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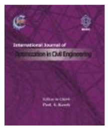

OPTIMIZATION OF AN OFFSHORE JACKET-TYPE STRUCTURE USING META-HEURISTIC ALGORITHMS

S. A. Hosseini[1,*,†] and A. Zolghadr[2]

[1]*Faculty of Passive Defense Engineering, Malek Ashtar University of Technology, Tehran, Iran*

[2]*School of Civil Engineering, Iran University of Science and Technology, Tehran-16, Iran*

ABSTRACT

Offshore jacket-type towers are steel structures designed and constructed in marine environments for various purposes such as oil exploration and exploitation units, oceanographic research, and undersea testing. In this paper a newly developed meta-heuristic algorithm, namely Cyclical Parthenogenesis Algorithm (CPA), is utilized for sizing optimization of a jacket-type offshore structure. The algorithm is based on some key aspects of the lives of aphids as one of the highly successful organisms, especially their ability to reproduce with and without mating. The optimal design procedure aims to obtain a minimum weight jacket-type structure subjected to API-RP 2A-WSD specifications. SAP2000 and its Open Application Programming Interface (OAPI) feature are utilized to model the jacket-type structure and the corresponding loading. The results of the optimization process are then compared with those of Particle Swarm Optimization (PSO) and its democratic version (DPSO).

Keywords: structural optimization; offshore structures; jacket-type platforms; cyclical parthenogenesis algorithm; CPA.

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1. INTRODUCTION

Economical considerations have always motivated researchers to propose and utilize new optimization methods for optimal design of structures. In structural optimization the aim is to minimize a function, usually taken as the weight of the structure of the total construction cost, while satisfying some behavioral constraints such as stress ratio, maximum displacement, and natural frequencies.

*Corresponding author: Faculty of Passive Defense Engineering, Malek Ashtar University of Technology, Tehran, Iran

†E-mail address: goldahmad83@yahoo.com (S. A. Hosseini)

Optimization methods which are usually used for structural optimization could roughly be divided into two major groups namely mathematical gradient-based methods and meta-heuristic algorithms. Gradient-based methods, as the name suggests, utilize gradient information of the involved functions in order to search the solution space for the optimal designs near an initial starting point. These methods are usually considered as local search techniques, which are dependent on the quality of the starting point. Moreover, derivation of the gradient information is usually costly and can be impractical in many cases.

On the other hand, meta-heuristic algorithms which are usually inspired by natural phenomena do not require any gradient information of the functions and are generally independent of the quality of the starting points. As a result, meta-heuristic optimizers are favorable choices when dealing with discontinuous, multimodal, non-smooth, and non-convex functions, especially when near-global optimum solutions are sought, and the intended computational effort is limited.

In the last few decades, different meta-heuristic optimization methods have been presented and successfully applied to different optimization problems including structural optimization. Some of the examples are Genetic Algorithms (GA) [1], Particle Swarm Optimization (PSO) [2], Ant Colony Optimization (ACO) [3], Harmony Search (HS) [4], Big Bang-Big Crunch (BB-BC) [5], Charged System Search (CSS) [6], Ray Optimization (RO) [7], Democratic PSO (DPSO) [8], Dolphin Echolocation (DE) [9], Colliding Bodies Optimization (CBO) [10], Water Cycle, Mine Blast and Improved Mine Blast algorithms (WC-MB-IMB) [11], Search Group Algorithm (SGA) [12], Ant Lion Optimizer (ALO) [13], Adaptive Dimensional Search (ADS) [14], Tug of War Optimization (TWO) [15], and Cyclical Parthenogenesis Algorithm (CPA) [16]. Although reliability-based optimization off-shore jacket-type structures is performed by Karadeniz, using sequential quadratic programming [17], to the authors knowledge meta-heuristic algorithms have not been used for structural design optimization of these kinds of structures.

CPA is a newly developed population-based meta-heuristic optimization method introduced by Kaveh and Zolghadr [16]. The main rules of the algorithm are derived from the reproduction behavior of some zoological species like aphids, which can alternate between sexual and asexual reproduction systems. It starts with a population of randomly generated candidate solutions metaphorized as aphids. The quality of the candidate solutions is then improved using some simplified rules inspired from the life cycle of aphids.

In this paper CPA is utilized for weight minimization of a jacket-type offshore platform according to API-RP 2A-WSD specifications. These types of structures are steel structures designed and constructed in marine environments for various purposes such as oil exploration and exploitation units, oceanographic research, and undersea testing. SAP2000 and its Open Application Programming Interface (OAPI) feature are utilized to model the jacket-type structure and the corresponding loading.

The remainder of the paper is organized as follows. In section 2, the main rules of Cyclical Parthenogenesis Algorithm (CPA) are reviewed. The optimization problem and API-RP 2A-WSD specifications are stated in section 3. A jacket-type offshore platform structure is optimized as a numerical example using CPA in section 4. In order to evaluate the performance of CPA the results are also presented to PSO and DPSO. Finally, some concluding remarks are presented in section 5.

2. CYCLICAL PARTHENOGENESIS ALGORITHM (CPA)

In this section Cyclical Parthenogenesis Algorithm (CPA) is introduced and described as a population-based meta-heuristic algorithm for global optimization. The main rules of CPA are explained using some key aspects of the lives of aphids as one of the highly successful organisms. Some of features of the lives of aphids such as their ability to reproduce with and without mating (cyclical parthenogenesis) can be beneficial from an optimization point of view.

2.1 Aphids and cyclical parthenogenesis

Aphids are small sap-sucking insects, and members of the superfamily Aphidoidea [18]. As one of the most destructive insect pests on cultivated plants in temperate regions, Aphids have fascinated and frustrated man for a very long time. This is mainly because of their intricate life cycles and close association with their host plants and their ability to reproduce with and without mating [19]. Fig. 1 shows some aphids on a host plant.

Figure 1. Aphids on a host plant

Aphids are capable of reproducing offspring with and without mating. When reproducing without mating, the offspring arise from the female parent and inherit the genes of that parent only. In this type of reproduction most of the offspring are genetically identical to their mother and genetic changes occur relatively rarely [19]. This form of reproduction is chosen by female aphids in suitable and stable environments and allows them to rapidly grow a population of similar aphids, which can exploit the favorable circumstances. Reproduction through mating on the other hand, offers a net advantage by allowing more rapid generation of genetic diversity, making adaptation to changing environments available [20].

Since the habitat occupied by an aphid species is not uniform but consists of a spatial-temporal mosaic of many different patches, each with its own complement of organisms and resources [19], aphids employ mating in order to maintain the genetic diversity required for increasing the chance of including the fittest genotype for a particular patch. This is the basis of the lottery model proposed by Williams [21] for explaining the role of reproduction through mating in evolution.

Some aphid species produce winged offspring in response to poor conditions on the host plant or when the population on the plant becomes too large. These winged offspring, which are called alates can disperse to other food sources [18]. Flying aphids have little control over the direction of their flight because of their low speed. However, once within the layer of relatively still air around vegetation, aphids can control their landing on plants and respond to either olfactory or visual cues, or both.

2.2 Description of cyclical parthenogenesis algorithm (CPA)

Cyclical Parthenogenesis Algorithm (CPA) is a population-based meta-heuristic optimization algorithm inspired from social and reproduction behavior of aphids. It starts with a population of randomly generated candidate solutions metaphorized as aphids. The quality of the candidate solutions is then improved using some simplified rules inspired from the life cycle of aphids.

Naturally, CPA does not attempt to represent an exact model of the life cycle of aphids, which is neither possible nor necessary. Instead, it encompasses certain features of their behavior to construct a global optimization algorithm.

Like many other population-based meta-heuristic algorithms, CPA starts with a population of Na candidate solutions randomly generated in the search space. These candidate solutions, which are considered as aphids, are grouped into Nc colonies, each inhabiting a host plant. These aphids reproduce offspring with and without mating. Like real aphids, in general larger (fitter) individuals within a colony have a greater reproductive potential than smaller ones. Some of the aphids prefer to leave their current host plant and search for better conditions. In CPA it is assumed that these flying aphids cannot fly much further due to their weak wings and end up on a plant occupied by another colony nearby. Like real aphids, the agents of the algorithm can reproduce for multiple generations. However, the life span of aphids is naturally limited and less fit ones are more likely to be dead in adverse circumstance. The main steps of CPA can be stated as follows:

Step 1: Initialization

A population of Na initial solutions is generated randomly:

$$x_{ij}^{0} = x_{j,min} + rand(x_{j,max} - x_{j,min}) \qquad j = 1,2,...,n \tag{1}$$

where x_{ij}^{0} is the initial value of the jth variable of the ith candidate solution; $x_{j,\max}$ and $x_{j,\min}$ are the maximum and minimum permissible values for the jth variable, respectively; rand is a random number from a uniform distribution in the interval [0, 1] separately generated for any aphid and any optimization variable; n is the number of optimization variables. The candidate solutions are then grouped into N_c colonies, each inhabiting a host plant. The number of aphids in all colonies N_m is equal.

Step 2: Evaluation, reproduction, and flying

The objective function values for the candidate solutions are evaluated. The aphids on each plant are sorted in the ascending order of their objective function values and saved in a Female Memory (*FM*). Each of the members of the female memory is capable of reproducing a genetically identical clone in the next iteration without mating.

In each iteration, Nm new candidate solutions are generated in each of the colonies in addition to identical clones. These new solutions can be reproduced either with or without mating. A ratio F_r of the best of the new solutions of any colony are considered as female aphids, the rest are considered as male aphids.

2.3 New solutions generated without mating

A female parent is selected randomly from the population of all female parents of the colony (identical clones and newly produced females). Then, this female parent reproduces a new offspring without mating by the following expression:

$$x_{ij}^{k+1} = F_j^k + \alpha_1 \times \frac{randn}{k} \times (x_{j,\max} - x_{j,\min}) \qquad j = 1,2,\ldots,n \tag{2}$$

where x_{ij}^{k+1} is the value of the jth variable of the ith candidate solution in the (*k+1*)th iteration; F_j^k is the value of the corresponding variable of the female parent in the kth iteration; randn is a random number drawn from a normal distribution and α_1 is a scaling parameter.

2.4 New solutions generated with mating

Each of the male aphids selects a female using randomly in order to produce an offspring through mating:

$$x_{ij}^{k+1} = M_j^k + \alpha_2 \times rand \times (F_j^k - M_j^k) \qquad j = 1,2,\ldots,n \tag{3}$$

where M_j^k is the value of the jth variable of the male solution in the kth iteration and α_2 is a scaling factor. It can be seen that in this type of reproduction, two different solutions share information, while when reproduction occurs without mating the new solution is generated using merely the information of one single parent solution.

2.5 Death and flight

When all of the new solutions of all colonies are generated and the objective function values are evaluated, flying occurs with a probability of P_f where two of the colonies are selected randomly and a winged aphid reproduced by and identical to the best female of Colony1 flies to Colony 2. In order to keep the number of members of each colony constant, it is assumed that the worst member of Colony2 dies.

Step 3: Updating the colonies

Update the Female Memories of all colonies by saving the best (Na) solutions of the last two generations.

Step 4: Termination

Steps 2 and 3 are repeated until a termination criterion is satisfied. The pseudo code of CPA is presented in Table 1.

Table 1: Pseudo-code of the CPA algorithm

```
procedure Cyclical Parthenogenesis Algorithm
begin
Initialize parameters;
    Initialize a population of Na random candidate solutions;
    Group the candidate solutions in Nc colonies with each having Nm members;
Evaluate and Sort the candidate solutions of each colony and save the best Nm ones in Female Memory

    while (termination condition not met) do
        for m: 1 to Nc
                Reproduce an identical solution by each of the solutions of the Female Memory
                Divide the newly generated offspring into male and female considering Fr
                for i: 1 to Fr×Nm
                Generate new solution i without mating using Eq. (2)
                end for
                for i: Fr×Nm+1 to Nm
                Generate new solution i through mating using Eq. (3)
                end for
                if rand<Pf
                Select two colonies randomly
                Generate a winged identical offspring from the best solution of Colony1
                Eliminate the worst solution of Colony2 and move winged aphid to Colony2
                end if
        Evaluate the objective function values of new aphids
        Update the Female Memory
        end for
    end while
end
```

3. OPTIMIZATION OF A JACKET-TYPE OFFSHORE PLATFORM

Weight minimization of a skeletal structure like a jacket-type offshore platform can be mathematically stated as follows:

$$\begin{gathered} \textit{Find } X = [x_1,x_2,x_3,...,x_n] \\ \textit{to minimizes } Mer(X) = f(X) \times f_{penalty}(X) \\ \textit{subject to} \end{gathered} \tag{4}$$

$$g_i(X) \leq 0, \quad i=1,2,\ldots,m$$
$$x_{imin} \leq x_i \leq x_{imax}$$

where X is the vector of design variables, which are the outer diameters and the thicknesses of the tubular members of platform; n is the number of design variables; g_i is the ith behavioral constraint; m is the number of behavioral constraints; $Mer(X)$ is the merit function which is to be minimized; $f(X)$ is the cost function which is the weight of the structure here; $f_{penalty}(X)$ is the penalty function which is used in order to make the problem unconstrained; x_{imin} and x_{imax} are the lower and upper bounds for the design variable x_i.

The cost function is expressed as:

$$f(X) = \sum_{i=1}^{nm} \rho_i L_i A_i \tag{5}$$

where ρ_i , L_i, and A_i are the material density, length, and the cross-sectional area of member i.

Different penalty functions could be used in order to make the problem unconstrained. In this study, Exterior penalty function method is employed, which can be stated as:

$$f_{penalty}(X) = 1 + \sum_{i=1}^{m} \max(0, g_i(X)) \tag{6}$$

In this paper the combination of dead load and wave load is considered as one of the most critical loading conditions applied to jacket-type offshore platforms. The mass of the deck is assumed to be the main source of dead load. The self weights of the tubular members of the platform are also considered.

Extreme wave load conditions are considered where the corresponding loads are calculated using Morison’s equation in the airy (linear) wave theory and the deepwater condition in accordance to the specifications of API-RP 2A-WSD [22]. The computation of the force exerted by waves on a cylindrical object depends on the ratio of the wavelength to the member diameter. When this ratio is large (>5), the member does not significantly modify the incident wave. The wave force can then be computed as the sum of a drag force and an inertia force, as follows:

$$F = F_D + F_I = C_D \frac{w}{2g} AU|U| + C_m \frac{w}{g} V \frac{\delta U}{\delta t} \tag{7}$$

where F is the hydrodynamic force vector per unit length acting normal to the axis of the member; F_D is the drag force vector per unit length acting to the axis of the member in the plane of the member axis and U; F_I is the inertia force vector per unit length acting normal to the axis of the member in the plane of the member axis and dU/dt; C_D is the drag coefficient; w is the weight density of water; g is the gravitational acceleration; A is the projected area normal to the cylinder axis per unit length (= D for circular cylinders); V is the displaced volume of the cylinder per unit length (= *πD2/4* for circular cylinders); *D* is the effective diameter of circular cylindrical member including marine growth; *U* is the component of the velocity vector (due to wave and/or current) of the water normal to the axis of the member; $|U|$ is the absolute value of *U*; C_m is the inertia coefficient; $\frac{\delta U}{\delta t}$ is the component of the local acceleration vector of the water normal to the axis of the member.

According to API-RP 2A-WSD cylindrical members subjected to combined axial force and flexure should be proportioned to satisfy both the following requirements at all points along their length:

$$\frac{f_a}{F_a}+\frac{C_m\sqrt{f_{bx}^2+f_{by}^2}}{\left(1-\frac{f_a}{F_e^{'}}\right)F_b}\leq 1.0 \tag{8}$$

$$\frac{f_a}{0.6F_a}+\frac{\sqrt{f_{bx}^2+f_{by}^2}}{F_b}\leq 1.0 \tag{9}$$

when $\frac{f_a}{F_a}\leq 0.15$ the following formula may be used in lieu of the foregoing two formulas:

$$\frac{f_a}{F_a}+\frac{\sqrt{f_{bx}^2+f_{by}^2}}{F_b}\leq 1.0 \tag{10}$$

where f_a, f_{bx}, and f_{by} are the normal stresses due to axial force and bending moment about *x* and *y* axes, respectively. The allowable tensile stress for cylindrical members subjected to axial tensile loads should be determined from:

$$F_t = 0.6F_y \tag{11}$$

The allowable axial compressive stress F_a should be determined considering the buckling from the following formulas for members with a *D/t* ratio equal to or less than 60:

$$F_a=\frac{\left[1-\frac{(Kl/r)^2}{2C_c^2}\right]F_y}{5/3+\frac{3(Kl/r)}{8C_c}-\frac{(Kl/r)^3}{8C_c^3}} \quad for\ Kl/r<C_c \tag{12}$$

$$F_a=\frac{12\pi^2E}{23(Kl/r)^2} \quad for\ Kl/r\geq C_c \tag{13}$$

where K is the effective length factor, l is the unbraced length and r is the radius of gyration. C_c is the critical slenderness ratio separating elastic and inelastic buckling regions ($C_c = \sqrt{12\pi^2 E / F_y}$).

For members with a D/t ratio greater than 60, the critical local buckling stress (Fxe or Fxc, whichever is smaller) should be substituted for F_y in determining Cc and Fa.

$$F_{xe} = 2CEt / D \tag{14}$$

$$F_{xc} = F_y \times [1.64 - 0.23(D/t)^{1/4}] \leq F_{xe} \tag{15}$$

where C is the critical elastic buckling coefficient, for which the theoretical value of C is 0.6. However, a reduced value of C = 0.3 is recommended by API-RP 2A-WSD in order to account for the effect of initial geometric imperfections. D is the outside diameter and t is the wall thickness of the member.

The allowable bending stress, Fb, should be determined from

$$F_y = 0.75F_y \quad for \quad \frac{D}{t} \leq \frac{10,340}{F_y} \tag{16}$$

$$F_y = [0.84 - 1.74\frac{F_y D}{Et}]F_y \quad for \quad \frac{10,340}{F_y} \leq \frac{D}{t} \leq \frac{20,680}{F_y} \tag{17}$$

$$F_y = [0.72 - 0.58\frac{F_y D}{Et}]F_y \quad for \quad \frac{20,680}{F_y} \leq \frac{D}{t} \leq 300 \tag{18}$$

where SI Units should be used when determining D/t limits. The maximum beam shear stress, fv, for cylindrical members is

$$f_v = \frac{V}{0.5A} \tag{19}$$

where V is the transverse shear force and A is the cross sectional area. The allowable beam shear stress, Fv, should be determined from:

$$F_v = 0.4F_y \tag{20}$$

4. NUMERICAL EXAMPLE

An example offshore jacket-type structure as shown in Fig. 2 is considered as the numerical example. The structure is composed of 60 cylindrical members, which are modeled as beam elements. These elements are categorized into 6 groups in a symmetrical manner as shown in Fig. 2a (all horizontal diagonal elements which could not be seen in the figure are grouped as group 6). For each design group there are two design variables i.e. outer diameter

(D) and wall thickness (t), which are all considered to be continuous. The topology and geometry of the structure is kept unchanged during the optimization process. Thus, this is a sizing optimization problem with 12 variables. The outer diameters can continuously change between 50 cm and 150 cm, while the wall thickness of the members can vary between 1 cm and 10 cm.

Material density ($\boldsymbol{\rho}$) and modulus of elasticity (E), yeild stress (F_y), and Poisson ratio (ν) are taken as 7849 kg/m^3 and 2.04×10^6 kg/cm^2, 3867 kg/cm^2, and 0.3 respectively. Water density (w), maximum wave height (H_{max}), and wave period (T) are 1025 kg/m^3, 18.29 m, and 12 sec, respectively. Drag coefficient (C_D) and inertia coefficient (C_m) are taken as 0.6, 1,5. The mass of the deck is assumed to be 4.2×10^6 kg.

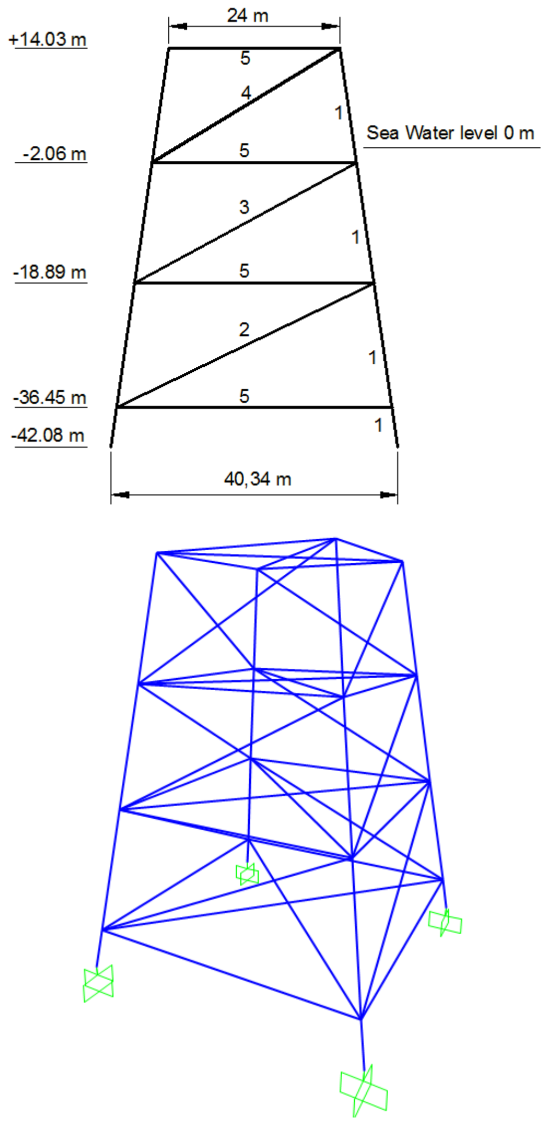

Figure 2. An example offshore jacket structure (a) side view (b) finite element model

The optimization problem is solved using the CPA and the results are compared to those of PSO and DPSO. The algorithms are coded in MATLAB, while the structural analysis and design is performed using SAP2000. Open Application Programming Interface (OAPI) feature is utilized to access SAP2000 through MATLAB. The problem is solved 10 times using each of the meta-heuristic algorithms in order to account for the probabilistic nature of the optimization methods. 60 agents and 200 iterations are used for all of the algorithms resulting in 12000 structural analyses. These agents are grouped into 4 (N_c=4) colonies for CPA. Other internal parameters are taken as F_r=0.4, α_1=1 and α_2=2. A linear function increasing from 0 to 1 is considered for P_f. These values are chosen based on an extensive parameter study by Kaveh and Zolghadr [16]. The best results of the different algorithms are summarized in Table 2.

Table 2: Optimal results obtained by different meta-heuristic methods

Element group	PSO	DPSO	CPA
D1 (cm)	102.40	106.98	123.57
D2 (cm)	109.25	139.74	112.98
D3 (cm)	126.44	109.99	148.12
D4 (cm)	50.00	52.27	50.00
D5 (cm)	61.34	66.97	68.80
D6 (cm)	106.86	105.95	104.53
t1 (cm)	2.32	2.14	1.76
t2 (cm)	1.00	1.00	1.00
t3 (cm)	1.00	1.00	1.00
t4 (cm)	3.02	1.00	1.07
t5 (cm)	1.00	1.00	1.00
t6 (cm)	1.00	1.00	1.00
Best weight (kg)	1.7119e6	1.6347e6	1.6280e6
Mean weight (kg)	1.7545e6	1.6545e6	1.6389e6
Standard deviation	3.2601e4	2.1941e4	1.1926e4
No. of structural analyses	12000	12000	12000

It can be seen in Table 2 that the CPA has obtained the best result both in terms of accuracy and robustness between the compared methods. The weight of slightest structure found by CPA is 1.6280e+006 kg, which is 0.4% and 4.9% lighter than those found by DPSO and PSO. The mean of the weights of the structures found by CPA is 1.6389e6 kg which is about 1% and 7% less than those of DPSO and PSO. The convergence curves of the best runs of the meta-heuristic algorithms are plotted in Fig. 3.

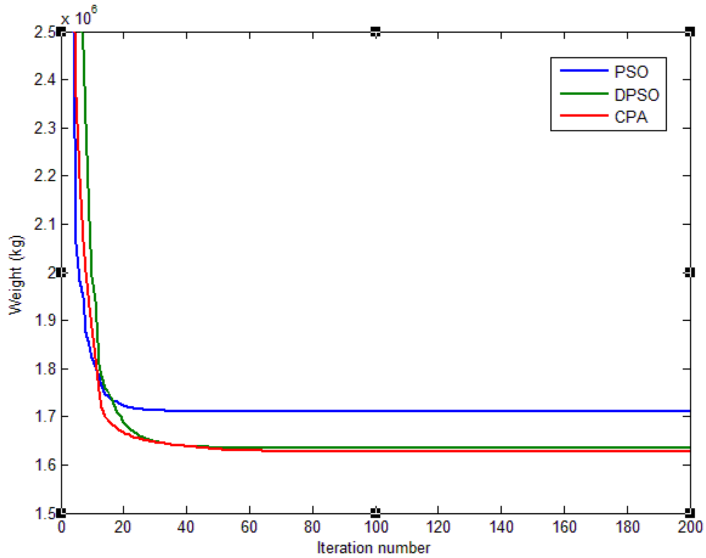

Figure 3. convergence curves of the best runs of different algorithms

5. CONCLUSION

In this paper weight minimization of a jacket-type offshore platform is carried out using meta-heuristic algorithms. These structures are steel towers designed and constructed in marine environments for various purposes such as oil exploration and exploitation units, oceanographic research, and undersea testing. OAPI feature is utilized in order to access SAP2000, which used for the analysis and design of the structure, through MATLAB. The structure is optimized under dead loads and wave loads, which are calculated using Morison's equation in the airy (linear) wave theory and the deepwater condition in accordance to the specifications of API-RP 2A-WSD.

The optimization procedure is performed using the newly developed Cyclical Parthenogenesis Algorithm (CPA). CPA is a nature-inspired population-based meta-heuristic algorithm which is based on some key aspects of the lives of aphids as one of the highly successful organisms, especially their ability to reproduce with and without mating.

Numerical results indicate that the performances of CPA and DPSO are meaningfully better than that of standard PSO both in terms of accuracy and robustness. It could also be observed that the CPA performs slightly better than DPSO both in terms of best weight and statistical information. The better performance of CPA could be attributed to its convergence operators. Utilization of multiple search colonies and fly and death mechanisms can help the algorithm perform a proper balance between exploration and exploitation tendencies resulting in a powerful performance.

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