Computers and Structures 179 (2017) 75–94

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Optimum design of steel lattice transmission line towers using simulated annealing and PLS-TOWER

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ARTICLE INFO

Article history:
Received 22 March 2016
Accepted 13 October 2016

Keywords:
Structural optimization
Steel lattice transmission line towers
Simulated annealing
Sizing and layout optimization
PLS-TOWER software

ABSTRACT

This paper presents a new optimization tool for automated design of steel lattice transmission line towers in real-world engineering practice. This tool has been developed by integrating the simulated annealing (SA) optimization algorithm into the commercial PLS-TOWER software to optimize steel lattice towers for minimum weight according to ASCE 10-97 design specification using both size and layout design variables. In this context, a novel two-phase SA algorithm is specifically developed and compared with a typical SA formulation in three weight minimization problems of real-world steel lattice towers for high voltage overhead transmission lines between 110 and 400 kV. The optimized designs and the CPU time required by the two SA variants are reported for each test problem and then compared with the currently available structural configurations resulting from a conventional design process in order to quantify material saving achieved through optimization.

1. Introduction

Transmission line towers serve to keep the conductors above the ground transferring electricity from the energy sources to the communities. In recent years, electric transmission grids have been undergoing drastic changes due to increasing energy demand throughout the world. The new conductor types, increased public awareness on aesthetics and environmental consciousness, and the need for higher capacity lines have resulted in great pressure on designers to develop economic and optimally designed towers. Various types of towers are used in the transmission grids, including steel lattice, steel polygonal, concrete, wood and hybrid types [1]. However, due to their high strength-to-weight ratios steel lattice type is often preferred by majority of the utilities.

The design optimization of steel lattice towers has always been a difficult task due to a large number of design variables, in which size, layout and sometimes topology design variables should often be considered simultaneously in order to minimize the weights of the structures. Therefore, it has drawn attention of numerous researchers for a long time. Due to advancement in computing technology, in the recent years, the research on this topic has become even more popular. Mitra and Wolfenden [2] introduced a dynamic programming algorithm to optimize the transmission line route. Therein, the towers were selected from a suite of available tower structures and the proposed method determined the arrangement of suspension towers producing the minimum overall cost of the line. Sheppard and Palmer [3] developed an algorithm based on dynamic programming technique to optimize transmission towers, in which the algorithm sought for the number of panels and bracing configurations to form the lightest designs for the towers. Natarajan and Santakumar [4] optimized transmission towers using both layout and size design variables, where a nonlinear constrained optimization technique was integrated with a reliability analysis to obtain the minimum weight of a tower for a desired reliability index. Rao [5] employed a derivative-free nonlinear optimization technique for minimum weight design of high-voltage transmission line towers under a set of control parameters, including geometrical parameters as well as tensions in conductors and ground-wires. The technique was applied to a 400 kV double circuit tower, resulting in 12% saving in the weight of the tower. Taniwaki and Ohkubo [6] performed a study to minimize the cost of steel transmission towers consisting of circular piped members subject to both static and seismic loads. After transforming the primary optimum design problem into a convex and separable approximate subproblem by using direct and reciprocal design variables, they solved the resulting subproblem by a dual method in a two-stage optimization process. In Guo and Li [7], an adaptive genetic algorithm was introduced and

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http://dx.doi.org/10.1016/j.compstruc.2016.10.017
0045-7949/

implemented in four different optimization models of steel transmission towers considering size, layout and topology design variables. Likewise, Chunming et al. [8] utilized a genetic algorithm for optimization of a 500 kV tower structure, where cross-sectional areas and material types of the members were selected as design variables.

Despite significant theoretical developments in the field of structural optimization as well as emergence of new optimization techniques in the last few decades, the popularity of structural optimization in engineering design practice is still very limited and scarce. This situation may be attributed to several reasons. Firstly, most of the optimization methods developed in the literature have some drawbacks as far as their applications to real engineering problems are concerned. Some earlier methods, such as mathematical programming (MP) techniques, were not able to effectively meet the design requirements imposed in practical applications [9,10]. On the other side, the recently developed methods, such as metaheuristic search techniques, can handle all requirements of practical design problems owing to their simple and easy-to-implement optimization algorithms [11–15], yet they often require prohibitively long computing time to converge to a solution especially for large-scale structures subjected to numerous load combinations. Kaveh and his co-authors have recently proposed a cascade optimization procedure to reduce the number of objective function evaluations for problems with numerous design variables by operating the algorithm over a number of optimization stages, where the number of design variables employed is gradually increased stage after stage [16,17]. Secondly, the researchers have not sufficiently exhibited power and usefulness of structural optimization techniques in real-design problems chosen from the industry practice. Rather, a set of test problems chosen from existing structural optimization literature have often been used in published articles to demonstrate and verify a newly proposed algorithm or strategy. In these test problems the structures are subjected to a few load cases only and most practical aspects of actual design process are omitted, even though a code of design practice is employed in some of them. Accordingly, the optimum designs produced to such test problems remain worthless in the standpoint of a designer. Hence, more work and effort are required to feature practical applicability and usefulness of structural optimization in industry practice. This way, it will be possible to spread structural optimization tools in engineering design practice. One of such attempts was recently carried out in Flager et al. [18], where it was shown that optimum design of the roof structure of a 65,000 seat athletics stadium led to an estimated cost savings of approximately four million US dollars compared to its design produced by an engineering team using conventional design process.

This study addresses practical optimum design of steel lattice transmission line towers in real-world engineering practice. The considered optimum design problem was formulated as achieving the minimum weight design of steel lattice towers using both size and layout design variables simultaneously under a set of strength and serviceability constraints imposed according to ASCE 10-97 [19] design specification. Besides, all the fabrication, detailing and assembly requirements of steel lattice towers were taken into consideration as geometric constraints in order to produce optimized designs of the towers which are viable and directly applicable in real-life practice. The resulting design optimization problem was solved using simulated annealing (SA) optimization algorithm. Simulated annealing, first introduced by Kirkpatrick et al. [20] and Cerny [21], is a nature inspired meta-heuristic optimization technique which mimics the cooling mechanism of metallic atoms to attain the minimum energy state. The technique soon gained a worldwide popularity and found plenty of applications in various disciplines of science and engineering owing to its simple implementation and enhanced search characteristics. Some applications of the technique in the realm of structural optimization have been reported in Refs. [22–28]. Successful improvements of the technique were also proposed to improve its search and convergence features in several publications, such as Moh and Chiang [29], Chen and Su [30], Genovese et al. [31], Lamberti and Pappalettere [32], Lamberti [33], Hasançebi et al. [34], etc. The simulated annealing algorithm used in this study is essentially based on the improvement of the technique as formulated in Hasançebi et al. [34]. In addition, a so-called two-phase SA algorithm was proposed in this study as an exclusive method for acquiring optimum design of steel transmission towers more rapidly with an annealing algorithm. In the first phase of this method, only the layout parameters are optimized by the annealing algorithm while the steel members are sized with a fully stressed design based heuristic approach. The objective of the first phase is to improve the initial design rapidly in relatively less number of iterations (cooling cycles). In the second phase, the best design obtained in the prior phase is utilized as the initial solution, and the annealing algorithm is implemented anew for both layout and size variables together under a new set of annealing parameters.

The simulated annealing based algorithms developed for optimum size and layout design of steel lattice transmission line towers were integrated with commercial PLS-TOWER software [35] (developed by Power Line Systems, Inc.) to offer practicing engineers a useful tool which gives them ability to utilize full design and analyses features of PLS-TOWER during automated optimum design process as well as to pre- and post-process tower models using its graphical user interface. The PLS-TOWER, which is available in every design office working on energy transmission line structures, is the most well-known and recognized software by private corporations as well as state authorities. The software was specifically developed for analysis and design of steel lattice towers used in energy transmission lines. It allows for structural analyses of steel towers considering geometric nonlinearities, where the steel members can be sized according to almost all major design specifications in the world. In the study, the integration of simulated annealing algorithms with the PLS-TOWER software is performed such that the optimization module modifies the current solution and generates an alternative design with a new set of size and layout variables. A new finite element model (FEM) is generated in PLS-TOWER for this new design with the help of model generating module that has been specifically developed by the authors to automate construction of a new model in PLS-TOWER without any user interaction. The finite element solver of PLS-TOWER is then executed to analyze the new design and obtain member forces, joint support reactions and joint displacements. Depending on the size of the model and type of analyses chosen (i.e., linear or non-linear), the whole analysis process may take from a fraction of seconds to several minutes. The results of the analyses are collected in group summary tables, which display all details of member and connection design for the most critical element of each member group. The PLS-TOWER is also automated to perform all design checks and calculate the resulting weight of the structure. The results obtained from PLS-TOWER design module are sent back to optimization module for objective function calculations in conjunction with an integrated penalty function.

The numerical efficiency of the SA based optimization algorithms developed here was investigated on three real-world lattice steel towers for various high-voltage overhead transmission lines between 110 and 400 kV. In these examples, suspension or tension transmission line towers were optimized to achieve minimum weight designs using three layout variables and a selected number of member-size groups in line with the practical design of such