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Mooring Cost Sensitivity Study Based on Cost-Optimum Mooring Design

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ABSTRACT: *The paper describes results of a sensitivity study on an optimum mooring cost as a function of safety factor and required maximum offset of the offshore floating structure by finding the anchor leg component size and the declination angle. A Harmony Search (HS) based mooring optimization program has been applied to conduct this study. This mooring optimization model was integrated with a frequency-domain global motion analysis program to assess both cost and design constraints of the mooring system. To find a trend of anchor leg system cost for the proposed sensitivity study, optimum costs after a certain number of iteration were found first and they were compared. For a case study a turret-moored FPSO with 3 X 3 anchor leg system was considered. To better guide search for the optimum cost, three different penalty functions were applied. The results show that the presented HS-based cost-optimum offshore mooring design tool can be used to find optimum mooring design values such as declination angle and horizontal end point separation as well as cost-optimum mooring system in case either the required maximum offset or factor of safety varies.*

1. Introduction

As other engineering design cycles the offshore mooring design requires significant amount of design cycles with the satisfaction of the complex design constraints in order to achieve an economically competitive solution (Ryu et al., 2007). Ryu et al. (2007) presented anchor leg cost optimization via harmony search and concluded that the harmony search was able to find cost optimum solutions. Fylling (1997) and Fylling and Kleiven (2000) address an application of mooring optimization of deepwater mooring and riser risers. A single point mooring of an FPSO was selected for a case study.

This study focuses on mooring cost sensitivity of the anchor leg system optimized by using harmony search (HS) algorithm. Parameters that change for this sensitivity study include safety factor and required maximum offset of the floating platform.

This paper addresses HS-based mooring optimization determining length and diameter of each mooring component, declination and horizontal end point separation distance that satisfies required safety factor of the mooring line top tension, maximum platform offset, and bottom chain length. In this paper the HS algorithm is summarized first. Secondly, applied penalty functions are presented. Lastly, mooring cost sensitivity results for a deepwater FPSO moored by 3 x 3 anchor leg system are summarized.

2. Harmony search algorithm

Compared to other simulation-based meta-heuristic optimization algorithms such as simulated annealing, tabu search, and generic algorithm (Simpson et al., 1994; Cunha and Sousa, 1999), HS was adopted from musical process of finding 'pleasant harmonies.' For instance, when several notes from different musical instruments are played simultaneously on a random basis and this process is repeated, there is a possibility to find better harmonies. In HS, these better harmonies are saved in a certain size of memory by replacing the worst harmony in the memory until the pre-defined maximum number of improvisation, generating a new harmony, is reached.

HS has relatively simple structure and does not require complex mathematical gradients for the functions in optimization process. Thus, it is free from mathematical divergence in the middle of computation (Geem, 2006b). HS also does not require starting values for design variables. Thus, it has better chance to find global optimum rather than to be entrapped in local optima (Geem et al., 2001). By nature, HS can efficiently handle discrete variables as well as continuous variables (Lee and Geem, 2005). However, conventional gradient methods handle continuous variable only, which causes a problem when design variables have discrete values, such as commercial sizes made in a factory.

To round continuous values up to discrete values may cause the final design worse (Geem, 2006a).

When compared with genetic algorithm (GA) as another popular soft-computing method, HS overcame the drawback of GA's major mechanism by explicitly considering the relationship among design variables (Geem, 2006c).

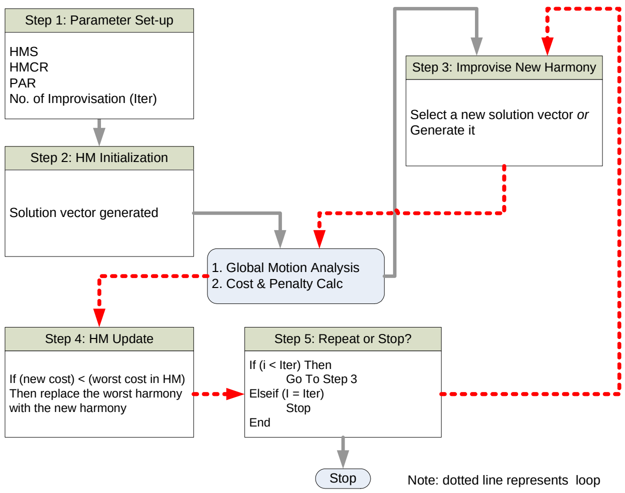

Fig. 1 Flow chart of HS algorithm for designing a cost-optimal mooring system (Ryu et al., 2007).

Fundamental five steps of a HS for the cost-optimum mooring system design are shown in Fig. 1, and they are detailed in Ryu et al. (2007). A typical mooring design cycle is summarized in Fig. 2. In this present study mooring design for only intact case was considered.

3. Penalty Functions

Implemented three design constraints include (1) factor of safety (FS) for the top tension of the intact case, (2) no uplift of the bottom chain, and (3) required maximum platform offset. To better guide search for a cost optimum solution, following three different types of penalty functions were employed for the above mentioned three design constraints, respectively:

$$p_1 = c \times (T_{\max} / MBL)^2 \quad (1)$$

$$p_2 = c_{average} \quad (2)$$

$$p_3 = c \times (d_{\max} / d_{\max,design})^2 \quad (3)$$

where $p_i (i = 1, 2, 3)$ represents cost penalty, c calculated material cost, $c_{average}$ average cost of the saved harmony memory, $T_{\max}$ calculated maximum top tension, MBL minimum break load, $d_{\max}$ calculated maximum offset, and $d_{\max,design}$ required maximum design offset.

4. Case Study: FPSO Mooring Design

As a case study an FPSO turret-moored by 3 x 3 chain-wire-chain anchor leg system is considered. The FPSO with a permanent turret mooring system in water depth (WD) of 800m was defined as the base case. The FPSO vessel particulars used are detailed in Ryu et al. (2007). Followed is the summary of the design constraints for the base case:

- maximum FPSO offset = 7.5% of water depth;
- FS for intact case top tension = 1.67 (minimum break load MBL); and
- no uplift at the anchor position.

Each anchor leg is made up of a combination of studless chain and spiral strand wire rope. The objective function (i.e. total cost of mooring system) is also simplified as:

$$C = \sum_{i=1}^{N} f(L_i, d_i) \quad (4)$$

where $f(L_i, d_i)$ is the cost of mooring component i with length L_i and d_i diameter , and N is the number of mooring components in the mooring system.

The sign conventions utilized for the analysis of motions and loads in earth-fixed and vessel-fixed local coordinate systems are summarized in Ryu et al. (2007). The nine anchor legs for the FPSO vessel are arranged in three groups of 3 anchor legs each. One group of anchor legs is oriented 15 degrees CCW from North; the other two groups are arranged 120 degrees apart from the Northern group.

The anchor leg fairleads are separated by 13 degrees in each group on the turret, and arranged on an 8-meter radius. The anchor legs depart the turret at 5-degree spacing between adjacent legs in a group. The anchor radius is variable to be determined as a result of the optimization process. The ballast load draft (8.55m) was applied.

4.1 Design environmental condition

The design environmental condition is summarized in Table 1. A JONSWAP spectrum was used to model both the wind waves and the swell, while the NPD spectrum was used to model the gustiness of the wind.

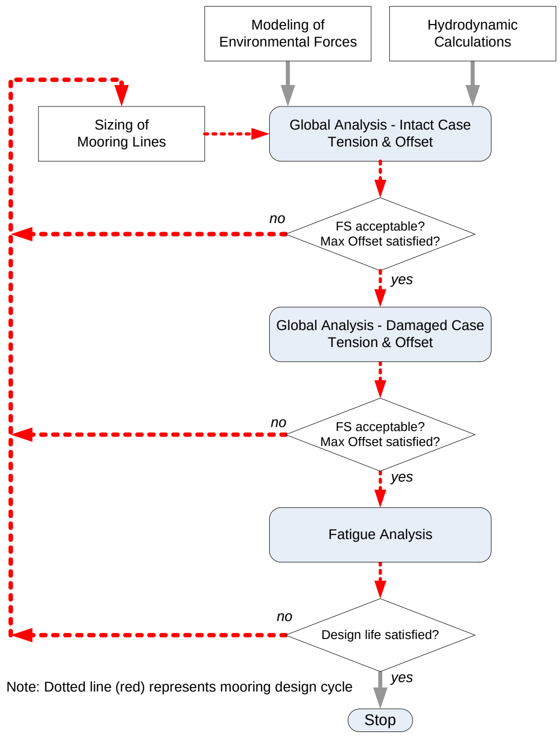

Fig. 2 Flowchart of typical mooring design cycle

Table 1 Summary of design environmental condition.

	Value	Heading [deg]
Wind	39 knots	185
Current	21 knots	185
Wave	Hs = 109 m	215
	Tp = 137 s	
	γ = 212	
Swell	Hs = 10 m	215
	Tp = 130 s	
	γ = 277	

4.2 Estimate of mooring line properties and cost

Expressions for mooring line properties such as minimum break load (MBL), axial stiffness and weight were derived using catalogue data supplied by manufacturers. For wire rope the properties can be described as a function of diameter *d* using the formula: $y = A \times d^B$, where *d* is the diameter of the line in millimeters, and A and B are constant. Table 2 provides the coefficients for the various properties of the rope.

For chain, R4 was chosen for the study and the following formulas were applied for its properties:

$$\mathrm{MBL} = 0.0274 \times \mathrm{d}^2 \times (44 - 0.08 \times \mathrm{d})/9.81$$

$$\mathrm{EA} = (11.86 \times \mathrm{d}^2 - 0.042 \times \mathrm{d}^3) \times 10^4/9810 \qquad (5)$$

$$W = A \times d^2$$

where *A* for wet weight is 0.0170 and 0.0195 for dry weight. The cost estimate of the studless chain and wire is based on the following equations:

$$C_{chain} = 0.06320 \times d^2 \times l \qquad (6)$$

$$C_{wire} = 0.03415 \times d^2 \times l \qquad (7)$$

where *C* is cost in USD ($), *d* the diameter in mm, and *l* the length in meter.

4.3 Harmony search computation

A total of 1,000 iterations were performed for each case to find cost-optimal mooring designs, and Fig. 3 shows the trend of average total anchor leg system cost in harmony memory. The horizontal end point separation between fairlead and anchor is shown in Fig. 4. Figure 5 presents a histogram of the top chain declination angle distribution after 1,000 iterations.

Table 2 Coefficients for estimation of wire rope properties.

	Unit	A	B
MBL	MT	0.1025	19927
Axial Stiffness	MN	0.1512	19010
Wet Weight	kg/m	00045	1.9871
Dry Weight	kg/m	00065	1.9582

Table 3 Input bound for fairlead declination angle.

	Lower (deg)	Upper (deg)
Declination	20	70

In this case study, the applied values of the HS parameters are: HMS = 10 HMCR = 0.95 PAR = 0.8 and NI = 1,000. The input lower and upper bounds for each design parameter, i.e. declination angle, lengths and diameters of top chain, wire, and bottom chain are summarized in Table 3.

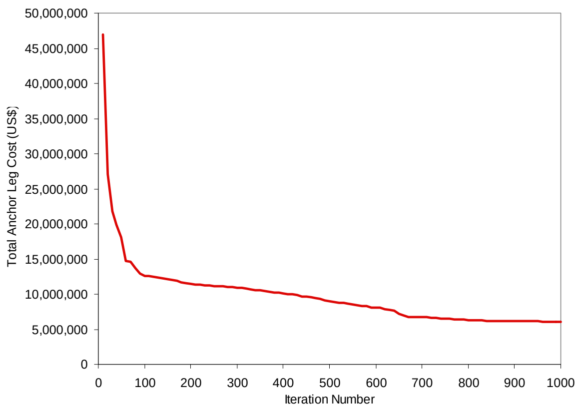

Fig 3 Anchor leg cost of averaged cost in HM (base case).

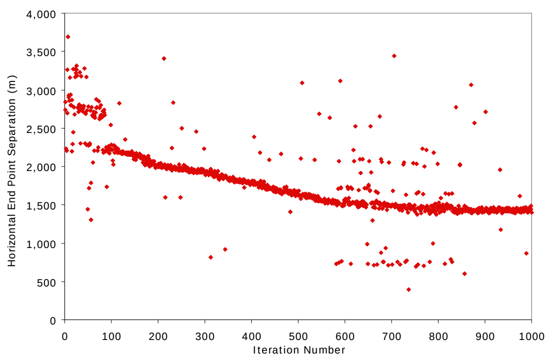

Fig 4 Horizontal end point separation (base case).

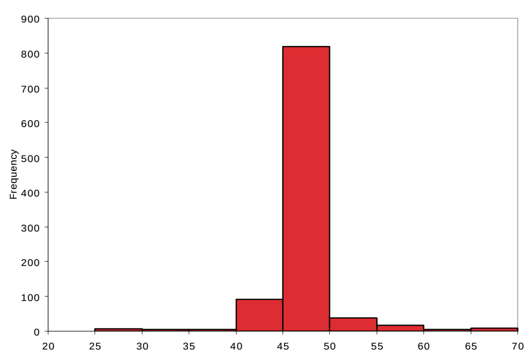

Fig 5 Histogram of top chain declination angle (base case).

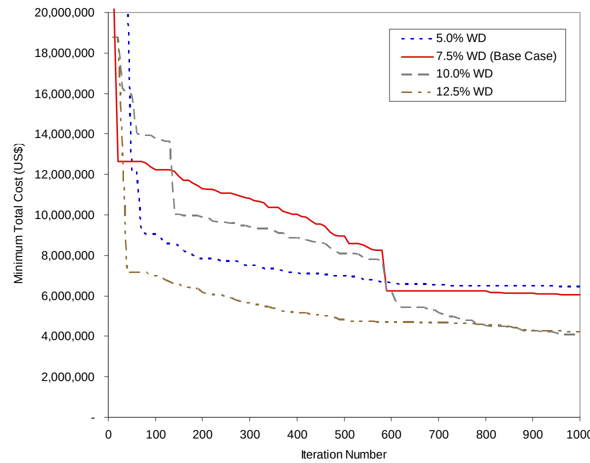

Fig 6 Minimum anchor leg cost vs. required maximum offset.

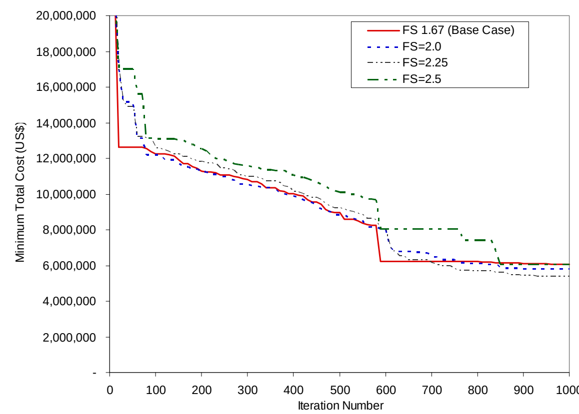

Fig 7 Minimum anchor leg cost vs. safety factor.

Figures 6 and 7 present the trend of the minimum anchor leg cost in the harmony memory as either required maximum offset or factor of safety changes.

5. Conclusions

A mooring optimization design tool using the harmony search algorithm and a frequency domain global analysis tool was applied to conduct the cost sensitivity as a function of required maximum offset and safety factor of the mooring system. The trend of cost-optimal mooring design search over 1,000 iterations was compared.

A case study on a permanent turret mooring system for an FPSO in deepwater was conducted. The results show that the safety factor does not significantly affect the optimum mooring system cost while the required maximum offset could be a big factor for the total cost of the mooring cost.

To better find a feasible, cost optimum mooring system, three different types of penalty functions were applied. As shown in the iteration trend of the declination angle and horizontal end point separation, it is also shown that harmony search is capable of finding optimum design values as well as cost-optimum mooring system.

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