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Layout and size optimization of suspension bridges based on coupled modelling approach and enhanced particle swarm optimization

Hongyou Cao [a], Xudong Qian [a,*], Zhijun Chen [b], Hongping Zhu [b]

[a] Department of Civil and Environmental Engineering, National University of Singapore, 117576, Singapore
[b] School of Civil Engineering & Mechanics, Huazhong University of Science & Technology, Wuhan 430074, China

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ABSTRACT

This paper presents a computationally efficient optimal design approach for suspension bridges. The proposed method utilizes a coupled suspension-bridge modelling approach, which integrates an analytical form-finding method with the conventional finite element (FE) model to enhance the FE modelling efficiency during the optimization process. This study also employs an enhanced particle swarm optimization (EPSO), which introduces a particle categorization mechanism to handle the constraints instead of the commonly used penalty method, to improve the computational efficiency of the optimization procedure. The numerical investigation examines the feasibility and computational efficiency of the proposed method on the optimization of a three-span suspension bridge with both size and geometric design variables. The results demonstrate that the proposed method successfully overcomes the difficulties in the FE-based suspension bridge optimization, while considering the bridge geometric parameters (the sag-to-span ratio and side-to-central span ratio) as design variables, and improves significantly the computational efficiency of PSO-based methods as used in large-scale and complex structural optimization problems.

1. Introduction

The cable-supported bridges, especially the suspension bridges, are flexible structures, which exhibit strong geometric nonlinearity. Their structural performances are extremely sensitive to the layout and size parameters [1–3]. The cost based optimization for suspension bridges faces critical obstacles in the conventional design approaches, which entail a cumbersome trial-and-error procedure to finalize the design [4]. The engineering design of modern suspension bridges requires efficient solutions coupled with advanced optimization procedure to determine the optimal size and layout of the bridge.

Traditional engineering design optimizations predicate commonly on a series of parametric or sensitivity analyses to evaluate the structural response with respect to the varying design variables [5,6]. This method, however, becomes challenging to identify the global optimum when applied to cable-supported bridges due to the increase in the design variables and the growing complexity caused by geometric nonlinearity. Recent development in the modern optimization theories, which tackle these difficulties, has found various applications in cable-stayed bridges, including the size and geometric optimization [7–13], the cable stretching force optimization [14–18], and the dynamic performance optimization under earthquakes [19,20]. Meanwhile, many metaheuristic optimization algorithms instead of the traditional gradient-based approaches have emerged to seek the global optimum for complex problems in recent years. Hassan and his co-workers utilized the genetic algorithm (GA) to determinate the optimal post-tensioning cable force for cable-stayed bridges [15] and structural parameters for a semi-fan composite cable-stayed bridges [11,13]. Lute et al. [10] combined the GA and the support vector machine (SVM) to enhance the computational efficiency of the cable-stayed bridge optimization. In contrast to the cable-stayed bridges, the development of suspension bridge optimization based on the optimization theories remains relatively stagnant over the years. Nieto et al. [4] proposed a gradient-based approach to optimize the deck section of a suspension bridge considering the aero-elastic and kinematic constraints. Kusano et al. [21] extended this method to the size optimization of the main cable and the bridge deck for long-span suspension bridges with probabilistic flutter constraint. Lu et al. [22] achieved the optimization for the hanger stretching force in a self-anchored suspension bridge during the hanger installation process. Lonetti et al. [3] proposed an optimal design methodology to predict the optimum post-tension force and the dimension of the cable system for the hybrid cable-

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* Corresponding author.
E-mail address: qianxudong@nus.edu.sg (X. Qian).

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Nomenclature

$\mathbf{F}_i$	nodal force vector
$\mathbf{x}_i$	the coordinate vector
L_o	the unstrained length of the cable element
E	Young's modulus
A	cross sectional area of the element
w	self-weight per unit length of the element
R_i	reaction force
N_i	the force acting on the lower anchorage point of the hanger
d_x^i	the horizontal distance between the two neighboring hangers
f	the sag of the cable at the central span
L_m	the length of the mid-span
L_s	the length of the side-span
L_a	the horizontal distance between the end of the bridge and the cable anchorage
H_s	the length of the shortest hanger at the mid-span
H_b	the height of the pylon below the deck
H_a	a parameter controls the length of the shortest hanger at the side-span
B	the width of the bridge
h^k	the length of the k^{th} hanger
G_h^k	the self-weight of the k^{th} hanger
T_j^k	the tension of the k^{th} element at the right node
T_i^k	the tension of the k^{th} element at the left node
C_i	the cost factor of the material per unit volume
$\mathbf{d}$	vector of design variables
$\mathbf{d}_{lower}$	the lower bound vector of the design variables
$\mathbf{d}_{upper}$	the upper bound vector of the design variables
α_i	constraint function
α_i^*	the bound of constraint function
$\mathbf{v}_k^i$	velocity vector
$\mathbf{p}_k^i$	personal best position
$\mathbf{p}_k^g$	global best position
$\mathbf{r}_1$	random vector with magnitudes between 0 and 1
$\mathbf{r}_2$	random vector with magnitudes between 0 and 1
ω	inertia weight
$\omega_{\max}$	the maximum inertia weight
$\omega_{\min}$	the minimum inertia weight
c_1	cognitive parameter
c_2	social parameter
$T_{\max}$	the maximum iteration step

stayed suspension bridges with fixed geometric parameters. These researches focus on the dimension and/or hanger force without considering the effect of the layout of the suspension bridge, such as the side-to-central span ratio and the sag-to-span ratio. Even though these two geometric parameters are essential to the structural behaviour of a suspension bridge [1], the existing literatures covering both the size (the dimension of the structural members) optimization and the geometry optimization (the side-to-central span ratio and sag-to-span ratio) are not available.

The finite element (FE) based optimization of the suspension bridge faces a critical challenge in the modelling technique. This arises as the bridge does not follow a fixed configuration for varying geometric parameters during the optimization process. Moreover, different from cable-stayed bridges and other types of bridges, the FE model for a suspension bridge should be based on its gravity-deformed configuration under the dead load. The suspension bridge modelling procedure therefore requires a form-finding analysis to determine, though iterations, the key parameters, including the nodal position and the initial cable tension, necessary to build the FE model [23,24]. A computationally efficient and robust form-finding method is thus crucial to the suspension bridge optimization. Since the optimization of a suspension bridge involves strong geometric nonlinearity, various load cases, numerous types of constraints, a large number of continuous and discrete design variables, the traditional gradient-based local optimization methods become inefficient in identifying the global optimum. Although the global search optimization algorithms, e.g., GA [10,11,13,15], the particle swarm optimization (PSO) [15,25,26], and the harmony search (HS) [27–29], have demonstrated their capabilities in some engineering applications due to their global search ability and capabilities in handling complex constrained problems. However, the low convergence rate in the optimization process hinders greatly their applications to large-scale structures [30,31]. Therefore, a computationally efficient global search optimization algorithm becomes essential in extending such methods to the suspension bridge optimization.

This study aims to develop an efficient optimization method, coupling the size and geometry optimization of the suspension bridge. The current work proposes an efficient approach for the suspension bridge modelling, which integrates an analytical form-finding approach derived from the exact catenary theory with the conventional FE modelling strategy. This study also employs an enhanced PSO algorithm, which introduces a particle categorization mechanism into the standard PSO, to reduce dramatically the number of FE analyses required in the optimization process without compromising the search ability of the PSO algorithm.

The remainder of this paper is organized as follows. Section 2 presents the coupled approach for the suspension bridge modelling based on the catenary theory. Section 3 outlines the formulation of the suspension bridge, including the design variables, objective function and constraint function. Section 4 discusses the enhanced PSO approach utilized in this study. Section 5 evaluates the efficiency of the proposed approach according to a three-span suspension bridge with both size and geometry variables. Section 6 summarizes the main conclusions of this study.

2. A coupled approach for suspension bridge modelling

The optimization procedure of a suspension bridge typically requires numerous FE-based structural analyses to calculate the structural response for each potential design. In contrast to the frame or truss structures, whose configurations depend solely on the nodal positions and the element connectivity, suspension bridges exhibit strong geometric nonlinearities and their configurations are load dependent. The suspension bridge modelling therefore requires a form-finding analysis to determine the gravity-deformed nodal positons of the main cable, the unstrained length of each cable element and the initial internal forces of the elements. This section proposes an efficient suspension bridge modelling approach, which couples an analytical form-finding method with the conventional FE modelling, to facilitate the repetitive FE calculations during the optimization process.

2.1. Form-finding analysis

Various form-finding approaches for suspension bridges have evolved over the years. These methods separate generally into