OPTIMIZATION OF STEEL CATENARY RISERS USING BIO-INSPIRED ALGORITHMS

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Abstract. *The design of a riser is very time consuming, since a large number of parameters (e.g.: thickness, top angle, and material properties) are involved and tight safety requirements must be met. This leads to the study of tools, such as optimization algorithms, that can speed up the process of elaborating a feasible riser project for certain conditions. Considering that some of the parameters in the design of a riser can assume a discrete set of values, the utilization of mathematical programming algorithms becomes unfeasible. It is then necessary to use metaheuristic algorithms, such as Genetic Algorithm and Particle Swarm Optimization. In this context, this paper presents a study on the application of bio-inspired algorithms, including GA and PSO, to the design optimization of steel catenary risers. The problem consists of finding the riser material and wall thickness that minimize the cost to fabricate a viable riser, in conformance with the requirements of technical standards. The main hypotheses that were adopted are presented, along with the description of the methodology employed. The results show that a significant reduction in riser cost is achieved when the riser is divided in multiple segments with different thickness and material. The efficiency of the utilized algorithms in finding an optimum riser design for the specified conditions is confirmed by the obtained numerical results.*

Keywords: Bio-inspired algorithms, Optimization, Risers

1   INTRODUCTION

Risers are essential part of offshore systems during both drilling and production of oil and gas. These structures provide means for drill strings to reach the well and convey the fluids from the wellhead at the seabed to a floating platform on the sea surface. They can be fabricated with distinct materials, from various grades of steel to titanium and composite materials. Furthermore, these structures can be installed in different configurations, from free-hanging catenary to configurations that include floating elements.

Independent of the material and configuration, all risers are subjected to diverse types of loadings, including hydrostatic internal and external pressures, weight and buoyancy, weight of internal fluid, waves, currents, and vessel motion. For each riser design, a large number of load cases is generated since several environmental load conditions must be taken into account. These load cases must be numerically simulated to assure that certain riser design will remain integral throughout the operating life of the offshore system. Additionally, there is a sizable solution space to be explored, which results in a considerable long time to perform all the simulations needed. However, this process can be speed up if it is treated as an optimization problem.

The robustness of optimization algorithms applied to the design of risers is illustrated in Larsen and Hanson (1999), Cunliffe *et al.* (2004), Pina *et al.* (2011), Silva *et al.* (2013). Larsen and Hanson (1999) developed a program that generates an optimized steel catenary riser design using a Sequential Quadratic Programming scheme. In Cunliffe *et al.* (2004) the utilization of a Genetic Algorithm (GA) is illustrated for the design of a titanium catenary gas export riser. Genetic algorithm tries to find the global optimum of the problem adopting the concepts of natural selection, proposed by Darwin, and genetic inheritance, proposed by Mendel (Arora, 2004). Silva *et al.* (2013) implemented different kinds of algorithms, including GA, for the optimization of composite risers in free hanging configuration. On the other hand, Particle Swarm Optimization (PSO) is inspired by the social behavior of biological groups (e.g. birds flock) in search for food. Particles, which represent potential solutions, fly through the search space seeking better solutions based on the individual and swarm learning (Bratton, 2007). In Pina *et al.* (2011) the efficiency of this type of algorithm applied to the design of steel riser in lazy-wave configuration is demonstrated.

2   OPTIMIZATION MODEL

The optimization model aims to minimize the cost of Steel Catenary Risers (SCRs), subjected to multiple load cases. The riser analysis is performed using an inextensible cable model, which considers weight, buoyance, sea current and platform offset. The relevant parameters for the model are the water density, oil density, internal diameter of the riser, top angle, internal pressure at the top of the riser, pressure during hydrostatic test, and number of riser segments.

The design variables are the material and wall thickness of each segment. In the implementation, each design candidate is represented by a matrix with the number of rows equal to the number of variables (in this case, material and thickness) and number of columns equal to the number of segments. In the integer encoding chosen for this problem, materials (API 5L Grade B, X42, X46, X52, X56, X60, X65, X70, X80) are represented by numbers 1 to 9, and possible thickness values (5 mm, 7.5 mm, 10 mm, 12.5 mm, 15 mm, 17.5 mm, 20 mm, 22.5 mm, 25 mm, 27.5 mm, 30 mm, 32.5 mm, 35 mm, 37.5 mm, 40 mm, 42.5 mm, 45 mm, 47.5 mm, 50 mm, 52.5 mm) are represented by numbers 1 to 20. The mechanical

properties (e.g.: yield stress, Young's modulus, specific weight) of commercially available materials can be found in technical standards, as in American Petroleum Institute (2004).

The objective function chosen for the purpose of this study was the cost of the riser given by

$$f_{obj} = \sum_{i=1}^{n} \pi (R_e^2 - R_i^2) LC \tag{1}$$

where n is the number of riser segments, R_i and R_e are the outer and inner radius of the segment, L is the length of the segment and C is the cost (per m^3 of material) of material of the segment. For each material a relative cost, proportional to its resistance, was considered. The resistance and cost of steel are greater for the higher grade steels. However, a reduction of fabrication cost for a higher grade steel may be possible, since it permits a reduction in thickness.

The restrictions applied follow the design checks for the ultimate limit state (ULS), in the normal safety class, defined in DNV-OS-F201 (2010). To avoid bursting of the structure, the following condition must be satisfied at all cross sections:

$$P_{li} - P_e \leq \frac{P_b}{\gamma_m \gamma_{SC}} \tag{2}$$

where P_{li} is the local incidental pressure, P_e is the external pressure, γ_m is the material resistance factor (1.15), γ_{SC} is a safety class factor (1.14), P_b is the burst resistance.

The requirement to avoid buckling of the riser due to the external pressure is given by

$$P_e - P_{\min} \leq \frac{P_{\mathrm{Pr}}}{\gamma_c \gamma_m \gamma_{SC}} \tag{3}$$

where P_{min} is the minimum internal pressure, P_{Pr} is the resistance against buckling propagation, γ_c is a condition factor that assumes the value of 1.0 for no buckle propagation; must be satisfied.

To guarantee the integrity of the riser under combined loading, the following restrictions must be satisfied:

$$\{\gamma_{SC}\gamma_m\}\left\{\left(\frac{T_{ed}}{T_k}\right)^2\right\} + \left(\frac{p_{ld} - p_e}{p_b}\right)^2 \leq 1 \tag{4}$$

$$\{\gamma_{SC}\gamma_m\}^2\left\{\left(\frac{T_{ed}}{T_k}\right)^4\right\} + \{\gamma_{SC}\gamma_m\}^2\left(\frac{p_e - p_{\min}}{p_c}\right)^2 \leq 1 \tag{5}$$

where P_{ld} is the local internal design pressure, P_c is the hoop buckling capacity, T_k is the plastic axial force resistance, and T_{ed} is the design effective tension given by

$$T_{ed} = \gamma_F T_{eF} + \gamma_E T_{eE} \tag{6}$$

where T_{eF} is the effective tension from functional loads, T_{eE} is the effective tension from environmental loads, γ_F is the factor for functional loads (1.1) and γ_E is the factor for environmental loads (1.3). The burst resistance (P_b), resistance against buckling propagation (P_{Pr}), hoop buckling capacity (P_c) and plastic axial force resistance (T_k) were calculated as determined in DNV-OS-F201 (2010).

3 NUMERICAL EXAMPLES

For the numerical examples, the water density ρ_w is 1025 kg/m³, oil density ρ_o is 880 kg/m³, internal diameter of the riser is 0.125 m, top angle α is 20°, internal pressure at the top of the riser p_d is 30 MPa, pressure during hydrostatic test p_{ht} is 37.5 MPa. The load cases considered in the riser design are presented on Table 1. The water depth was considered 1500 m. Two current profiles were considered: in the first one, the ocean velocity is 0 m/s; in the second one, a polygonal current profile varying from 1.0 m/s at sea top and 0 m/s at the sea bottom is applied.

Table 1. Load cases

Load case nº	Offset	Position	Fluid density	Pressure at the top	Current profile
1	8.5%	Far	ρ_o	p_d	1
2	8.5%	Near	ρ_o	p_d	1
3	8.5%	Far	0	0	1
4	8.5%	Near	0	0	1
5	3.0%	Far	ρ_w	p_{ht}	1
6	3.0%	Near	ρ_w	p_{ht}	1

The algorithm parameters for the Genetic Algorithm and for the Particle Swarm Optimization are presented in Table 2. A population of 100 individuals with 50 generations is considered for both methods.

Table 2. Algorithm parameters

	GA	PSO
Crossover	0.9	0.9
Mutation	0.05	0.05
Global topology	NA	Global best
Particle inertia	NA	Linear, from 0.9 to 0.4
Cognitive factor	NA	Linear, from 2.5 to 0.0
Social factor	NA	Linear, from 0.0 to 2.5

For means of comparison, a riser with only one segment, which has length of 2520 m and internal radius of 0.125 m, was first optimized. The optimum design for these conditions is a riser made of API 5L grade B steel and wall thickness of 0.035 m. Both algorithms found this solution, but for GA the convergence was achieved in the 6th generation, while, for PSO, the convergence was achieved in the 3rd generation.

Then, a steel riser with three segments was optimized. The first, second and third segments lengths are 800, 1000 and 720 m, respectively. All segments have the same internal radius (0.125 m). The optimum design for these conditions is a riser in which the first segment is made of API 5L X52 steel and has wall thickness of 0.0225 m, the second segment is made of API 5L X42 steel and has wall thickness of 0.0275 m and the third segment is made of API 5L grade B steel and has wall thickness of 0.035 m. Both algorithms found this optimum solution, but again convergence was achieved earlier for PSO.

The adopted methodology of dividing the riser in segments, which have material as free variable, allows materials with higher resistances to be used just in the portions of the riser with higher requirements, implying in overall reduction of riser cost. When comparing the solutions for the riser with one segment and the riser with three segments, a reduction of about 7.2% in the total cost of the riser was achieved. In terms of optimization, it can be seen that a better solution is found when multiple segments are admitted, since a larger search space is considered.

4   CONCLUSION

This study addressed the application of bio-inspired algorithms for the optimization of steel catenary risers. In the adopted methodology, the possibility of considering a riser with multiple segments, represented an advantage when referring to cost reduction. The utilization of a simple analysis procedure in the optimization model, proved to be efficient in simulating the load conditions described, with an acceptable execution time.

Optimum solutions, which represent the riser with the lowest cost that fulfills requirements of technical standards for the specified conditions, were found for all the numerical examples presented by both algorithms tested, proving the robustness of the proposed methodology and its computer implementation. When comparing the performance of the tested algorithms, Particle Swarm Optimization proved to have a better performance for the numerical examples simulated, since converge is achieved earlier.

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