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Mooring Pattern Optimization Using A Genetic Algorithm

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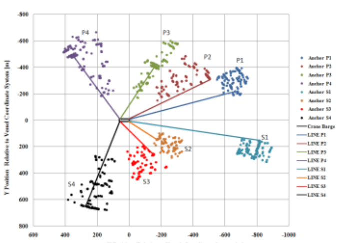
Graphical abstract



Abstract

In this paper, a constraint Genetic Algorithm is used for the purpose of mooring pattern optimization. The Genetic Algorithm is applied through a mathematical formulation which is introduced to define a typical mooring system optimization problem. The mathematical formulation is used in a case study on a spread moored crane barge, operating in the vicinity of a jacket type platform, in order to minimize its surge motions towards the platform. For this purpose, a set of criteria regarding clearances between anchors and seabed preinstalled facilities (pipelines), and also between the crane barge and the jacket platform are presented and considered. An automatic process of repetitive analyses implementing a MATLAB code as an interface between the Genetic Algorithm and a mooring system analysis program is used, and an optimum solution is resulted by performing 4000 quasi-dynamic analyses in time domain. The effectiveness of the Genetic Algorithm in leading to an optimum mooring system pattern is studied and it is shown that using a proper formulation of the problem, the Genetic Algorithm can be a very useful tool for finding an optimum pattern for mooring systems in fields with constraints on anchor locations and vessel motions.

Keywords: Mooring pattern; optimization; genetic algorithm

1.0 INTRODUCTION

Excessive vessel motions while encountering harsh environments may cause offshore operations of moored floating units to stop, as a result, finding an optimum mooring system design which leads to limited vessel excursions, while satisfying other constraints can be known as one of the most important aspects of a mooring system design, and it is the main focus of this research. Where the constraints include; line tensions, anchor positioning, and lines clearance from other installed facilities.

Different parameters of a mooring system can be considered as a target for a mooring system optimization problem. These parameters include; line profile (paid-out length, pretension, and fairlead to anchor horizontal distance), line material, and the mooring system pattern. The process of such optimization is often time consuming since it requires a large number of trial and error sequences. In order to address this issue, the present research introduces an automatic procedure in which the Genetic Algorithm (GA) is used as an optimization tool. For this purpose, an interface MATLAB code is developed to link the mooring system analyses with the GA. The effectiveness of the GA as an optimization tool for mooring systems is shown through a case study on a spread moored crane barge.

(Shafieefar and Rezvani, 2007) implemented a Genetic Algorithm for mooring system optimization of floating platforms using a frequency domain approach. Although the frequency domain approach has the benefit of being less time consuming and costly, approximations due to linearization of nonlinear effects are inevitable in this method (Bureau Veritas, 2008), (Barltrop, 1998). In order to avoid these approximations, in this research, the mooring system analysis is performed in time domain.

2.0 GENETIC ALGORITHM

The Genetic Algorithm is a stochastic global search method that uses the principles of natural biological evolution at groups of potential solutions called generation. At each generation, a new set of solutions is created by selecting individuals according to their level of fitness in the problem domain and breeding them together using operators simulated from natural genetics.

The first GAs were developed in the 1960s. In 1975, Holland's book (Holland, 1992), which had been originally conceived for the study of adaptive search in Artificial Intelligence, formally established GAs as valid search algorithms.

GAs operate on a population of potential solutions applying the principle of survival of the fittest to produce better and better approximations to a solution. This process leads to the evolution of populations of individuals that are better suited to their environment than the individuals that they were created from, just as in natural adaptation.

One of the disadvantages of GAs is their high computational cost, due to the large number of evaluations of the objective function necessary to achieve numerical convergence. To cope with this, a proper set of the GA operators must be used, based on the problem type. For the implementation details of the GA operators, the authors refer to (Holland, 1992), (Wu and Chow, 1995), and (Mitchell and Davis, 1998). The overall process of the GA as used in this paper is shown in Figure 1.

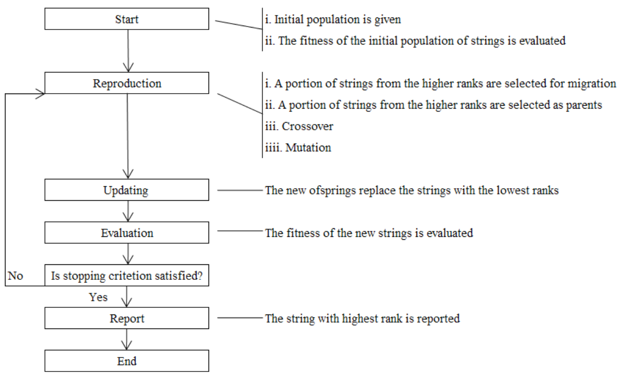


Figure 1 Flowchart of the GA process

3.0 MOORING SYSTEM ANALYSIS

Ultramarine MOSES software is used for the purpose of mooring system analysis. Using this tool, vessels are modeled by a set of points and panels. Excitation loads are calculated using a 3D diffraction calculation based on the vessel geometry and mass distribution data. The excitation forces which are taken into account could be grouped into three categories; static forces (current, wind, and a mean wave force) which result in static displacement of the vessel, direct wave forces (forces at the wave frequency) giving the wave frequency motions, and non wave frequency forces (wave drift and wind gusts) which lead to low frequency motions.

In order to calculate the excursion of a moored vessel, the first step is to get the static equilibrium position. This is the position in which the sum of all (mean) external and restoring forces on the vessel equals to zero. The offsets are then calculated relative to the static equilibrium position; however it is possible to calculate the offsets relative to any other point by doing a simple transfer on the coordinates. Then, the total motions of the vessel may be resulted from adding the low frequency and wave frequency parts in which the QTFs and RAOs are respectively used. The line tensions are correspondingly resulted from the low frequency and wave frequency and static parts. Figure 2 depicts the overall process of the calculations required for mooring line tension estimation.

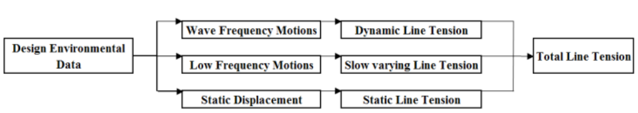


Figure 2 Mooring lines tension calculation

In this research, mooring line tensions and the vessel offsets are calculated using a coupled quasi-dynamic analysis in time domain. Direct loading on mooring lines are ignored in order to reduce the required analysis time of repetitive time domain analyses. For basic theories regarding hydrodynamic calculations the authors refer to (Journée and Massie, 2001) and (Barltrop, 1998).

4.0 MATHEMATICAL FORMULATION

The mooring system optimization problem is formulated in the following form:

Find α which minimizes;

$$Minimize\ E(\alpha) \qquad \alpha = \{\alpha_1, \dots, \alpha_j\} \tag{1}$$

Subject to;

$$\alpha_{j\ min} \le \alpha_j \le \alpha_{j\ max} \qquad j = 1, \dots, n \tag{2}$$

$$g_k(\alpha) \ge 1.67 \qquad k = 1, \dots, m \tag{3}$$

Where in, $E(\alpha)$ is the objective function, which can be defined, in correspondence to the problem (it is the surge motion of the vessel in this research). In Equation (2), the lower and upper bounds for the variables are defined, where n is the number of variables included in a solution vector (α). In Equation (3), m represents the number of mooring lines, $g_k(\alpha)$ is the safety factor of line tension. The value of 1.67 is recommended by (API RP 2SK, 2005) for dynamic analysis of an intact mooring system and is defined by the following formula;

$$Tension\ Safety\ Factor\ (S.F.) = \frac{Minimum\ Breaking\ Load}{Line\ Tension} \quad \text{Eq. (4)}$$

Using a fitness function definition, the objective function minimization problem transforms to the fitness maximization problem. For this purpose the fitness function F and the penalty function P are defined as follows:

$$F = 1 - \frac{\varphi}{\varphi_{max}} \tag{5}$$

$$\varphi = E \cdot P \tag{6}$$

$$P = 1 + 3\sum_{k=1}^{m} \Gamma_k \tag{7}$$

$$\Gamma_k = 0 \quad \text{if } g_k(\alpha) \ge 1.67 \quad k = 1, \dots, m \tag{8}$$

$$\Gamma_k = 1 \quad \text{if } g_k(\alpha) < 1.67 \quad k = 1, \dots, m \tag{9}$$

Using the penalty function method, the constraint optimization problem is converted to an unconstrained problem. The above equations denote that, as long as all line tension safety factors are greater than 1.67, there is no amplification and no penalty on the objective function value ($P = 1$). Otherwise, a penalty value as defined in Equation (7) will be multiplied to the objective function value in order to impose a high cost for violation of line tension constraint.

In each generation of the GA process, the solution vectors α are ranked based on their fitness value. Then the solutions with higher fitness values are chosen for reproduction, and those with lowest fitness values are gradually eliminated.

5.0 CASE STUDY

For the purpose of mooring pattern optimization, in this research, a crane barge operating near a jacket type platform and moored via a spread mooring system is considered. The importance of the optimization in such a problem is that the vessel and the mooring lines must be kept clear from the jacket structure. As a result, the motion of the vessel towards the jacket must be limited. In addition, there are limitations for selecting the position of anchors due to seabed pipe lines. The criteria regarding clearances of mooring lines, vessel, and the jacket platform will be discussed in section 5.2.

Figure 3 shows a plan view of the operation field, where the vessel is moored using 8 mooring lines; lines P1 to P4 are the port side moorings and lines S1 to S4 are the starboard side lines.

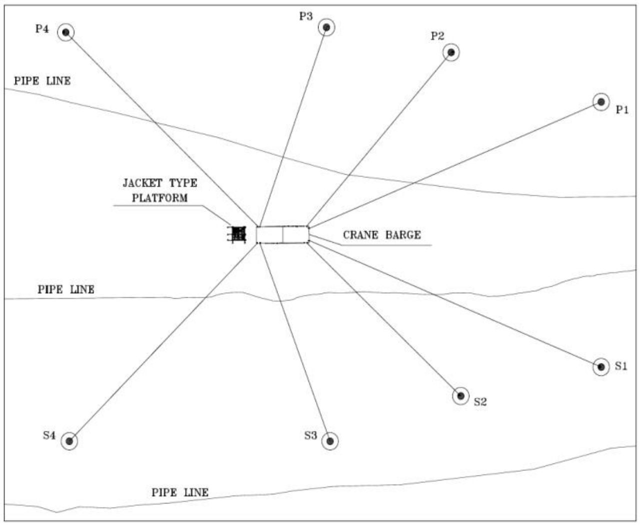


Figure 3 Plan view of the operation field

5.1 Environmental Condition

Based on (API RP 2SK, 2005), in case of a temporarily moored vessels operating in the vicinity of other structures, two sets of environmental conditions should be considered; a maximum design condition with a return period of at least 10 years, and a maximum operating condition. The maximum design condition must be selected base on annual statistics resulted from a met-ocean survey in the location, while the maximum operating condition is defined as the combination of maximum wind, waves, and current in which the unit can continue to work. This condition shall not exceed the maximum design condition (API RP 2SK, 2005).

Therefore, in order to simulate the operating moored vessel, the mooring system pattern is optimized considering the maximum operating condition and it is assumed that when the environment exceeds the maximum operating condition the operation will be stopped and the vessel will be moved to stand-off position.

5.2 Constraitns due to Clearances

For the current problem, a clearance of 10 meters between mooring lines and the jacket platform is recommended by (Noble Denton, 2002). It also recommends a minimum 3 meters clearance between the vessel and the platform during the operation. In addition, the following clearances between a mooring line and a seabed asset such as pipe-line are recommended in the same guideline:

- When an anchor is placed on the same side of a subsea asset as the crane vessel, it should not be placed closer to the subsea asset than 100 meters.
- When the subsea asset lies between the anchor and the crane vessel, the final anchor position should be not less than 200 meters from the subsea asset.

The above mentioned criteria define the constraints which must be considered in the optimization problem. Where the vessel surge motion toward the platform must be limited and the anchor positions must be selected so that the clearance criteria are met. Figure 4 shows the criteria for the clearance between mooring lines - jacket, and vessel - jacket.

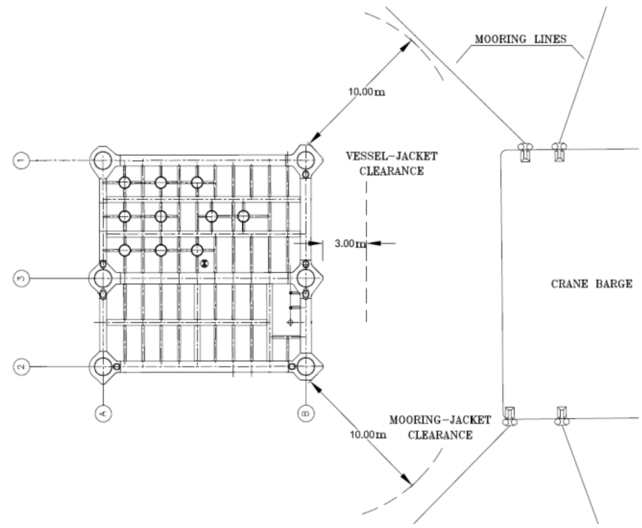


Figure 4 Clearance criteria

5.3 Numerical Application

The crane barge, previously shown in Figure 3, is subjected to mooring pattern optimization in a water depth of 60 m. The mooring system is comprised of 8 lines; 4 lines in each side. As discussed in section 5.2 the problem constraints are defined according to the recommended guidelines for a crane barge operating in the vicinity of other structures. The constraints for anchor positions considering the criteria presented in section 5.2 are shown in Table 1. Line azimuths are defined relative to vessel x axis, positive counter clockwise.

Table 1 Constraints on anchor positions

Lines	Line Azimuth [deg]	Fairlead-Anchor Horizontal Distance [m]
P1	From -184 to -154	From 618 to 818
P2	From -146 to -116	From 212 to 412
P3	From -132 to -102	From 176 to 376
P4	From -68 to -32	From 220 to 420
S1	From 154 to 184	From 618 to 818
S2	From 116 to 146	From 212 to 412
S3	From 102 to 132	From 176 to 376
S4	From 32 to 68	From 220 to 420

The crane barge has a length of 121.92 m, width of 30.48 m, depth of 8.69 m, and a 4.30 m draft. All mooring lines have the same sectional and strength properties as presented in Table 2.

Table 2 Mooring lines properties

Properties	Value	Unit
Type	Wire Rope	[-]
Diameter	32	[mm]
E-modulus	77846	[MPa]
Mass in water	0.00373	[ton/m]
Minimum Breaking Load (MBL)	72.40	[ton]

In order to reduce the number of variables in the optimization program, a pretension equal to 7 ton is considered for all the mooring lines except for lines P1 and S1 having a pretension of 15 ton. As a result, the lines length is automatically calculated with the mooring analysis software based on the horizontal distance from fairlead to anchor and the pretensions. The starting point of the optimization process is defined considering the values given in Table 3.

Table 3 Anchor positions at starting point

Anchor ID	P1	P2	P3	P4	S1	S2	S3	S4
Anchor-Fairlead Horizontal Distance [m]	718	312	276	320	817	308	323	380
Azimuth [deg]	-169	-131	-117	-53	160	125	110	70

The maximum operational environment is considered as presented in Table 4.

Table 4 Maximum operational environment

Wave spectrum	JONSWAP
Gamma	1.4
Significant wave height	3.5 [m]
Tp (Peak Period)	6 [sec]
Wind speed	20 [m/s]
Current Speed at water level	0.5 [m/s]

Since the objective of the optimization is to minimize the surge motion of the crane barge, following a sensitivity analysis, it is found that the maximum environmental loads, in vessel x direction, happen when the wave, wind, and currents are collinearly applied to the vessel with a heading of 225 degree. As a result, all environmental components come from 225 degree relative to x axis of the vessel. Vessel axes are shown in Figure 5 beside the environmental heading convention.

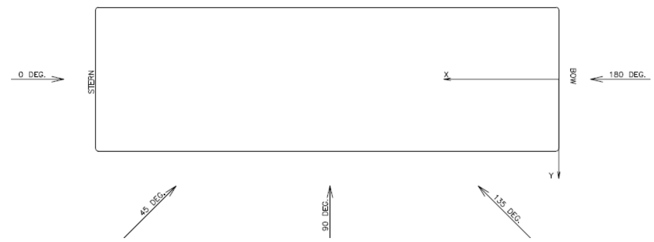


Figure 5 Environmental heading definition

Mooring system analysis results for the system defined by the starting point values are presented in Table 5.

Table 5 Lines tension at starting point

Anchor ID	P1	P2	P3	P4	S1	S2	S3	S4
Line Tension [ton]	28.62	62.74	63.85	48.69	18.75	10.72	33.27	50.00
Safety Factor	2.53	1.15	1.13	1.49	3.86	6.75	2.18	1.45

Considering the minimum acceptable safety factor of 1.67 for the lines tension based on Equation (4), Table 6 shows that lines P2, P3, P4, and S4 were broken at the defined starting point and the mooring system at the starting stage of the optimization fails to moor the vessel.

The GA parameters are considered as presented in Table 6. As it can be seen in this table, a two-point crossover with a probability of 0.5 is considered in this research. The mutation probability is also equal to 0.5. It means that, except for the number of strings determined by "Elite Count" parameter (in this research; 2), which will survive in the next generation, the other strings will be replaced by new off-springs while half of them are built using the crossover operator and the other half are mutated using the mutation operator.

Table 6 Genetic algorithm parameters

Parameter	Value
Crossover Probability	0.5
Crossover Type	two-point
Mutation Probability	0.5
Number of Generations	100
Population size	40
Elite Count	2

5.4 Optimization Results

Figure 6 shows the optimized mooring system together with all the points considered for the anchor positions during the optimization process. Where, 4000 mooring system analyses have been performed, in time domain, using different combinations of these anchor positions.

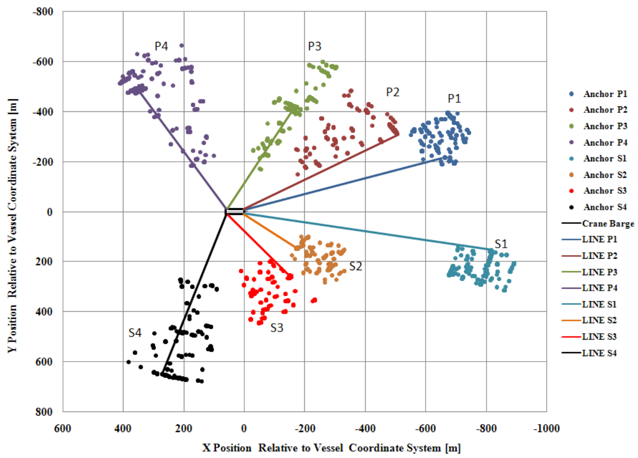


Figure 6 Optimized mooring system and anchor positions considered in the optimization process

All the anchoring points shown in Figure 6 are considered in the optimization process satisfying the constraints for positioning of the anchors (as presented in Table 1).

The optimized anchor positions resulted from the optimization process are presented in Table 7.

Table 7 Optimized anchor positions

Anchor ID	P1	P2	P3	P4	S 1	S2	S3	S4
Anchor-Fairlead Horizontal Distance [m]	68 3.4	59 3	45 3.7	55 4.9	8 3 4	22 6. 4	32 9. 6	67 6. 6
Azimuth [deg]	- 16 2.5	- 14 9.6	- 11 8.6	- 58. 64	1 7 0	14 2. 2	13 0	71 .7 1

The values presented in the above tables belong to the anchor positions of the optimized mooring system which is shown in Figure 6. The line tensions and safety factors for the optimized system are presented in Table 8.

Table 8 Optimized mooring system - line tension

Anchor ID	P1	P2	P3	P4	S1	S2	S3	S4
Line Tension [ton]	32. 45	37. 92	31. 86	35. 98	17. 97	6.4 5	21. 78	32. 65
Safety Factor	2.2 3	1.9 1	2.2 7	2.0 1	4.0 3	11. 22	3.3 2	2.2 2

As it can be seen in the resulted line tensions, all the mooring lines have safety factors greater than 1.67. Knowing that a few lines were broken at the starting point of the optimization process (see Table 5), the results presented in the table above are in line with the concept of the optimization. It must also be mentioned that the surge motion of the vessel relative to its equilibrium position is 0.86 m after optimization of the mooring system while the mooring system at the starting point was failed

As it could be expected, the results also show that the portside lines i.e. lines P1 through P4, experience higher tensions compared with the starboard side lines (lines S1 through S4) because of the environmental loads heading considered.

■6.0 CONCLUSION

This research shows the robustness of the Genetic Algorithm in optimization of mooring pattern subjected to different constraints for the anchor positions and mooring lines tension. In a similar manner, since the design parameters in a mooring system are discrete (not continues), it can be concluded that GA can be suitable for engineering problems dealing with discrete parameters by developing proper interface codes between the GA and industrial software, like what has been used in this research between Ultramarine MOSES and MATLAB.

In this paper, an equal probability is used for crossover and mutation operators. A sensitivity analysis on the values defined for GA operators could reveal the proper range for each one beside their effect on the trend toward the optimum design. This topic will be addressed in future works.

In this research, the mooring system analysis is performed in time domain, which yields more accurate and realistic results in comparison with the frequency domain analyses, by including all nonlinear effects of a mooring system analysis, however it is more time consuming and costly.

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