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MOORING COST OPTIMIZATION VIA HARMONY SEARCH

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ABSTRACT

A mooring system optimization program has been developed to minimize the cost of offshore mooring systems. The paper describes an application of the optimization program constructed based on recently developed harmony search optimization algorithm to offshore mooring design which requires significant number of design cycles. The objective of the anchor leg system design is to minimize the mooring cost with feasible solutions that satisfy all the design constraints. The harmony search algorithm is adopted from a jazz improvisation process to find solutions with the optimal cost. 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. As a case study, a single point mooring system design of an FPSO in deepwater was considered. It was found that optimized design parameters obtained by the harmony search model were feasible solutions with the optimized cost. The results show that the harmony search based mooring optimization model can be used to find feasible mooring systems of offshore platforms with the optimal cost.

INTRODUCTION

The mooring design of offshore platforms requires relatively significant amount of design cycles since a desired solution must satisfy the complex design constraints and be economically competitive. The complexity of these mooring design constraints may result from coupling between platform motion and mooring/riser system, maximum offset constraint of the riser system, multiple number of design parameters defining anchor leg system components, and uniqueness of site-dependent environmental conditions including water depth, wave/current/wind condition, seabed condition, etc. When the optimal cost is sought for this complex mooring design, the design process becomes even more complex.

Mooring design is to find an appropriate stiffness which is stiff enough and soft enough at the same time since the mooring system needs to satisfy mainly two design constraints: (1) required maximum horizontal offset and (2) reduction of extreme forces acting on the platform caused by interactions between environmental forces and platform responses. To reduce the trial and error effort in mooring design, Fylling (1997) addresses an application of mooring optimization of deepwater mooring systems. A nonlinear optimization program with frequency-domain analysis of mooring systems was presented, and the results showed that the suggested optimization could be a powerful tool for concept development and finding a feasible solution (Fylling, 1997). Fylling and Kleiven (2000) presented the simultaneous optimization of mooring lines and risers.

Geem et al. (2001) developed a harmony search (HS) meta-heuristic optimization algorithm which was adopted from the musical process of searching for ‘pleasant harmonies’ such as jazz improvisation (Geem, 2006). HS has been applied to various engineering problems including water supply network design, truss structure design, river flood estimate, and traveling salesperson problem (Geem at al. 2001, Geem 2006, Kim et al. 2001, Geem and Tseng 2002, Lee and Geem 2004).

A single point mooring of an FPSO was selected for a case study. Deepwater and ultra-deepwater application of FPSOs becomes more attractive since they have advantages in early production and relatively big storage capacity compared to other types of offshore platforms. As we target for deeper water oil/gas fields, more technical challenges are confronted. For instance, prediction of deepwater oil offloading buoy motion becomes more difficult (Duggal and Ryu, 2005, Ryu, et al., 2006). Technical challenges due to deepwater and ultra-deepwater oil fields and project execution challenges due to the fast track schedule become a trend in FPSO projects (Wyllie, 2004). This deeper water and fast track trend naturally suggests a way of fast finding of a site and requirement specific feasible mooring design.

This paper addresses HS-based mooring optimization determining the length and diameter of each mooring component that satisfies mooring line tension safety factor, maximum platform offset, and bottom chain length. Firstly, the HS algorithm is summarized. Secondly, formulation of the mooring design is described. Thirdly, a case study on the mooring system of a deepwater FPSO was conducted.

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; Lippai et al., 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.

Fundamental five steps of a HS are shown in Figure 1, and they are summarized as follows:

Step 1: Design variable / algorithm parameter initialization;
Step 2: Harmony memory initialization;
Step 3: Generation of a new harmony;
Step 4: Harmony memory update if needed; and
Step 5: Improvisation stopping criterion check.

Step 1: Design variable / algorithm parameter initialization

The optimization is expressed as follows:

$$\text{Minimize} \quad f(x) \tag{1}$$

$$\text{Subject to} \quad x_i \in X_i, i = 1,2,\ldots,N \tag{2}$$

where $f(x)$ is an objective function; x is the vector of each design variable x_i; X_i is the set of the possible values of each design variable which is bounded by the pre-defined range of the design variable; N is the total number of design variables.

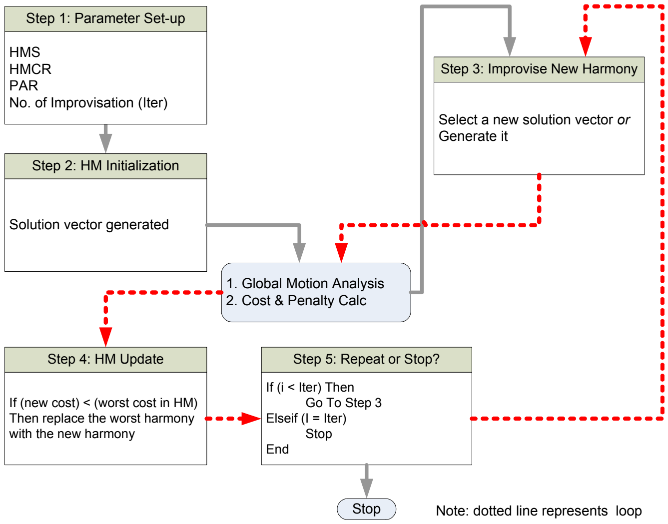

Figure 1. Flow chart of HS algorithm for designing a cost-optimal mooring system.

In the mooring system design, the objective function is the mooring system cost which is a function of material weight, connecting components, installation equipments, certificates, etc. To simplify the problem, only the material weight was considered in this study. Therefore, the diameters and lengths of each mooring component are design variables.

Four HS algorithm parameters that need to be initialized are harmony memory size (HMS), harmony memory considering rate (HMCR), pitch adjusting rate (PAR), and maximum number of improvisations (NI). All the harmonies found are stored in the harmony memory which has a form of (HMS) × (N+1) matrix. Columns one through N store design variable values, and the last column contains the objective function values.

Step 2: Harmony memory initialization

The initial HM memory consists of HMS different solution vectors. Each solution vector has diameter and length values for each mooring component and the total cost of the mooring system. In this study, there are three different anchor leg components (top chain, wire, and bottom chain), and HM memory is shown in Eq. (3).

$$\text{HM} = \begin{bmatrix} l_1^1 & l_2^1 & l_3^1 & d_1^1 & d_2^1 & d_3^1 \\ l_1^2 & l_2^2 & l_3^2 & d_1^2 & d_2^2 & d_3^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ l_1^{HMS} & l_2^{HMS} & d_3^{HMS} & d_1^{HMS} & d_2^{HMS} & d_3^{HMS} \end{bmatrix} \Rightarrow \begin{Bmatrix} c^1 \\ c^2 \\ \vdots \\ c^{HMS} \end{Bmatrix} \tag{3}$$

where l is length of each anchor leg component, d diameter, and c cost for each solution vector.

Step 3: Generation of a new harmony

Improvisation or generation of a new harmony is performed based on three rules: (i) memory consideration, (ii) pitch adjustment, and (iii) random selection. Detailed process of improvisation is found in Geem (2006).

Step 4: Harmony memory update

If the new cost is better than the worst cost in the HM, the worst harmony vector is replaced by the new harmony vector. For the mooring design optimization problem, the global motion analysis is conducted to judge how the mooring system performs in terms of maximum offset, top tension, and the bottom chain length during steps 3 and 4.

Step 5: Stopping Criterion

A conditional statement is applied to judge whether this harmony search loop needs to repeat or stop.

MOORING COST OPTIMIZATION

In this study, to show the implementation of the harmony search algorithm, following only three design constraints were applied:

1) maximum platform offset;
2) factor of safety (SF) for intact case top tension; and
3) zero degree angle of anchor.

The objective function (i.e. total cost of mooring system) is also simplified as:

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

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

One of the design constraints mentioned above for the intact mooring condition is that some minimum amount of bottom chain (zero degree angle of anchor) remains on the seabed. This will ensure that there is no significant uplift forces on the anchor which is undesirable in the case of drag embedded anchors. An added benefit, especially in conditions with shallow water, is that the anchor leg will maintain its "catenary" character, and snaploads are prevented.

For three design constraints, three different penalty functions can be applied to better lead the search algorithm to find feasible solutions by considering the proportionality of how off the suggested solution vector is from the boundary defined by the design constraints.

CASE STUDY: DEEPWATER FPSO MOORING DESIGN

An FPSO with a permanent turret mooring system in water depth of 1,000m was chosen for this study, and the FPSO vessel particulars are summarized in Table 1.

The global analysis of the FPSO vessel and mooring has been conducted with several software packages and numerical tools. A vessel motion analysis was performed with 3D diffraction analysis, utilizing the Higher Order Boundary Elements Method (HOBEM). The analysis provided the wave frequency vessel response in the form of displacement Response Amplitude Operators (RAOs). For the wind and current loads on the vessel, use was made of our extensive in-house database of wind tunnel test results.

The global analysis has been performed in the frequency domain with the program SPMsim. SPMsim is a comprehensive mooring analysis package that can be used to evaluate the behavior of single point mooring systems. Reported output includes FPSO offsets, anchor leg tensions and amount of chain on bottom.

Each anchor leg is made up of a combination of studless chain and spiral strand wire rope. The upper part of the anchor leg or "top chain" that connects to the vessel consists of studless chain and its purpose it to provide an easy means of adjusting the length of the mooring line during installation to account for the uncertainties such as anchor location and as built component length. The top chain is typically fixed to the vessel using flapper-type chain stoppers.

The intermediate segment of the anchor leg consists of spiral strand wire rope. The choice of wire rope instead of chain is driven by the need for a high strength-to-weight ratio in order to minimize the vertical load on the turret bearings. Spiral strand construction is preferred over six-strand construction where the design life exceeds 10 years. Optionally the wire rope can be sheathed with MPDE to provide design lives of more than 20 years.

Table 1: FPSO Vessel Particulars

PARAMETER	UNITS	BALLAST LOAD	FULL LOAD
Length Overall, LOA	meters	274.0	274.0
Length Between Perpendiculars, LBP	meters	264.0	264.0
Breadth (mld.)	meters	48.0	48.0
Depth (mld)	meters	23.2	23.2
Camber(at Midship)	meters	1.0	1.0
Cb		0.8	0.8
Displacement	m.tons	85184.0	180745.0
Draft @ A.P.	meters	9.0	17.7
Draft (mean)	meters	8.5	17.0
Draft @ F.P.	meters	8.2	16.3
Length of Vessel @ Waterline	meters	259.9	268.9
Beam of Vessel @ Waterline	meters	48.0	48.0
Water Plane Area	meter^2	10472.0	11489.1
LCG from A.P.	meters	141.9	137.6
VCG from KEEL, corrected (KG)	meters	12.6	15.0
VCB (KB)	meters	4.4	8.9
KMT	meters	26.2	20.3
GMT	meters	14.2	6.8
Free-Surface Correction	meters	0.6	1.5
GMT Corrected	meters	13.6	5.3
KML	meters	531.0	332.2
Roll Gyradius (Apprx.)	meters	18.6	13.4
Pitch Gyradius (Apprx.)	meters	61.6	61.5
Yaw Gyradius (Apprx.)	meters	62.9	62.2
Bilge Radius	meters	2.0	2.0
Bilge Keel Width	meters	0.8	0.8
Bilge Keel Length	meters	115.2	115.2
Bilge Keel Start Position from FP	meters	55.6	55.6
Heave Natural Period	seconds	9.5	11.0
Roll Natural Period	seconds	12.0	13.6
Pitch Natural Period	seconds	8.6	9.8

Note:
Vessel particulars include internal turret and topsides weight

The lower segment of the anchor leg or "bottom chain" consists of studless chain and its purpose is to provide the elasto-gravitational restoring force.

The sign conventions utilized for the analysis of motions and loads in earth-fixed and vessel-fixed local coordinate systems are shown in Figure 2.

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. Eight risers and one umbilical were connected to the turret.

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 1708 meters from FPSO center. The ballast load draft (8.55m) was applied. FPSO vessel motion RAOs are presented in Figures 3 through 11.

The mooring system needs to be designed such that the mooring system performance meets the offset requirement for risers in the worst environment and provides the minimum amount of bottom chain with the optimal mooring system cost.

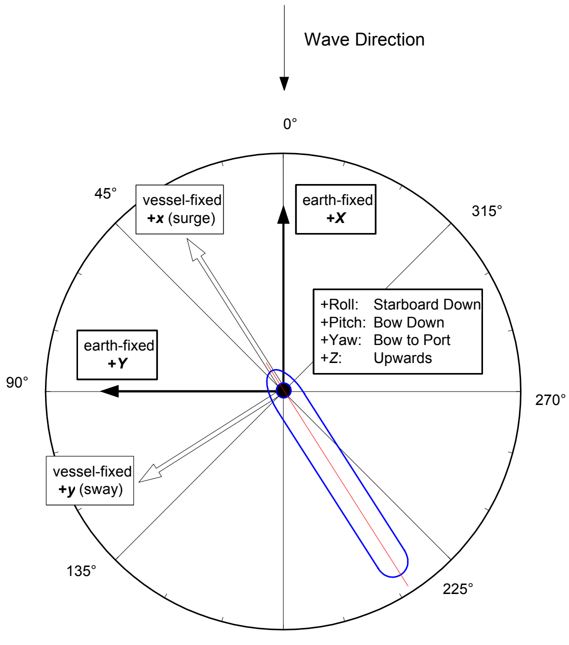

Figure 2. Sign conventions utilized for the analysis of the motions and loads.

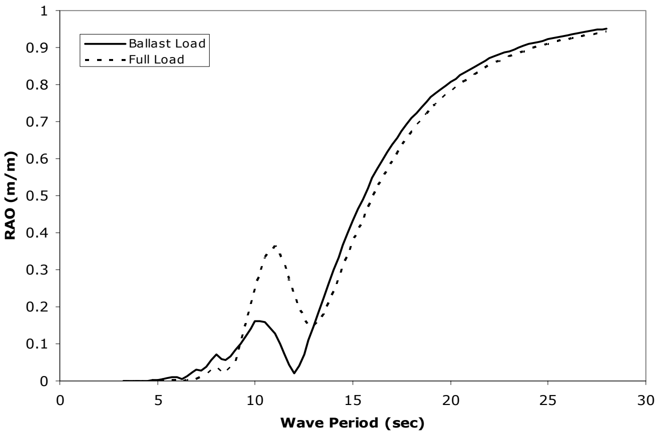

Figure 3. Surge RAO for 180 heading.

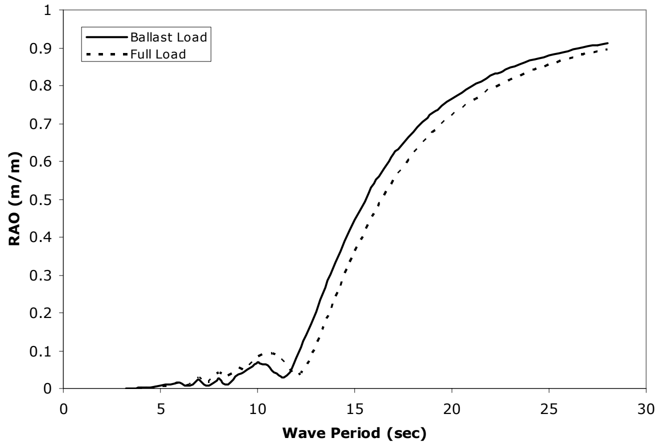

Figure 4. Heave RAO for 180 heading.

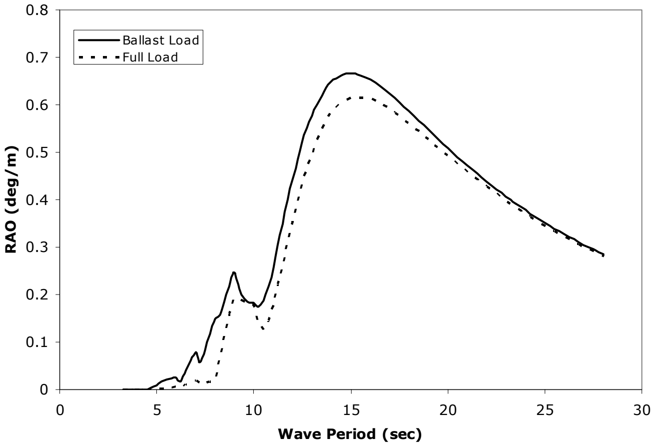

Figure 5. Pitch RAO for 180 heading.

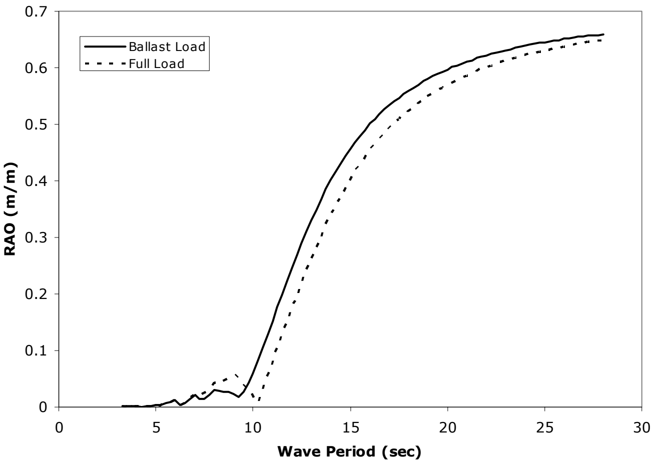

Figure 6. Surge RAO for 225 heading.

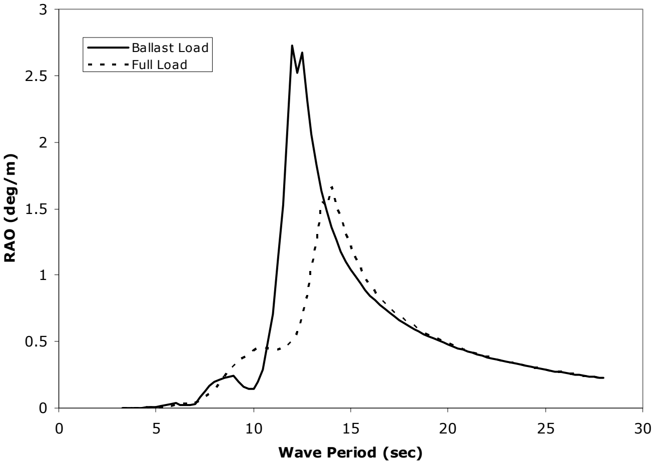

Figure 9. Roll RAO for 225 heading.

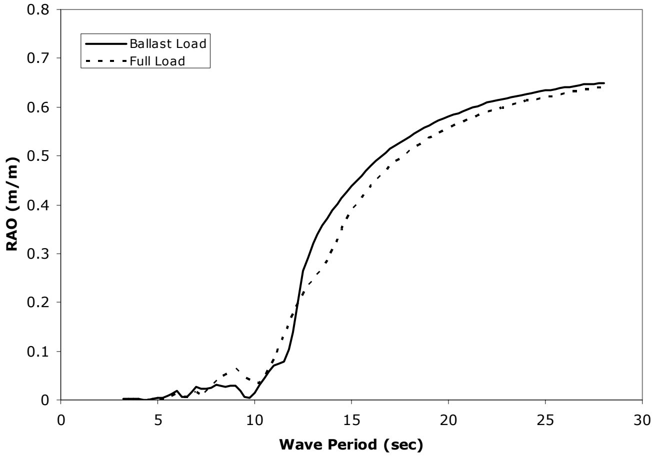

Figure 7. Sway RAO for 225 heading.

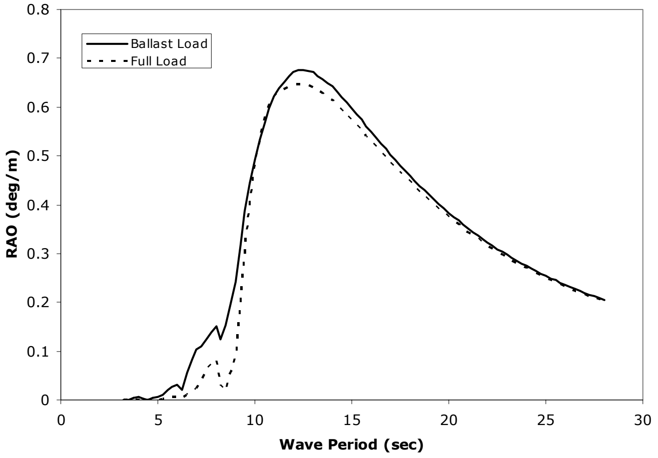

Figure 10. Pitch RAO for 225 heading.

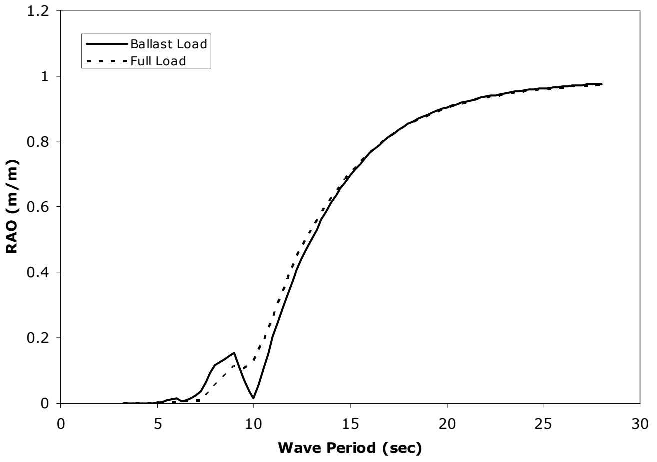

Figure 8. Heave RAO for 225 heading.

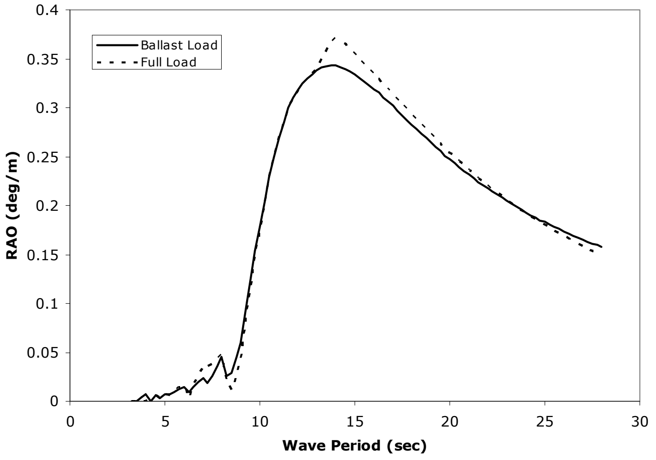

Figure 11. Yaw RAO for 225 heading.

Design Environmental Condition

The design environmental condition is summarized in Table 2. 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.

Table 2: Summary of design environmental condition.

Wind	39 knots	185 deg
Current	2.1 knots	185 deg
Wave	Hs = 10.9m Tp = 13.7s gamma = 2.12	215 deg
Swell	Hs = 1.0m Tp = 13.0s gamma = 2.77	215 deg

Mooring Line Property Estimate

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: $y = A \times d^B$ wherein d is the diameter of the line in millimeters, and A and B are constant. Table 3 provides the coefficients for the various properties of the rope.

Table 3: Coefficients for estimation of wire rope properties.

	Unit	A	B
MBL	MT	0.1025	1.9927
Axial Stiffness	MN	0.1512	1.9010
Wet Weight	kg/m	0.0045	1.9871
Dry Weight	kg/m	0.0065	1.9582

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

$$\begin{aligned} \mathrm{MBL} &= 0.0274 \times \mathrm{d}^2 \times (44 - 0.08 \times \mathrm{d})/9.81 \\ \mathrm{EA} &= (11.86 \times \mathrm{d}^2 - 0.042 \times \mathrm{d}^3) \times 10^4/9810 \\ W &= A \times d^2 \end{aligned} \tag{5}$$

where A for wet weight is 0.0170 and 0.0195 for dry weight.

Cost Estimate Function

The actual cost of a mooring system depends on a variety of factors such as component size, market conditions, shipping distance and method of installation. For deep water the cost of installation can easily approach the cost of the components. In order to reduce the complexity of the cost function, costs of the chain and wire rope components were derived as a function of component volume using average prices encountered on recent projects. The cost estimate of the studless chain and wire is based on the following equations:

$$C_{chain} = 0.06320 \times d^2 \times l \tag{6}$$

$$C_{wire} = 0.03415 \times d^2 \times l \tag{7}$$

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

Harmony Search Computation

A total of 2,000 iterations were performed to find optimal mooring designs, and Figures 12 through 15 show the trend of each mooring component's length and diameter changes. The total mooring cost is presented in Figure 16 as a function of iteration.

The input lower and upper bounds for each design parameter, i.e. lengths and diameters of top chain, wire, and bottom chain are summarized in Table 4.

Table 4: Input lower/upper bounds for each design parameter.

Bound	Length (m)			Diameter (mm)		
	Top Chain	Wire	Bottom Chain	Top Chain	Wire	Bottom Chain
Lower	10	100	100	50	50	50
Upper	200	2000	2000	150	150	150

Figure 12. Maximum top chain length in harmony memory.

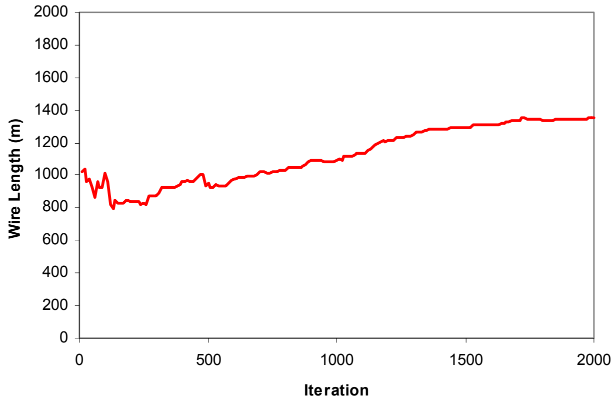

Figure 13. Maximum wire length in harmony memory.

Figure 14. Maximum bottom chain length in harmony memory.

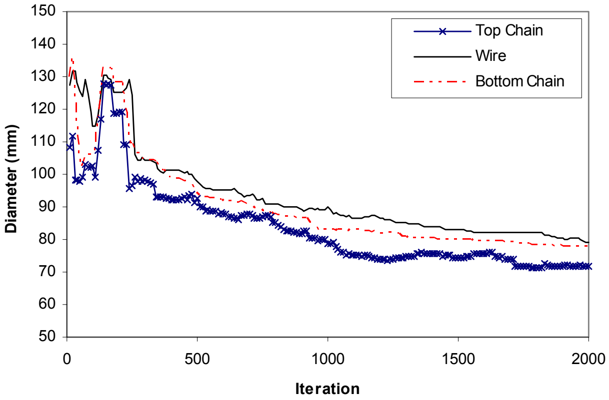

Figure 15. Maximum diameters (top chain, wire, bottom chain) in harmony memory.

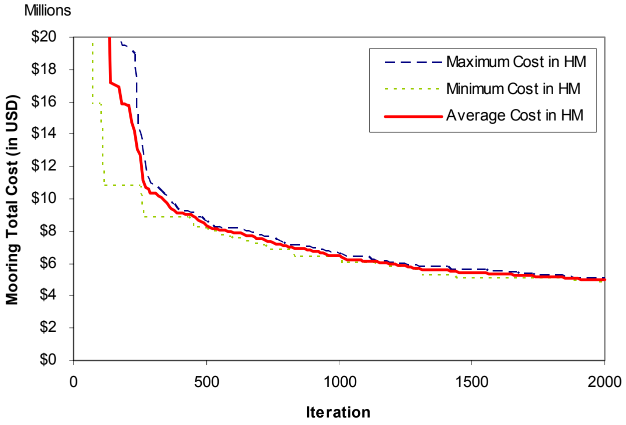

Figure 16. Max, min, and mean costs in harmony memory.

The mooring system cost starts to converge after approximately 50 iterations as shown in Figure 16. Table 5 presents the harmony memory (HMS=10) when 2,000th improvisation was done. Total ten different costs show the similar amount of the total mooring cost.

Table 5: Harmony memory when 1,000th improvisation.

HM	Length (m)			Diameter (mm)			Total Cost
	Top Chain	Wire	Bottom Chain	Top Chain	Wire	Bottom Chain	
1	103.1	1365.0	573.9	72.1	78.5	77.3	$4,841,188
2	118.1	1356.0	584.8	70.7	81.9	76.5	$5,079,789
3	121.7	1368.7	563.8	71.2	80.0	79.7	$5,079,409
4	121.4	1347.4	585.8	73.0	78.4	78.0	$4,937,878
5	110.1	1378.0	551.1	69.6	78.4	80.2	$4,919,718
6	102.2	1372.7	565.9	71.1	77.4	79.7	$4,862,802
7	105.6	1332.8	618.0	74.6	77.8	77.8	$4,940,975
8	107.8	1363.9	571.7	69.9	82.6	74.9	$4,982,931
9	110.7	1347.3	587.3	71.0	80.8	75.0	$4,900,828
10	109.5	1336.2	609.7	73.0	77.8	80.2	$5,048,703

CONCLUDING REMARKS AND FUTURE WORK

A mooring optimization design tool using the harmony search algorithm and a frequency domain global analysis tool was proposed to minimize the cost of the mooring system. This proposed cost-optimal mooring design tool successfully finds feasible mooring systems. A case study on a permanent turret mooring system for an FPSO in deepwater was conducted. The results show that the objective function (i.e. mooring system cost) converges well and harmony search provides several feasible mooring systems.

To find a feasible mooring system, only three design constraints were adopted. However, actual mooring design practices require more complex design constraints, for instance, anchor position, mooring line separation angle, number of mooring lines, and various connecting components. In addition, the cost function can also be complicated.

A constant penalty cost is applied to all infeasible solutions in this study so that they are not included in the HM. However, when the infeasible design solution vector does not satisfy the mooring design constraints, a penalty can be applied to the cost function to enhance the optimum solution search.

In conclusion, a new HS-based mooring optimization tool, has a potential for fast finding the cost-optimal mooring system.

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REFERENCES

Cunha, M.C. and Sousa, J., “Water Distribution Network Design Optimization: Simulated Annealing Approach,” J. Water Resour. Plann. Mgmt, ASCE, 1999, 125(4), 215-221.

Duggal, A.S. and Ryu, S., “The Dynamics of Deepwater Offloading Buoys,” Fluid Structure Interactions and Moving Boundary Problems, WIT Press, 2005, pp. 269-278.

Fylling, I. and Kleiven, G., “Integrated Optimized Design of Riser and Mooring System for Floating Production Vessels,” Proceedings of OMAE 2000 Conference, Ocean Engineering Symposium, New Orleans, USA, February 14-16, 2000.

Fylling, I., “Optimization of Deepwater Mooring Systems,” Proceedings of the Offshore Mediterranean Conference, Ravenna, March 19-21, 1997.

Geem, Z.W. and Tseng, C.-L., “New Methodology, Harmony Search and Its Robustness,” 2002 Genetic and Evolutionary Computation Conference, 2002, pp. 174-178.

Geem, Z.W., “Optimal Cost Design of Water Distribution Networks Using Harmony Search,” Engineering Optimization, Vol. 38, No. 3, April 2006, pp. 259-280.

Geem, Z.W., Kim, J.H. and Loganathan, G.V., “A New Heuristic Optimization Algorithm: Harmony Search,” Simulation, 2001, 76(2), 60-68.

Geem, Z.W., “Improved Harmony Search from Ensemble of Music Players,” Lecture Notes in Artificial Intelligence, Oct. 9, 2006, 4251, 86-93.

Kim, J.H., Geem, Z.W. and Kim, E.S., “Parameter Estimation of the Nonlinear Muskingum Model Using Harmony Search,” J. Am. Water Resour. Ass., 2001, 37(5), 1131-1138.

Lee, K.S. and Geem, Z.W., “A New Structural Optimization Method Based on the Harmony Search Algorithm,” Comput. Struct., 2004, 82(9/10), 781-798.

Lee, K.S. and Geem, Z.W., “A New Structural Optimization Method for Structures with Discrete Sizing Variables,” Proceedings of 2004 Conference of the Structural Engineering Institute, ASCE, 1-11, Nashville, USA, May 22-26 2004.

Lippai, I., Heaney, J.P., and Laguan, M., “Robust Water System Design with Commercial Intelligent Search Optimizers,” J. Comput. Civil Engng, ASCE, 1999, 13(3), 135-143.

Ryu, S., Duggal, A.S., Heyl, C.N., and Liu, Y., “Prediction of Deepwater Oil Offloading Buoy Response and Experimental Validation,” Int. J. of Offshore and Polar Engineering, pp 290-296, Dec. 2006.

Simpson, A.R., Dandy, G.C., and Murphy, L.J., “Generic Algorithms Compared to Other Techniques for Pipe Optimization,” J. Water Resour. Plann. Mgmt, ASCE, 1994, 120(4), 423-443.

Wyllie, M., “Fast Track FPSO’s for Deepwater and Ultra-Deepwater,” Offshore Technology Conference, Houston, Texas, May 3-6, 2004.