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REVIEW ARTICLE

DEEPWATER MOORING SYSTEM EQUIVALENT TRUNCATED INTELLIGENT OPTIMIZATION DESIGN

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ABSTRACT

Offshore oil and gas exploration forward deepwater and ultra-deepwater, due to marine engineering pool limitation, it is very difficult to use conventional reduced scale do full-depth system model test, so hybrid model test techniques are used and equivalent truncation design is required. The truncated mooring system mathematical model is mainly designed based on static characteristics similar criteria, writing the single mooring line nonlinear equations of static equilibrium algorithms, to get single mooring line tension and mooring system restoring force, choosing the objective function appropriately, various parameters of truncated mooring system are designed by using Genetic Algorithm through programming software MATLAB. The results calculated by the developed program are compared with the hydrodynamic calculation software Orca Flex, to check the accuracy. Based on the designed parameters, the truncated mooring line top tension-displacement curve and system restoring force curve are drawn by using the developed program, and compared with the full-depth system. Hydrodynamic calculation software AQWA is applied to calculate the dynamic characteristic difference between the two systems. A turret moored FPSO of 1500m water depth is as an example to make the equivalent truncated optimization design of 700m. The results show that the developed program is feasible.

Key Words: Equivalent truncation, Optimization design, Mooring system, FPSO.

INTRODUCTION

Deep-sea oil and gas exploration forward deepwater and ultra-deep water, many new floating offshore production platforms are developed, such as FPSO (Floating Production Storage and Offloading tankers), Spar (column platforms) and so on, their working depth up to 1000m ~ 3000m and even to deeper. Physical model tests are needed when design and construction of offshore platforms to get the motion response, mooring line forces and some other performance parameters. As the platform working depth deeper and ocean conditions harsh, it is very difficult to conduct model tests in limited marine engineering pool, by 1:50 ~ 1:70 which is recognized as the best model reduced scale (ITTC, 1999).

Hybrid model test method combining numerical model and physical test is by far the most effective method of deep-sea platform model test, and the most feasible and the most widely used is the "passive truncated + simulation " model test method (Luo and Baudic, 2003). Refer to mooring system characteristics and marine engineering test pool scale limitation, according to the equivalent truncated design criteria, equivalent truncated mooring system is designed to consist with the full depth mooring system characteristics.

Mooring system equivalent truncated design criteria (Waals and Van Dijk, 2004) recognized internationally are:

1) To ensure horizontal restoring force characteristics consistently between truncated mooring system and full-depth mooring system;

2) To ensure the quasi-static coupling consistently with the main platform motion response;
3) To ensure the "representative" single mooring line tension properties consistently;
4) To ensure fluid damping force in waves and currents consistently.

To solve the problems, many experts and scholars of ship and marine engineering study in-depth about the equivalent truncated design. Wang (Wang Qiang and Zhang Huoming, 2012) made 700m equivalent truncation mooring system optimization design of a working depth of 1500m single column platform (SPAR), by applying the improved mutative scale chaos algorithm. Although the results are high accuracy, the chaos algorithm control parameter selection is rough, and it has larger workload to determine each parameter the upper and lower limitation by using control variable method. Zhang (Zhang Huoming *et al.,* 2006) selected hybrid discrete variables simulated annealing and discrete complex method to make 160m truncated optimized design for a full depth of 320m FPSO, and conducted the full depth and truncated mooring system model tests. Sun (Sun Yihua, 2009) proposed the concept of level truncation, and truncated a 1500m depth platform through multi-objective optimization method by only changing the mooring line's middle segment .

In fact, the four design criteria may not fully meet in equivalent truncated optimization, mainly consider static characteristic similar criteria (ITTC, 2005), that 1) and 3). 2) and 4) are the system dynamic characteristic similar criteria, and numerical results obtained need take long time to do time domain analysis, so they are not suitable for the truncation optimizing design phase.

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Relying on marine engineering test pool of Harbin Engineering University, whose model test depth is 10m, a turret moored FPSO of 1500m water depth as an example, selecting taut mooring system, model reduced scale as 1:70, 700m equivalent truncated optimal design is made.

Optimization Model

Static Characteristics Calculation

The mooring system total horizontal restoring force characteristic curve and a single mooring line tension-displacement characteristic curve are calculated first before truncated optimized design. When calculating static characteristics for multi-component elastic mooring line, firstly, based on the known vertical distance between seafloor and top mooring point *h* and top pretension of each mooring line, the single mooring line static equilibrium equations are established. Initial horizontal force *H* and initial horizontal span $X_{s,0}$ of each mooring line are gotten.

$$z_{i,2} = \frac{H}{\omega_i} * \left[\sqrt{1+\left(\frac{V_{i,2}}{H}\right)^2} - \sqrt{1+\left(\frac{V_{i,1}}{H}\right)^2}\right] + \frac{H*s_i}{EA_i} * \left[\left(\frac{V_{i,1}}{H}\right) + \frac{\omega_i * s_i}{2H}\right] \quad (i=1,2,\cdots,m) \qquad \text{(1)}$$

$$V_{i,2} = V_{i,1} + \omega_i * L_i \quad (i=1,2,\cdots,m) \qquad \text{(2)}$$

$$V_{1,1} = V_{seabed} \qquad \text{(3)}$$

$$T = \sqrt{V_{m,2}{}^2 + H^2} \qquad \text{(4)}$$

$$\sum_{i=1}^{m} z_{i,2} = h \qquad \text{(5)}$$

$$x_{i,2} = \frac{H}{\omega_i} * \left[\sinh^{-1}\left(\frac{V_{i,2}}{H}\right) - \sinh^{-1}\left(\frac{V_{i,1}}{H}\right)\right] + \frac{H*s_i}{EA_i} \quad (i=1,2,\cdots,m) \qquad \text{(6)}$$

$$X_{s,0} = \sum_{i=1}^{m} x_{i,2} \qquad \text{(7)}$$

Where, $z_{i,2}$, $x_{i,2}$ are respectively vertical distance and horizontal span of i-th mooring line segment; *H* is horizontal force; ω_i, s_i, EA_i are respectively wet weight per unit length, overhang length, axial stiffness of *i*-th segment; $V_{i,2}$, $V_{i,1}$ are respectively top and bottom vertical force of *i*-th segment; *m* is the number of mooring line segments; $V_{1,1}$ is the vertical force at the contact point of the seabed; *T*, $V_{m,2}$ are respectively tension and vertical force at top mooring point; *h* is the vertical distance between seafloor and top mooring point; $X_{s,0}$ is initial horizontal span. Secondly, giving the top mooring point horizontal mobile displacement *dx* in sequence, new horizontal span $X_{s,j}$ corresponding to each mooring line is respectively calculated.

$$X_{s,j} = \sqrt{X_{s,0}{}^2 + dx^2 - 2 * X_{s,0} * dx * \cos\theta} \quad (j=1,2,\cdots n) \qquad \text{(8)}$$

Where, θ is azimuth angle of mooring line; *n* is number of discrete points.

Thirdly, based on vertical distance between seafloor and top mooring point and each step new horizontal span, the single mooring line static equilibrium equations are established. Through cycle solving, horizontal force *H* and top tension *T* are obtained at each *dx*.

$$X_{s,j} = \sum_{i=1}^{m} x_{i,2} \quad (j=1,2,\cdots n) \qquad \text{(9)}$$

Lastly, each mooring line horizontal force *H* at each *dx* projected to the system positive *x*-axis, added to get system horizontal restoring force at each *dx* in sequence, and the mooring system total horizontal restoring force characteristic curve and a single mooring line tension-displacement characteristic curve are obtained.

Optimization Algorithms

Based on genetic algorithm to solve optimization problem, simulating survival of the fittest mechanism of natural selection and genetic crossover and mutation genetics phenomenon, a global adaptive probabilistic search algorithm is developed. It has the parallelism and high search efficiency, assesses the merits of individual solutions only depending on the objective function value (Deb *et al.,* 2002) coding control variables as its operand, fully searches based on the change principles of probability in the solution area, and can avoid the search trapping in local optima. The calculation process is coding the chromosome, generating the initial population, calculating the fitness value, if not satisfying the termination condition, making selection, crossover and mutation, until satisfying the termination condition, termination and output the results.

Design Optimization

Generally, the truncated mooring system should be highly similar to the full depth system (Ormberg *et al.,* 1999) , the pre-tension of each mooring line is unchanged, mooring lines' number, type, material segments and arrangement are same as much as possible. In some cases, based on the above criteria, it is difficult to optimize the truncated mooring system static characteristics highly similar to the full depth system and it may be adjusted by increasing or decreasing the buoy and the weight appropriately.

Objective Function

Optimization objective is possibly to make the static characteristics difference between the designed truncated mooring system and the whole system minimum. The difference (Wang Qing-qing, 2011) can be represented by calculating the mean square root of sum of square of ordinate value difference between the two curves at the same horizontal axis value, as Fig.1 shown.

Numerically expressed through the following expression:

$$f(X) = \sqrt{\sum_{j=1}^{n}\left(\frac{Y_{(Trun)j} - Y_{(Full)j}}{Y_{(Full)j}}\right)^2 / n} \qquad \text{(10)}$$

Where, subscript *j* is the *j*-th discrete ordinates; *n* is the total number of discrete points; $Y_{(Trun)j}$, $Y_{(Full)j}$ are respectively the coordinates of truncated and full depth mooring system static characteristic curve at the *j*-th discrete ordinate value.

This equation can visually display the approximate degree of the two curves and avoid the impact of selecting the number of discrete points differently.

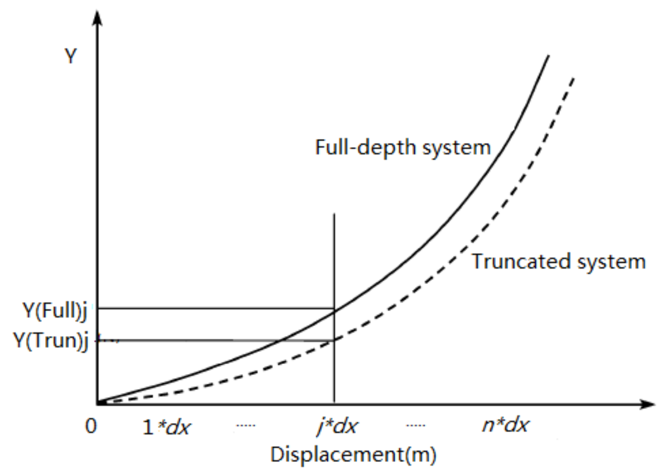

Fig. 1. Static characteristic curves comparison

Design Variables

The main design variables include mooring lines' each segment's wet weight per unit length, overhang length, axial stiffness, buoys / weights location and wet weight (if any), etc. Because of the different optimized number of segments and buoys/weights, the number of optimization variables is different. When only the middle wire is truncated, the variables are $\{w_{2t}, L_{2t}, EA_{2t}\}$. While bottom chain, middle wire and top chain all are truncated, the variables are $\{w_{1t}, L_{1t}, EA_{1t}, w_{2t}, L_{2t}, EA_{2t}, w_{3t}, L_{3t}, EA_{3t}\}$. Where, w_{1t}, L_{1t}, EA_{1t} are respectively wet weight per unit length, overhang length and axial stiffness of the bottom chain, the rest analogy.

Constraints

The truncated design optimization design variables have upper and lower limit, which can be determined based on actual engineering experience. Designed truncated mooring system as reduced model scale 1:70 must not exceed the maximum capacity of ocean engineering pool (available area is 50m*30m*10m) of Harbin Engineering University.

Therefore, the constraints of the optimization problem can be expressed as:

$$\begin{cases} X_i^l \le X_i \le X_i^u & (i = 1,2,\cdots N) \\ X_{s,k} < 1050 & (k = 1,2,\cdots M) \end{cases} \quad \cdots\cdots\cdots\cdots (11)$$

Where, X_i is variables; X_i^l, X_i^u are respectively the lower and upper limitation; N, M are respectively the number of variables and mooring lines; $X_{s,k}$ is horizontal span of k-th mooring line.

An Optimization Design Example

With a working depth of 1500m turret moored FPSO for example, its main scale parameters in Table 1.

Table 1. FPSO Main scale parameters

Description	Quantities
Length(m)	320
Breadth(m)	62.8
Depth(m)	33.2
Designed draft(m)	10.0
Displacement(t)	474400
Vertical height of gravity center(m)	22.7

The total height of the full depth mooring system is 1490m, with 4*3 distributed mooring arrangements, shown in Fig.2.

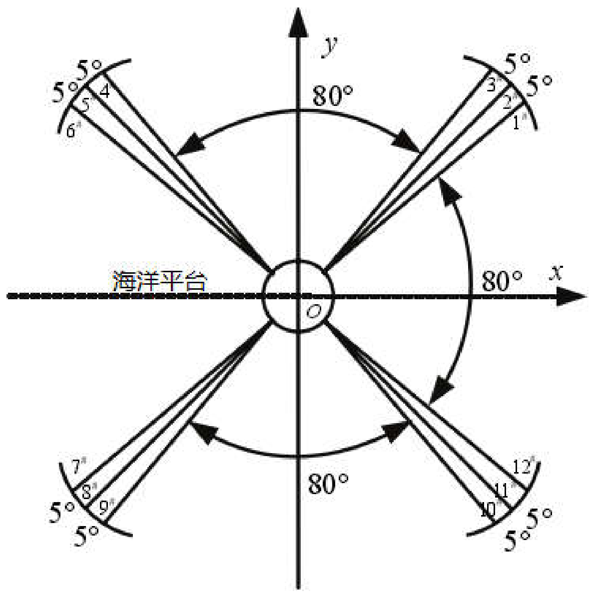

Fig. 2. Mooring system distribution

Each mooring line adopts chain-wire-chain structure model, with taut mooring mode, main parameters of mooring line in Table 2. The pretension of each mooring line is 2000kN.

Table 2. Main parameters of mooring lines

Description	Bottom chain	Wire	Top chain
wet weight per unit length ($N*m^{-1}$)	1544.81	378.8	1544.81
axial stiffness (MN)	666.17	784.64	666.17
length (m)	76.2	2500	76.2
Breaking strength (kN)	6971	7465	6971

The Developed Program Check

A single mooring line tension - displacement characteristic curve and system total horizontal restoring force characteristic curve and are calculated in every step of the truncated optimized iterative process. So computer programs are developed by using programming software MATLAB. To check the accuracy of written programs, taking the horizontal movement displacement range as 80m, compare the calculation results by written programs with by hydrodynamic software Orca Flex, shown in Fig.3. Fig.3 shows the developed program is correct and can be used in equivalent truncation optimization process.

700m Equivalent Truncation Optimization Design

Due to the lack of practical engineering experience, the variables are firstly selected a larger value range, shown in

Table 3. During trial, the optimization results do not meet the requirements at some case and the range of design variables need to be adjusted appropriately.

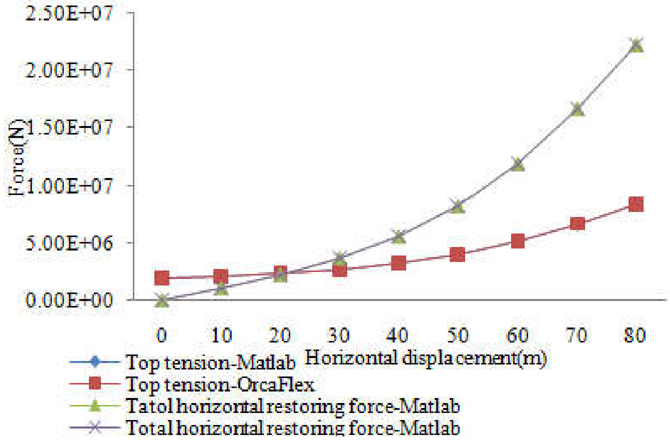

Fig. 3. Static characteristics check

Table 3. Upper and lower limit of design variables

Description	Lower limit	Upper limit
w_{1t}, w_{3t}($N*m^{-1}$)	1500	5000
w_{2t}($N*m^{-1}$)	500	2000
EA_{1t}, EA_{2t}, EA_{3t}(N)	1e5	5e8
L_{1t}, L_{3t}(m)	30	100
L_{2t}(m)	800	1400

Equivalent truncation optimization designs are made both only the wire truncated and three segments all truncated.

The 6th mooring line is selected to make truncation optimization design based on top tension consistency. The optimization results are shown in Table 4 and the top tension results are compared in Fig.4. The two Matlab optimization iteration convergence processes are respectively shown in Fig.5 and Fig.6.

Fig.4 shows that the differences of the 6th mooring line top tension values are very small between the truncation system and full depth system. Fig.5 shows the difference is 0.92% when only wire is truncated. The difference is 1.86% when all segments are truncated, as shown in Fig.6. So the truncation optimization design results based on top tension consistency are very desirable.

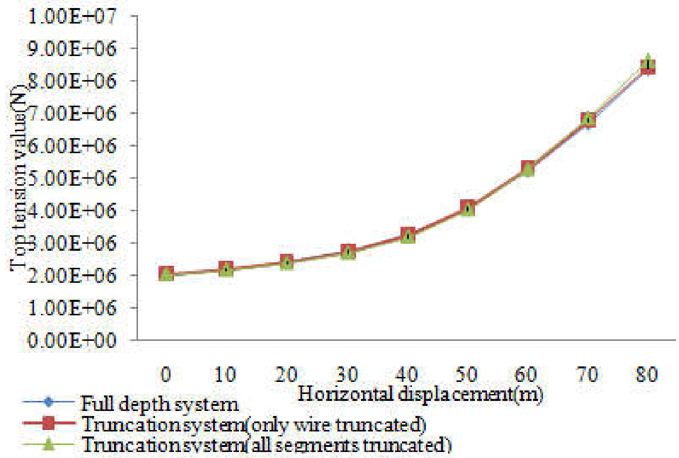

Fig. 4. Top tension results comparison

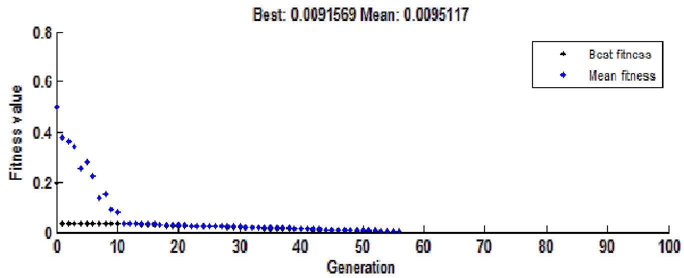

Fig. 5. Optimization iteration convergence process (only wire truncated)

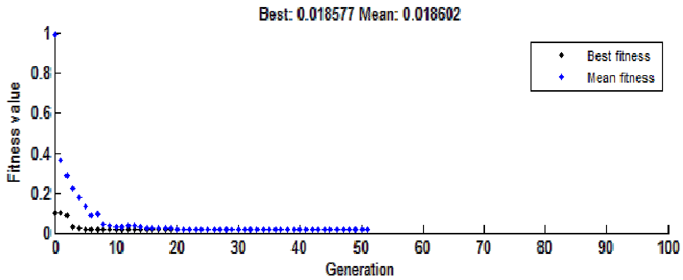

Fig. 6. Optimization iteration convergence process (all segments truncated)

The truncation optimization results based on system total horizontal restoring force consistency are shown in Table 5 and the system total horizontal restoring force results are compared in Fig.7.

Table 4. optimization results based on top tension consistency

Different segments truncated	Description	Bottom chain	Wire	Top chain
only wire	wet weight per unit length ($N*m^{-1}$)	1544.81	1414.43	1544.81
	axial stiffness (MN)	666.17	282.52	666.17
	Length (m)	76.2	878.48	76.2
all segments	wet weight per unit length ($N*m^{-1}$)	2187.83	1386.68	2187.83
	axial stiffness (MN)	234.70	354.68	234.70
	Length (m)	65.46	902.76	65.46

Table 5. optimization results based on total horizontal restoring force consistency

Different segments truncated	Description	Bottom chain	Wire	Top chain
only wire	wet weight per unit length ($N*m^{-1}$)	1544.81	1299.80	1544.81
	axial stiffness (MN)	666.17	163.83	666.17
	Length (m)	76.2	875.27	76.2
all segments	wet weight per unit length ($N*m^{-1}$)	1618.37	1314.33	1618.37
	axial stiffness (MN)	117.25	282.90	117.25
	Length (m)	40.24	982.53	40.24

The two Matlab optimization iteration convergence processes are respectively shown in Fig.8 and Fig.9. Fig.7 shows that the differences of total horizontal restoring force values are very small between the truncation system and full depth system. Because 1st and 12th mooring line of truncated mooring system have touchdown displacement when the horizontal displacement is greater than 70m, so larger errors are appeared. Fig.8 shows the difference is 4.08% when only wire is truncated. The difference is 3.06% when all segments are truncated, as shown in Fig.9. So the truncation optimization design results based on total horizontal restoring force consistency are desirable.

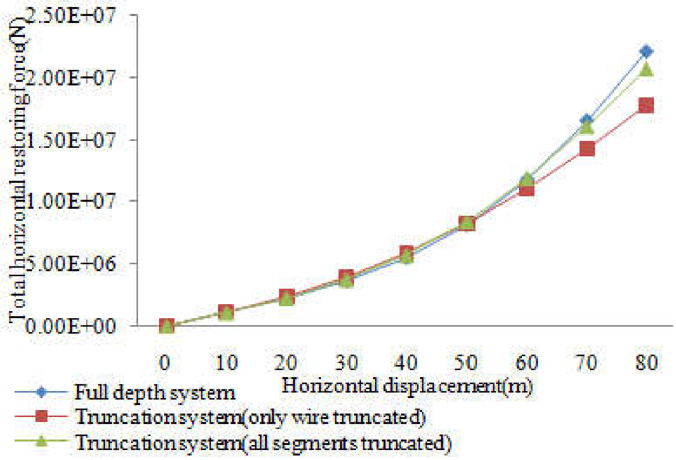

Fig. 7. Total horizontal restoring force results comparison

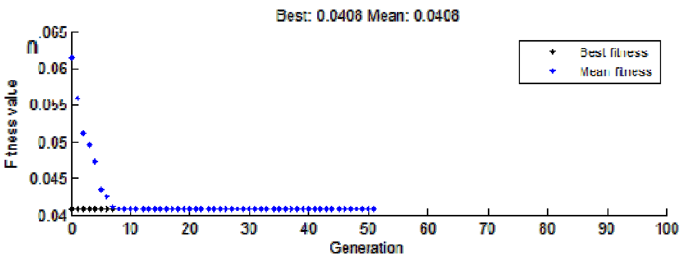

Fig. 8. Optimization iteration convergence process (only wire truncated)

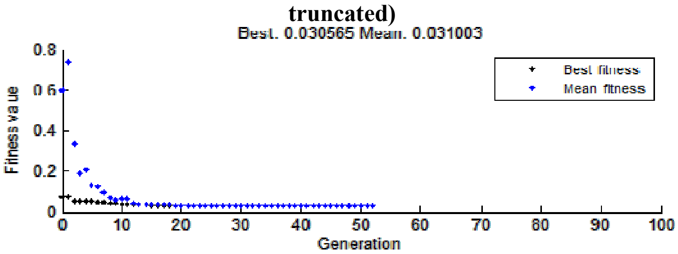

Fig. 9. Optimization iteration convergence process (all segments truncated)

Comparison of dynamic characteristics

Dynamic characteristics of the full-depth system and truncation system are calculated with hydrodynamic calculation software AQWA. Wave parameters are in Table 6.

Table 6. WAVE parameters

Wave height(m)	Period(s)	Direction
1.0	6.0	0

Time domain response curves of 6-th mooring line top tension are shown in Fig.10.

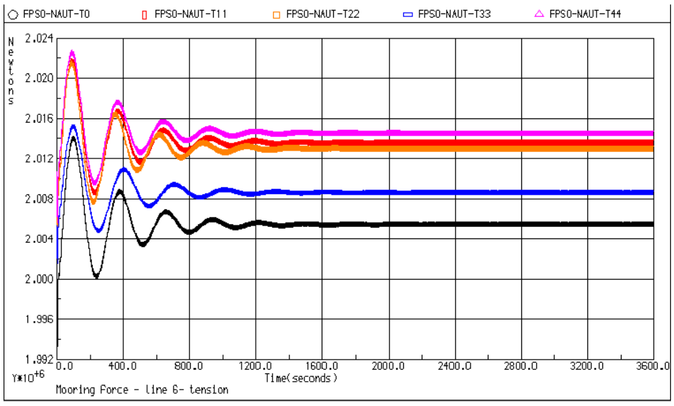

Fig. 10. Time domain response curves of 6-th mooring line top tension

In Fig.10, FPSO-TAUT-T0 is the full-depth system; the rest are truncation systems respectively based on the above four optimization results. Fig.10 shows mooring line top tension time domain response of truncation systems are in good agreement with the full-depth system. The biggest difference is less than 5%, so the optimization results are reasonable.

Conclusions

Because of the scale limitation of marine engineering test pool, when using the hybrid model testing technology for deepwater model test, equivalent truncated optimization design is acquired. Based on static characteristics similar criteria, choosing the objective function appropriately, the program is developed by using Genetic Algorithm with programming software MATLAB. A FPSO is as an example to make truncation design, the static characteristic results and dynamic results all show the optimization results are ideal. So the developed program is reliable. The program should be further optimized to improve operational efficiency and taking into account of more similar criteria to make truncation design.

REFERENCES

Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T. 2002. "A fast and elitist multiobjective genetic algorithm: NSGA-II," IEEE Transactions on Evolutionary Computation, 6 (2):182-197.

ITTC, 1999. "Report from the specialist committee on deep water mooring," Proc of 22nd ITTC. Seoul, Korea & Shanghai, China: ITTC, 377-398.

ITTC, 2005. "Testing and extrapolation methods loads and responses, ocean engineering, truncation of test models and integration with numerical simulations," Proc of 24th ITTC. Edinburgh, Scotland: *ITTC,* 1-5.

Luo, Y. and Baudic, S. 2003. "Predicting FPSO responses using model tests and numerical analysis," Proc of the 13th International Offshore and Polar Engineering Conf. Honolulu, Hawaii, USA: ISOPE, 167-174.

Ormberg, H., Stansberg, C. T. and Yttervik, R. 1999. "Integrated vessel motion and mooring analysis applied in hybrid model testing," Proc of the 9th International Offshore and Polar Engineering Conf. Brest, France: ISOPE, 339-346.

Sun Yihua, 2009. "Truncation of mooring system model of deepwater platform and experimental research," Shanghai: Shanghai Jiaotong University, 1-54.

Waals, O. and Van Dijk, R. R. T. 2004. "Truncation methods for deep water mooring systems for a catenary moored FPSO and a Semi taut moored semi submersible," DOT Conference, New Orleans, 2004.

Wang Qiang and Zhang Huoming, 2012. "Optimization design of equivalent water depth truncated mooring system based on chaos algorithm," Ship Engineering, 34(3):80-83.

Wang Qing-qing, 2011. "Experimental study on the hybrid model deepwater mooring semi-submersible platform," Shanghai: Shanghai Jiaotong University, 14-24.

Zhang Huoming, Yang Jianmin and Xiao Longfei, 2006. "Investigation on the usability of the model test based on equivalent water-depth truncation," *Journal of Shanghai Jiaotong University,* 40(6): 1059-1063.

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