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Charged system search for optimum grillage system design using the LRFD-AISC code

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ABSTRACT

Grillage systems are widely used in structures to cover large areas in bridge decks, ship hulls and floors. In this paper, the charged system search (CSS) algorithm is utilized to obtain the optimum design of grillage systems. This algorithm is inspired by the Coulomb and Gauss laws of electrostatics in physics and the governing laws of motion from Newtonian mechanics. The cross-sectional properties of beams are considered as the design variables. Comparison of the results with those of some previous studies shows the robustness of the new algorithm.

1. Introduction

Meta-heuristic algorithms are more suitable than conventional methods for structural optimum design due to their capability of exploring and finding promising regions in the search space in an affordable time [1]. Meta-heuristic algorithms tend to perform well for most engineering optimization problems [2–7]. This is because these methods refrain from simplifying or making assumptions about the original form.

One of the recent meta-heuristic optimization techniques is the charged system search (CSS), inspired by the governing laws of electrostatics in physics and the governing laws of motion from the Newtonian mechanics [8]. The CSS utilizes a number of solution candidates which are called charged particles (CPs). Each CP is treated as a charged sphere and it can exert an electrical force on the other agents (CPs) according to the Coulomb and Gauss laws of electrostatics. The resultant force acting on each CP creates an acceleration in consideration of Newton's second law. Finally, utilizing Newtonian mechanics, the position of each CP is determined at any time based on its previous position, velocity and acceleration in the space. In this study, the CSS is used to determine the optimum design of grillage systems.

Grillage systems are widely used in structures to cover large areas in bridge decks, ship hulls and floors. The aim of the optimum design of a typical grillage system is to determine the cross-sectional properties of its longitudinal and transverse beams such that the response of the system under the external loading is within the allowable limits defined by the code of practice, while the weight or the cost of the system becomes the minimum. In one of the early studies, the optimum design problem is formulated by treating the moments of inertia of the beams and joint displacements as design variables [9]. Stiffness, stress, displacement and size constraints are included in the design formulation. The effect of warping is taken into account in the computation of the stresses in the members and a genetic algorithm based method is developed for the optimum design of grillage systems which selects the optimum sections for the grillage elements from a set of standard universal beam sections and finds the optimum number of required beams for the grillage system [10]. A harmony search algorithm is utilized to determine the optimum W-sections for the members of grillage system from the set of LRFD-AISC sections in [11]. Also, the effect of the spacing between the longitudinal and transverse beams of a grillage system is investigated in [12] using a harmony search. In these studies, the deflection limitations and the allowable stress constraints are considered in the formulation of the design problem.

Here, the ability of the CSS in finding the optimum cross-sectional properties of longitudinal and transverse beams of some grillages is studied. The results are compared to those of the harmony search and genetic algorithm to illustrate the efficiency of the present approach.

2. Charged system search

The charged system search is based on electrostatic and Newtonian mechanics laws. The Coulomb and Gauss laws provide

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the magnitude of the electric field at a point inside and outside a charged insulating solid sphere, respectively, as follows [13]:

$$E_{ij} = \begin{cases} \dfrac{k_e q_i}{a^3} r_{ij} & \text{if } r_{ij} < a \\ \dfrac{k_e q_i}{r_{ij}^2} & \text{if } r_{ij} \geq a \end{cases} \tag{1}$$

where k_e is a constant known as the Coulomb constant; r_{ij} is the separation of the centre of sphere and the selected point; q_i is the magnitude of the charge; and a is the radius of the charged sphere. Using the principle of superposition, the resulting electric force due to N charged spheres is equal to [8]

$$\mathbf{F}_j = k_e q_j \sum_{i=1}^{N} \left(\frac{q_i}{a^3} r_{ij} \cdot i_1 + \frac{q_i}{r_{ij}^2} \cdot i_2 \right) \frac{\mathbf{r}_i - \mathbf{r}_j}{\|\mathbf{r}_i - \mathbf{r}_j\|}$$
$$\begin{cases} i_1 = 1, i_2 = 0 \Leftrightarrow r_{ij} < a \\ i_1 = 0, i_2 = 1 \Leftrightarrow r_{ij} \geq a. \end{cases} \tag{2}$$

Also, according to Newtonian mechanics, we have [13]

$$\Delta \mathbf{r} = \mathbf{r}_{new} - \mathbf{r}_{old} \tag{3}$$

$$\mathbf{v} = \frac{\mathbf{r}_{new} - \mathbf{r}_{old}}{\Delta t} \tag{4}$$

$$\mathbf{a} = \frac{\mathbf{v}_{new} - \mathbf{v}_{old}}{\Delta t} \tag{5}$$

where $\mathbf{r}_{old}$ and $\mathbf{r}_{new}$ are the initial and final position of a particle, respectively; $\mathbf{v}$ is the velocity of the particle; and $\mathbf{a}$ is the acceleration of the particle. Combining the above equations and using Newton's second law, the displacement of any object as a function of time is obtained as

$$\mathbf{r}_{new} = \frac{1}{2} \frac{\mathbf{F}}{m} \cdot \Delta t^2 + \mathbf{v}_{old} \cdot \Delta t + \mathbf{r}_{old}. \tag{6}$$

Inspired by the above electrostatic and Newtonian mechanics laws, the pseudo-code of the CSS algorithm is presented as follows [8].

Level 1: Initialization

Step 1. *Initialization*. Initialize the parameters of the CSS algorithm. Initialize an array of charged particles (CPs) with random positions. The initial velocities of the CPs are taken as zero. Each CP has a charge of magnitude (q) defined considering the quality of its solution as

$$q_i = \frac{fit(i) - fitworst}{fitbest - fitworst} \quad i = 1, 2, \ldots, N \tag{7}$$

where *fitbest* and *fitworst* are the best and the worst fitness of all the particles; $fit(i)$ represents the fitness of agent i. The separation distance r_{ij} between two charged particles is defined as

$$r_{ij} = \frac{\|\mathbf{X}_i - \mathbf{X}_j\|}{\|(\mathbf{X}_i + \mathbf{X}_j)/2 - \mathbf{X}_{best}\| + \varepsilon} \tag{8}$$

where $\mathbf{X}_i$ and $\mathbf{X}_j$ are the positions of the ith and jth CPs, respectively; $\mathbf{X}_{best}$ is the position of the best current CP; and ε is a small positive number to avoid singularities.

Step 2. *CP ranking*. Evaluate the values of the fitness function for the CPs, compare with each other and sort them in increasing order.

Step 3. *CM creation*. Store the number of the first CPs equal to charged memory size (CMS) and their related values of the fitness functions in the charged memory (CM).

Level 2: Search

Step 1. *Attracting force determination*. Determine the probability of moving each CP toward the others considering the following probability function:

$$p_{ij} = \begin{cases} 1 & \dfrac{fit(i) - fitbest}{fit(j) - fit(i)} > rand \vee fit(j) > fit(i) \\ 0 & \text{else} \end{cases} \tag{9}$$

and calculate the attracting force vector for each CP as follows:

$$\mathbf{F}_j = q_j \sum_{i, i \neq j} \left(\frac{q_i}{a^3} r_{ij} \cdot i_1 + \frac{q_i}{r_{ij}^2} \cdot i_2 \right) p_{ij} (\mathbf{X}_i - \mathbf{X}_j)$$
$$\begin{cases} j = 1, 2, \ldots, N \\ i_1 = 1, i_2 = 0 \Leftrightarrow r_{ij} < a \\ i_1 = 0, i_2 = 1 \Leftrightarrow r_{ij} \geq a \end{cases} \tag{10}$$

where $\mathbf{F}_j$ is the resultant force affecting the jth CP.

Step 2. *Solution construction*. Move each CP to the new position and find its velocity using the following equations:

$$\mathbf{X}_{j,new} = rand_{j1} \cdot k_a \cdot \frac{\mathbf{F}_j}{m_j} \cdot \Delta t^2 + rand_{j2} \cdot k_v \cdot \mathbf{V}_{j,old} \cdot \Delta t + \mathbf{X}_{j,old} \tag{11}$$

$$\mathbf{V}_{j,new} = \frac{\mathbf{X}_{j,new} - \mathbf{X}_{j,old}}{\Delta t} \tag{12}$$

where $rand_{j1}$ and $rand_{j2}$ are two random numbers uniformly distributed in the range (0, 1). m_j is the mass of the CPs, which is equal to q_j in this paper. The mass concept may be useful for developing a multi-objective CSS. Δt is the time step, and it is set to 1. k_a is the acceleration coefficient; k_v is the velocity coefficient to control the influence of the previous velocity. Here, k_a and k_v are taken as 0.5.

Step 3. *CP position correction*. If each CP exits from the allowable search space, correct its position using the HS-based handling approach as described for the HPSACO algorithm [14,15].

Step 4. *CP ranking*. Evaluate and compare the values of the fitness function for the new CPs; and sort them in an increasing order.

Step 5. *CM updating*. If some new CP vectors are better than the worst ones in the CM, in terms of their objective function values, include the better vectors in the CM and exclude the worst ones from the CM.

Level 3: Controlling the terminating criterion

Repeat the search level steps until a terminating criterion is satisfied.

3. Optimum design of grillage systems

3.1. Objective function

The optimum design problem of a grillage system is to reach a set of design variables corresponding to the minimum weight satisfying the behavioral and performance limitations which are adopted from the Load and Resistance Factor Design, American Institute of Steel Construction (LRFD-AISC) [16]. This can be expressed as

$$\begin{aligned} &\text{Find } \mathbf{A} = [A_1, A_2, \ldots, A_{ng}] \\ &A_i \in D_i \\ &\text{to minimize } W(\mathbf{A}) = \sum_{i=1}^{nm} \gamma_i \cdot A_i \cdot l_i \end{aligned} \tag{13}$$

where $\mathbf{A}$ is a set of design variables (cross-sectional areas); ng is the number of design groups; D_i is the allowable set of values for the design variable A_i given in the W-section list of LRFD-AISC; $W(\mathbf{A})$ is the weight of the structure; nm is the number of members making up the structure; γ_i is the material density of member i; l_i is the length of member i.