Optimization of Fundamental Natural Frequency of Structures Using VPL on the Example of Truss Towers

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Abstract

The work describes the use of VPL to optimize fundamental natural frequency of structures based on the example of steel lattice towers. For this purpose, a universal programming tool in Python using FEM was created, which allows the optimization of any bar structure in terms of its natural frequency. The capabilities of the tool are illustrated in several examples. It has been shown that by changing the tower geometry it is possible to obtain its higher spatial rigidity with a small increase in mass, it is possible to control the frequencies and forms of natural vibrations. Finally, the possibilities of further development of VPL applications in optimization of fundamental natural frequency of constructions and generative architecture were discussed.

Keywords: visual programming language, truss towers, natural frequency, optimalization

1. Introduction

1.1. VPL as a tool to optimize engineering structures

The problem of creating optimal engineering structures has been present in building theory and practice for many decades [1]. However, with the development of new computational methods, the capabilities of scientists and engineers in this field have increased significantly. At the same time, along with changes in the economic and social nature, contemporary designed constructions are characterized by much more economic efficiency than those designed several years ago [2].

In recent years, the design trend has become the use by engineers of the possibilities offered by various environments of visual programming language (VPL). Thanks to them, it is possible to design parametric structures that can be relatively easily changed and adapted to new investor requirements. VPL also allow the automation of the design process, they are a connection between traditional programming and classic computer-aided design (CAD). Thanks to them, it is also possible to combine various design environments into one coherent BIM model [3].

The next step in the development of engineering structures design is the extensive use of VPL as a tool for optimizing structures. By combining VPL with FEM-based calculation engines, engineers have full influence on the selection of structure geometry and optimization parameters. At present, however, the use of this technology is limited in practice to scientific applications. The problem is that the cooperation between commercial programs and VPL environments is still imperfect and works relatively slowly in practical applications. However, if VPL are used to optimize engineering structures, it is limited to static applications: optimization of the distribution of moments and cross-sectional forces in the structure, minimization of its total weight, energy optimization or searching for optimal organization of the construction [4]. In this work, a general tool based on FEM, VPL and Python has been created, which allows relatively simple extension of optimization issues to the problem of structural dynamics.

1.2. The problems of steel structure optimization in the aspect of generative architecture

Structure optimization issues are especially important when designing steel structures [5]. Steel bar structures are designed with relatively small safety reserves resulting from certainty of material properties and precision of the structure. At the same time, they are often build in series, which means their optimization is of great economic importance.

For the design of steel lattice towers, the issues of dynamics and stability of structures are very important [6]. The importance of structural dynamics is greater for towers of considerable height and slenderness. The general dependence is also that the low frequencies of free vibrations of the structure are not favourable from the engineer's point of view. They make lattice towers highly susceptible to dynamic wind impact, which may contribute to the introduction of the structure in resonance and its damage [7]. Therefore, the issue of creating tools that allow engineers to create optimal steel tower constructions in a relatively simple way, taking into account dynamic issues, is extremely important.

There is a significant trend in contemporary architecture called generative architecture [8]. Created geometries are usually unusual, quasi-organic. The structures obtained through the automatic design procedure are optimal, economical and interesting from an architectural point of view [9] [10]. In this work, I propose to use dynamic issues to create new geometric forms that can, similarly to classic engineering solutions, solve the problems of dynamics of steel lattice tower structures.

1.3. Purpose and scope of work

The purpose of this work is to create engineering tools based on VPL and FEM allowing for the optimization of constructions using dynamic issues. Preferred methods and algorithms can be used not only for steel lattice towers, but also more widely for the optimization of any bar structure. The algorithm has been implemented in the open VPL environment: DynamoBIM. To illustrate the capabilities of the tools created, sample steel tower designs for various geometries have been optimized. The results were analyzed and compiled in the form of tables, graphs and visualizations.

2. DynamoBIM environment

The DynamoBIM program (https://dynamobim.org) was chosen as the VPL work environment. It is characterized by openness and accessibility and is also relatively popular in the engineering environment. It is also possible for this environment to work with commercial engineering design programs.

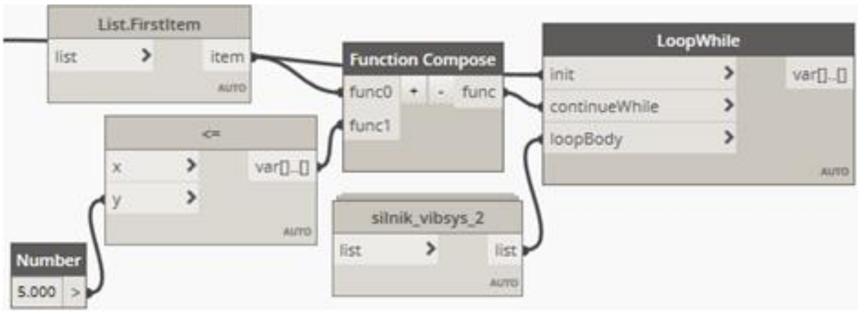


Figure 1. The main program block in the form of a while loop.

Working in this environment involves creating nodes and connecting them through graphical connections. Data lists are sent between nodes. You can create while loops and create your own nodes (complex procedures) (Figure 1). We also have the option of using Python scripts to create more computationally complex nodes. The effect of the algorithm in DynamoBIM can be visualized on an ongoing basis or sent to other programs for further processing.

3. Used numerical methods

3.1. Finite element method (FEM)

FEM was used to calculate the dynamics of the structure. The global OXYZ coordinate system has been introduced (Figure 2).

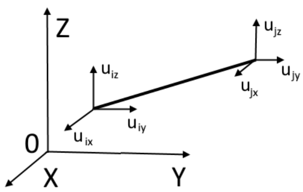


Figure 2. The nodal displacements in the global coordinate system

Then the nodal displacement vector was defined in this coordinate system (1):

$$u^e = [u_{ix} \quad u_{iy} \quad u_{iz} \quad u_{jx} \quad u_{jy} \quad u_{jz}]^T , \tag{1}$$

The analysis will be limited to testing the structure's own vibrations and we will assume no external loads. Then we define the system of FEM equations for a single finite element:

$$k^e u^e + m^e \ddot{u}^e = 0 \tag{2}$$

The classic finite truss element was used for calculations:

$$k^e = \frac{EA}{L}\begin{bmatrix} H & -H \\ -H & H \end{bmatrix},\ m^e = \frac{A\rho L}{6}\begin{bmatrix} 2H & H \\ H & 2H \end{bmatrix}, \text{H}=\begin{bmatrix} C_X^2 & C_X C_y & C_X C_Z \\ C_X C_y & C_Y^2 & C_Y C_Z \\ C_X C_Z & C_Y C_Z & C_Z^2 \end{bmatrix} \tag{3}$$

where

$C_X = \frac{L_X}{L}$, $C_Y = \frac{L_Y}{L}$, $C_Z = \frac{L_Z}{L}$, $L = \sqrt{L_X^2 + L_Y^2 + L_Z^2}$, E- Young's modulus, A – element cross-section area, L – element length, ρ – element density, L_X, L_Y, L_Z – element projection length on the coordinate system axes. Then matrix (3) was aggregated after all n finite elements:

$$K = \sum_{a=1}^{n} k_a^e, \qquad M = \sum_{a=1}^{n} m_a^e, \tag{4}$$

To find the frequencies of free vibrations and the corresponding forms of free vibrations of the structure, the values and eigenvectors of the matrix were found (4). The mathematical package https://numerics.mathdotnet.com/ available in the DynamoBIM environment and Python was used for calculations.

3.2. Gauss-Seidel method

A modified Gauss-Seidel method was used as the optimization method. It has been successfully used to optimize truss structures in engineering examples [1]. The modification of the classical method consisted of an interactive approach: all task parameters changed in accordance with the classic Gauss-Seidel approach. However, after setting the last parameter, the modified optimization algorithm returned to the first variable parameter again and cyclically in subsequent iterations modified all task parameters in turn. The stabilization of the objective function between successive iterations of the algorithm was considered the end of the algorithm:

$$f_{i+1} - f_i < 0.01 f_i \tag{5}$$

4. Examples

4.1. Introduction

To illustrate the possibilities of the created optimization tool, 3 examples of lattice tower optimization were proposed. The general geometry of the towers is shown in Figure 3. The towers are 6-level, have square bases and X-type lattices. In all examples, the quotient of the first natural frequency ω by the weight of the structure F was assumed as the function of the target f.

$$f = \frac{\omega}{F}, \tag{6}$$

In each case, the optimization goal was to find the global maximum of this function. This allowed the maximization of the value of the first frequency of free vibrations while maintaining the tower's weight as low as possible.

4.2. The effect of tower slenderness on optimization efficiency

At first, the effect of tower slenderness on optimization efficiency was examined. The following geometrical data of the towers was adopted: base width 1 m and constant width at the top of the tower 1.0m. The tower width was optimized on five equally divided levels. On each of them additional horizontal trusses stiffening the structure were used. To simplify the task, all the bar element was adopted as the same made of RK60x60x5 profile, regardless of the tower height. The geometric parameters of the towers obtained as a result of optimization are presented in Table 1:

Table 1. Optimized widths of individual tower levels at different heights of the entire structure.

h	a_1	a_2	a_3	a_4	a_5
[m]	[m]	[m]	[m]	[m]	[m]
10	1,39	1,54	1,33	0,9	0,5
20	1,79	2,11	1,82	1,20	0,71
30	2,07	2,55	2,18	1,42	0,85
40	2,31	2,93	2,49	1,61	0,95

h	a_1	a_2	a_3	a_4	a_5
[m]	[m]	[m]	[m]	[m]	[m]
50	2,50	3,24	2,75	1,75	1,03
60	2,64	3,48	2,94	1,86	1,1
70	2,77	3,73	3,14	1,97	1,17
80	2,89	3,95	3,31	2,07	1,23

The increase in the first natural vibration frequency was analyzed, as well as the increase in mass in relation to the non-optimized tower with straight, parallel belts. The results are summarized in the following chart:

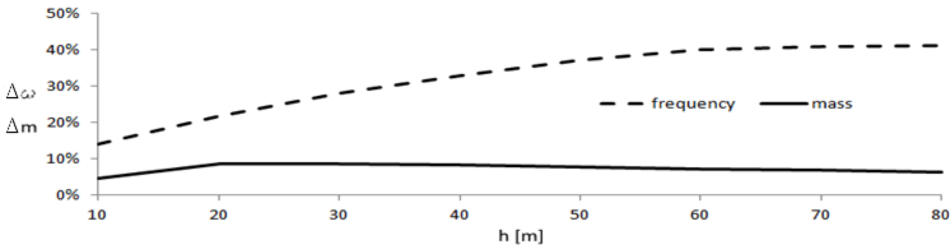


Figure 2. Relationship between the percentage change in mass Δm and the frequency $\Delta\omega$ of free vibrations as a result of tower structure optimization., where $\Delta m = \frac{m-m_0}{m_0}100\%$ and $\Delta\omega = \frac{\omega-\omega_0}{\omega_0}100\%$

The chart above shows that as the height of the structure increases, the efficiency of the optimization process increases - the first natural frequency increases much faster than the weight of the structure. Therefore, we will achieve better results of the optimization methods presented in this article in the case of constructions with greater slenderness.

4.3. Optimal tower shape for different base widths

The next example shows the possibility of using the structure optimization process described earlier for generative architecture applications. The shapes of structures obtained were analyzed depending on the width of the tower base. A constant height of 20 m and a constant width of 1 m at the top of the tower were assumed. In each case, the width of the five intermediate levels of the tower was optimized. Four towers with base widths of 2m, 3m, 5m and 10m were proposed for analysis. As a result of the optimization process, the tower shapes shown in Figure 3 were obtained:

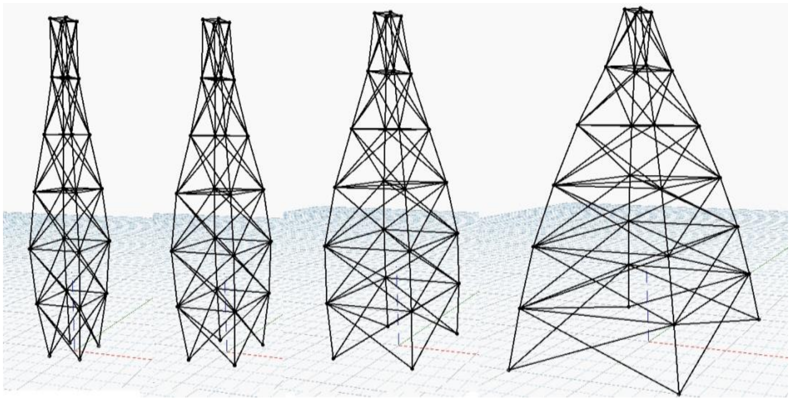


Figure 3. Optimized tower shapes for the base size: 2m, 3m, 5m and 10m.

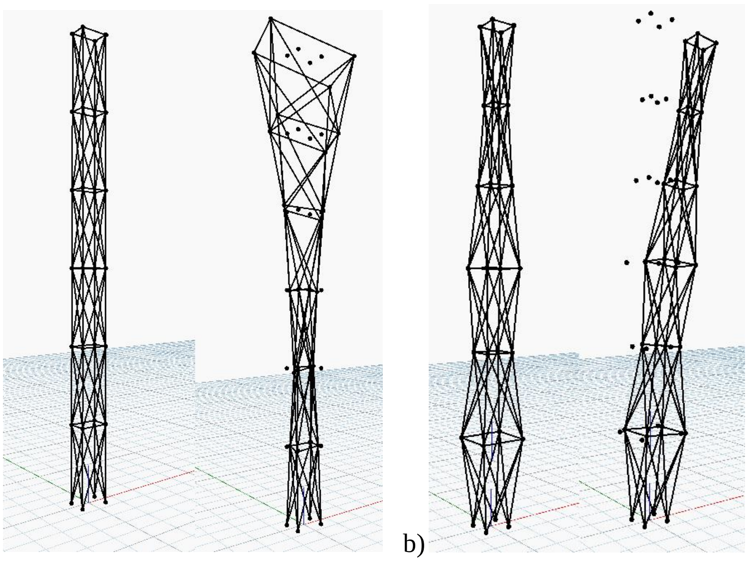
The above analysis shows that the tower shapes obtained are non-trivial, non-linear and technically feasible. We can conclude that the method used can be successfully used for generative design of rod structures.

4.4. Tower without horizontal bracing

The third example shows the effectiveness of this type of optimization as a tool to strengthen the structure. It was analyzed whether, by changing the proportions of individual tower elements, you can achieve the effect of strengthening it analogous to the classic bar addition. For this purpose, a tower 20 m high and 1 m wide was analyzed. All horizontal brows were removed from the analyzed tower, which caused it to lose stiffness and the first form of natural vibrations for the tower without optimization took the unfavourable form shown in Figure 4a. Then, the tower width was automatically optimized at levels 1-5, leaving the bottom and top tower bases constant. The results of the optimal tower geometry are presented in Table 2:

Table 2. Tower geometry before and after optimization.

	a_0	a_1	a_2	a_3	a_4	a_5	a_6
Optimal width of tower [m]	1.00	1.74	1.10	1.50	1.00	0.70	1.00



a) b)

Figure 4. The first form of the lattice tower's own vibrations without horizontal bracing: a) before optimization - an unusual form associated with the tower's formal deformation, b) after automatic optimization - the classic inclining form

The first natural vibration frequency for the tower after optimization turned out to be much higher, while the form of vibration returned to the classical tilting form (Figure 2b). It can therefore be assumed that a slight increase in the length of selected elements resulted in the strengthening of the entire structure, analogous to the use of classic bracing. The results of the analysis of the values of the first vibration frequencies of own towers before and after optimization and their weight are summarized in the table below:

Table 3. Values of the fundamental natural frequency, construction weights and the value of the objective function before and after optimization.

	Without optimatization	With optimatization	Change
Frequency of own vibrations [Hz]	1.28	2.71	112 %
Weight of structure [kN]	26.34	27.12	-3 %
Value of objective function [Ns]	48.59	99.93	106 %

It is worth noting that with a relatively small increase in tower weight of 3%, an increase in the first natural frequency of as much as 112% was obtained. Therefore, you can consider modifying the structure design geometry to strengthen it instead of adding classic reinforcements. It should also be noted that after optimization, in addition to the gain effect, we get a better aesthetic effect, the tower designed in a generative way in Figure 4b has better aesthetic and architectural qualities than a simple structure before optimization from Figure 4a.

5. Summary

In conclusion, we can say that the use of VPL to optimize the fundamental natural frequency of structures allows for relatively easy modification of the lattice structure geometry. Based on the analyzed examples, it can be seen that the importance of optimization is greater along with the slenderness of the tower and that it is possible to achieve spatial reinforcement of the structure analogously to the traditional use of reinforcements. It is also worth paying attention to the possibility of using this type of tools in generative architecture. In the longer perspective, the created tool can be extended to frame and shell constructions, and also made available to a wide range of engineers in the form of an additional package for the DynamoBIM program.

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