $D_1 = 120$ mm, $D_2 = 110$ mm, $D_3 = 100$ mm; wall thickness is fixed to 4 mm for the $D_1$ hollow section and 3 mm for hollow sections of diameters $D_2$ and $D_3$. In fact, only $D_1$ is a working parameter as we always define during the optimization process that: $D_2 = D_1 - 10$ and $D_3 = D_2 - 10$ with dimensions in mm;
- variable dimension of the equal angle section being initially $L_1 = 75$ mm (keeping the constant the thickness of 5 mm) is the second working parameter.

The limit values of the input parameters are: $D_{1\min} = 60$ mm, $D_{1\max} = 120$ mm; $L_{1\min} = 50$ mm, $L_{1\max} = 75$ mm. The optimization restrictions are: allowable maximum stress $\sigma_a = 150$ MPa and allowable maximum total deformation $u_{\text{total}} = 100$ mm; these limit values are the same for both static and dynamic structural analyses.

The vertical columns having hollow sections $D_1$ and $D_2$ are made from steel: density $\rho_s = 7850$ kg/m$^3$; Young’s modulus $E_s = 210$ GPa; Poisson’s coefficient $\nu_s = 0.3$. The horizontal trusses of diameter $D_3$, platform and angle sections are from aluminum having the properties: density $\rho_{\text{Al}} = 2770$ kg/m$^3$; Young’s modulus $E_{\text{Al}} = 71$ GPa; Poisson's coefficient $\nu_{\text{Al}} = 0.33$. For both materials we consider a linear elastic behavior and the ambient temperature of 22 ºC.

3. Finite element model of the tower

In the present study the software Ansys Workbench 2019 R3 is used to perform a dimensional optimization study of the tower, having as main objective function the mass minimization. Ansys Design Modeler [16] is used to create the parametric geometric model, Ansys Mechanical [17] for the static, modal and spectral seismic analyses, and Ansys Design Xplorer [18] for optimization by using CCD.

The geometry is not a complicated one, so a good quality FE mesh as shown in figure 3 is easily obtained with beam (for the columns) and shell (for the platforms) type elements of second order, having the following characteristics – size of elements: 150 mm; total number of nodes: 15966 (11905 beam and 4061 shell); total number of elements: 5492 (4231 beam and 1241 shell). Of course, some nodes are common for both beam and shell elements, and the estimation on the number of nodes belonging to each type of element is not exact. To these elements are added 20 elements with concentrated mass of type Mass21 as it will be described later.

The equal angle trusses are fixed in between them on the lateral surfaces of the lattice tower (figure 2 and figure 3) and with the hollow section trusses (beams), being properly fixed end to end (bonded). During the FE analyses (static and dynamic) no failure was noticed at the junctions.
4. Calculation procedures

The proposed study is carried out on three levels: static structural analysis, modal analysis, and response spectrum analysis. Based on the suite of three coupled analyzes the optimization process is performed by using the response surface optimization procedure as presented in figure 4.

4.1. Static structural analysis

In this study, the role of a static analysis is on one hand to determine the behavior of the structure under static loads and on the other hand to obtain a prestressed structure which is then studied through a seismic loading.

The structure is fixed at the base (A – fixed support), free at the top end and is subjected to gravity and wind loads. Besides standard gravity load, the wind loads are considered to increase with the height of the tower as shown in Fig. 6 with increasing value from line B to line G (figure 5). The action of the wind on an inland tower is introduced as a line pressure applied in the horizontal direction of smaller value close to the base of the tower (B – line pressure 40 N/m) and the highest value close to the top (G – line pressure 240 N/m). These values were estimated by using indications presented in [19, 20] for the action of winds on lattice towers. We also considered an additional weight given by 20 antennas of 10 kg mass each, imagined as being disposed as presented in figures 5 and 6. The concentrated mass is imposed by using in Ansys a special element, called Mass 21. They are punctiform elements, each placed in the centroid of a beam element.

![Figure 4. Optimization study scheme.](image)

![Figure 5. Boundary conditions and loads.](image)

![Figure 6. Antennas arrangement.](image)
After statically loading the unoptimized model ($D_1 = 120$ mm and $L_1 = 75$ mm working parameters) by the own weight of the tower and the weight of the antennas on one hand, and wind loads actions on the other hand, we obtained:

- maximum total displacement of 42.09 mm (figure 7) in the top region of the lattice tower;
- maximum equivalent von Mises stress of 71.84 MPa (figure 8) at the bottom of the structure.

4.2. Modal analysis

The modal analysis determines the natural frequencies and mode shapes of the tower which are established as important parameters in the design of the dynamically loaded tower. It can also serve as a starting point for a dynamic analysis, such as a response spectrum analysis as it is in this case.

The fixing conditions of the structure as well as all the obtained results in the static analysis are the bases for the pre-stress modal analysis.

The Block shifted Lanczos algorithm is a variation of the classical Lanczos algorithm, [21], where the Lanczos recursions are performed using a block of vectors, as opposed to a single vector. The Block Lanczos eigenvalue extraction method can be used for large symmetric eigenvalue problems and employs an automated shift strategy to extract the number of eigenvalues requested. We used a Block Lanczos algorithm for computing a few of the smallest eigenvalues and the corresponding eigenvectors of a large symmetric matrix. This method is especially powerful when searching for eigenfrequencies in each part of the eigenvalue spectrum. The convergence rate of the eigenfrequencies will be about the same when extracting modes in the midrange or in the higher range of the spectrum, as when extracting the lowest modes. First 15 natural frequencies were extracted having their values as presented in Table 1. Afterwards, these frequencies were considered as input data for the spectrum analysis.

| Mode | $f_1$ | $f_2$ | $f_3$ | $f_4$ | $f_5$ | $f_6$ | $f_7$ | $f_8$ | $f_9$ | $f_{10}$ | $f_{11}$ | $f_{12}$ | $f_{13}$ | $f_{14}$ | $f_{15}$ |
|------|------|------|------|------|------|------|------|------|------|-------|-------|-------|-------|-------|-------|
| Frequency [Hz] | 4.02 | 4.18 | 6.65 | 7.35 | 7.93 | 14.36 | 14.76 | 15.78 | 17.54 | 18.69 | 20.91 | 21.37 | 21.67 | 22.25 | 22.37 |

4.3. Response spectrum analysis

Response spectrum analysis is a linear perturbation procedure and is typically used to analyze response to a seismic event. Considering that the system response is linear in the frequency domain
our analysis is based on the natural modal responses, therefore the modal analysis is a prerequisite. The results from a response spectrum analysis are deterministic maxima. For a given excitation, the maximum response is calculated based upon the input response spectrum and the method is used to combine the modal responses. The combination method used in this study is the Rosenblueth's Double Sum Combination (ROSE command in Ansys) proposed by Rosenblueth and Elorduy [22], because the natural frequencies resulting from the modal analysis have closely spaced values. The ROSE algorithm is providing a model of evaluating modal correlation for the response spectrum analysis. Mathematically, the approach is built upon random vibration theory assuming a finite duration of white noise excitation. The ability to account for the modes coupling makes the response estimate from the ROSE method more realistic and closer to the exact time history solution.

The excitation is applied in the form of a response spectrum. The response spectrum can be displacement, velocity, or acceleration. For each spectrum value, there is one corresponding frequency. Excitation must be applied at fixed degrees of freedom.

The acceleration seismic excitation spectrum used in this paper is known as "Savannah river earthquake" and it is shown in figure 9 for a better representation. One input excitation spectrum is applied to all boundary condition defined in the model along the horizontal direction, so it is used a “single point” spectrum type.

![Figure 9. Graphical representation of the seismic excitation spectrum.](image)

The response spectrum analysis results obtained for the unoptimized model are to be observed in figure 10 for the total deformations and in figure 11 for the von Mises stresses.

![Figure 10. Total deformations for response spectrum](image)

![Figure 11. Von Mises stresses for response spectrum](image)
When the seismic spectrum loading is added to the loading given by the static analysis for the unoptimized model ($D_1 = 120$ mm, $L_1 = 75$ mm working parameters) the following results are obtained:

- maximum total displacement of 24.30 mm (figure 10) at the top of the tower;
- maximum equivalent von Mises stress of 45.70 MPa (figure 11) at the bottom of the tower;

The total mass of the tower is 7293.70 kg before optimization.

It can be observed that the maximum displacement and stress values resulting from the analysis are small and therefore the initial model can be modified by reducing the mass of the tower.

5. Optimization process

As mentioned before, the working parameters are $D_1$ and $L_1$ and we adopted the Central Composite Design (CCD) as a DOE procedure. The optimization solution algorithm used for the tower optimization is the nonlinear programming by quadratic Lagrangean (NLQPL), which is based on the gradient algorithm for models with only one objective function and several optimization restrictions.

In a preliminary design of the tower we chose randomly 9 variants considering $D_1$ equal to 60 mm, 90 mm and 120 mm and $L_1$ as 50 mm, 62.5 mm and 75 mm. The combinations of these two parameters tried to ensure all characteristic geometrical possibilities for $D_1$ and $L_1$, starting from the smallest values as 60 mm, respectively 50 mm in Design variant 6, and ending with the largest ones as 120 mm, respectively 75 mm for Design variant 9. As seen in table 2 the important output is the mass of the lattice tower, but also the maximum von Mises stress under static and seismic loads and total deformation for both cases. Results follow expected trends. Mass has a maximum value of 7293.7 kg and a minimum one of 4357.0 kg. For the minimum mass and seismic loads both von Mises stress and total deformation exceed the allowable values. It worth to mention that total deformation under seismic loads is small and not sensitive to the change of $D_1$ if $L_1 = 62.5$ mm but becomes high when $L_1 = 50$ mm (Design variants 4, 6, 7). In fact, in all these three variants von Mises stresses also exceed the allowable stress.

### Table 2. DOE preliminary design variants.

| Design variant | $D_1$ [mm] | $L_1$ [mm] | Total mass [kg] | Maximum equivalent von Mises stress (static loads) [MPa] | Maximum equivalent von Mises stress (seismic loads) [MPa] | Total deformation (static loads) [mm] | Total deformation (seismic loads) [mm] |
|----------------|------------|------------|----------------|----------------------------------------------------------|----------------------------------------------------------|--------------------------------------|--------------------------------------|
| 1              | 90         | 62.5       | 5825.4         | 94.89                                                    | 102.42                                                  | 56.82                                | 25.68                                |
| 2              | 60         | 62.5       | 4509.3         | 119.16                                                  | 131.52                                                  | 85.37                                | 26.58                                |
| 3              | 120        | 62.5       | 7141.5         | 76.18                                                    | 79.52                                                    | 43.17                                | 24.65                                |
| 4              | 90         | 50         | 5673.1         | 129.17                                                  | 302.46                                                  | 58.86                                | 89.76                                |
| 5              | 90         | 75         | 5977.6         | 87.99                                                    | 68.65                                                    | 55.49                                | 24.78                                |
| 6              | 60         | 50         | 4357.0         | 252.37                                                  | 684.37                                                  | 88.23                                | 121.64                               |
| 7              | 120        | 50         | 6989.3         | 148.97                                                  | 497.52                                                  | 44.94                                | 79.77                                |
| 8              | 60         | 75         | 4661.5         | 113.04                                                  | 125.27                                                  | 83.65                                | 25.83                                |
| 9              | 120        | 75         | 7293.7         | 71.84                                                    | 45.70                                                    | 42.08                                | 24.30                                |

More interesting is the influence of the two working parameters on the equivalent von Mises stress given by seismic loads (figure 12). The response surface has complicated variations giving as expected a maximum equivalent stress for Design variant 6. For $L_1 = 75$ mm the influence of $D_1$ is practically not important. Stresses remain of low values up to $L_1 = 62.5$ mm and afterwards increase significantly. It is interesting to underline that even for $D_1 = 120$ mm the stress values increase rapidly if $L_1$ is below 62.5 mm. At $D_1 = 90$ mm and $L_1 = 50$ mm (Design variant 4 in table 2) the equivalent stress drops unexpectedly to 302 MPa. This is probably due to the complex geometry of the tower; anyhow
the maximum stress exceeds the allowable one and such a design is not of interest. Anyhow, the structure is much more sensitive to the variation of $L_1$ than to the variation of $D_1$. The lateral rigidity of the tower is significantly influenced by the equal length angles section of dimension $L_1$.

![Figure12](image.png)

**Figure12.** Variation of the maximum equivalent von Mises stress according to the values of the two input parameters ($D_1$ and $L_1$) due to seismic loads.

The final stage of the optimization process considers three candidate designs as presented in table 3, having $L_1$ values around 60 mm and allowing the $D_1$ value to be 60 mm (Candidate design 1), 62.5 mm (Candidate design 2), or 90 mm (Candidate design 3) which gives conservative maximum values of stress and displacement. In fact, Candidate design 3 is the same as Design variant 1 from Table 3. The first two Candidate designs given in table 3 have working parameters around the values given for Design variant 2 ($D_1 = 60$ mm and $L_1 = 62.5$ mm) for which the mass was reduced to 5825.4 kg.

Following the solutions given by the optimization analysis, and in accordance with the restrictions specified above, it is observed that the optimal design variant corresponds to the values $D_1 = 60$ mm and $L_1 = 60$ mm, with $L_1$ chosen as integer.

**Table 3.** Optimization results.

| Optimization objective and parameters | Candidate design 1 | Candidate design 2 | Candidate design 3 |
|--------------------------------------|---------------------|---------------------|---------------------|
| Objective                            | Total mass [kg]     | 4477.80             | 4620.10             | 5825.40             |
| Input parameters                     | $D_1$ [mm]          | 60                  | 62.89               | 90                  |
|                                      | $L_1$ [mm]          | 59.91               | 61.19               | 62.50               |
| Output parameters                    | Maximum equivalent von Mises stress [MPa] (static loads) | 134.20 | 114.67 | 94.89 |
|                                      | Maximum equivalent von Mises stress [MPa] (seismic loads) | 148   | 125.28 | 102.42 |
|                                      | Total deformation [mm] (static loads) | 87.12 | 76.12 | 56.82 |
|                                      | Total deformation [mm] (seismic loads) | 27.34 | 26.52 | 25.68 |
The results show that the mass of the tower resulting from the optimization process is reduced to 4477.80 kg (initially having the value of 7293.70 kg). Also, the geometry of the two tower models, unoptimized and optimized, is significantly modified, as seen in figure 13, respectively figure 14.

![Figure 13. Initial tower model.](image1)
![Figure 14. Optimized tower model.](image2)

The values corresponding to the maximum equivalent von Mises stress (134.20 MPa) due to static loads, respectively maximum equivalent von Mises stress (148 MPa) due to seismic loads and also the values corresponding to the maximum total deformation for both cases obtained for the optimized model (87.12 mm static and 27.34 mm seismic) do not jeopardize the integrity of the structure. It is to be noticed that after optimization the dynamic total deformations are for all three Candidate designs significantly smaller (2-3 times) than the ones given by the static loading (gravity and wind) that appear at the top of the tower. After the optimization, the maximum dynamic total deformations appear on the equal angle profile at the bottom of the tower, and this is because it decreases its dimension $L_1$. The seismic total maximum deformation of the unoptimized tower was 24.30 mm (figure 10) at the top of the tower. The deformation increased a little bit (27.34 mm) after optimization, but this time on the equal angle at the bottom of the tower as in the static analysis. However, it is still much smaller than the allowable value considered as 100 mm.

6. Conclusions
The optimization model considered the use of two geometric working parameters as defining geometric input variables, two output parameters as the allowable values of total displacement and equivalent stress imposed as optimization constraints, and the objective function which required the minimization of the tower mass.

The use of CCD design combined with FE analyses gave in this research rapid calculations as to study the influence of the working parameters on the mass reduction of the tower. The obtained response surface (figure 12) puts into evidence that the tower is much more sensitive to the variation of the equal angle dimension than to the variation of the outer diameter of the hollow section columns, as influencing the lateral rigidity of the structure. The optimization process applied for the three final candidate designs showed that the seismic total deformations grow for the optimized tower construction in a very reasonable limit.

After the optimization analysis was performed for both static and seismic loadings a considerable reduction of the tower mass of almost 39 % can be obtained compared to the initial design, allowing the maximum equivalent von Mises stress and the maximum total deformation to increase without exceeding the allowable values.

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