J. Marine Sci. Appl. (2012) 11: 208-215
DOI: 10.1007/s11804-012-1124-3

Investigation on Optimization Design of an Equivalent Water Depth Truncated Mooring System Based on INSGA-II

Huoming Zhang*, Wenjun Gao, Qiang Wang, Juan Jiang and Zhou Zhao

College of Metrology Technology and Engineering, China Jiliang University, Hangzhou 310018, China

Abstract: At present, equivalent water depth truncated mooring system optimization design is regarded as the priority of hybrid model testing for deep sea platforms, and will replace the full depth system test in the future. Compared with the full depth system, the working depth and span are smaller in the truncated one, and the other characteristics maintain more consistency as well. In this paper, an inner turret moored floating production storage & offloading system (FPSO) which works at a water depth of 320m, was selected to be a research example while the truncated water depth was 80m. Furthermore, an improved non-dominated sorting genetic algorithm (INSGA-II) was selected to optimally calculate the equivalent water depth truncated system, considering the stress condition of the total mooring system in both the horizontal and vertical directions, as well as the static characteristic similarity of the representative single mooring line. The results of numerical calculations indicate that the mathematical model is feasible, and the optimization method is fast and effective.
Keywords: deep sea platforms; hybrid model test; equivalent water depth truncated mooring system; optimization design
Article ID: 1671-9433(2012)02-0208-08

1 Introduction

With the development of the offshore oil and gas resources moving gradually to deep water areas, many new types of platforms fit for deep-sea exploitation have emerged (Buchner *et al.*, 1999; Sheng and Xiao, 2003). Deep sea platforms will strongly vibrate with the effect of the waves, wind power, stream, ice load, and various loads of machinery and equipment on the platform. In order to avoid tipping, a good offshore mooring system is very important.

Generally, a physical model test and numerical calculation are used in the research of water depth mooring systems. However, when using the method of numerical calculation to do research, there is a great amount of hypothetical data, which may lead to an unreliable result, while the physical model method does not have this defect. Therefore, is the latter is widely used in ocean engineering circles (Zhang *et al*,. 2007a). Additionally, the deep sea platform and mooring system are large in size, and the scale model with a typical ratio from 1:50 to 1:70 is still beyond the limit of the currently used test pools. Thus, the hybrid model testing method (Stansberg *et al*., 2000; Zhang *et al*., 2004; Baarholm and Palazzo, 2004), combining the physical model test and numerical calculation, is considered as the most feasible and promising method in deep sea platform model tests.

In the hybrid model testing, the primary task is to design the equivalent water depth truncated system according to the characteristics of a full depth system, and to allow it to replace the test in the existing pool scales. Compared with the full depth system, the working depth and span are smaller in the truncated one, and the other characteristics are maintained as consistently as possible (Su *et al*., 2007). The question, then, is how to design the truncated depth system to match the consistency of characteristics. The problem is related to the optimization algorithm. It is known that the problem of the optimization design of an equivalent water depth truncated mooring system is a multi-objective optimization problem, so the analysis method must be based on a multi-objective optimization algorithm (Su *et al.*, 2008). In this paper, the INSGA is selected.

The non-dominated sorting genetic algorithm (NSGA) was first put forward by Srinivas and Kalyanmoy in 1994, who first put the non-dominated sorting conceptions into the field of multi-objective optimization, achieving good results. However, the NSGA itself has many deficiencies, stated as following: (1) High in computational complexity. (2) Lack of elite strategy. (3) The sharing radius must be specified. This leads to an unsatisfactory result when the problem is high dimensional or multimodal. Therefore, Kalyanmoy *et al.* (2000) gave the method of NSGA-II, which is an improved NSGA, to solve the above problems.

However, there are still some shortcomings in NSGA-II. In this paper, the high level strategy is improved based on the NSGA-II according to reference (Zhang *et al*., 2010). Also, a crossover operator of binary simulation and mutation

Received date: 2012-02-23.
Foundation item: Supported by the National Natural Science Foundation of China (Grant No. 10602055) and Natural Science Foundation of Zhejiang Province (Grant No. Y6110243).
***Corresponding author Email:** zhm102018@163.com

operator of non-uniform distribution are used to make the algorithm more stable and better maintain the population diversity.

2 Improved non-dominated sorting genetic algorithm-II (INSGA-II)

The elitist strategy of the NSGA-II is described as following; parents are combined with children and the best individuals selected to maintain the population excellence from a population of size 2 N. Thus, it easily falls into the local optimal solution. Accordingly, to avoid early convergence, an improved elitist strategy is proposed.

First, the first level of the non-dominated individuals is obtained though fast non-dominated sorting to the population of 2 N, which is called the Pareto solution. Then not all of the Pareto solutions are filled into the next generation but some individuals are properly "abandoned". Repeat the process above each level, and there will be a majority of elite individuals which remain in the population while a few are "abandoned" after multistage sorting. It will not only ensure that the most elite individuals remain in the population of the next generation, but also keep all elites from participating in one generation to the next, thereby preventing the population from early convergence or falling into a local optimal solution.

In addition, a simulated binary crossover and non-uniform mutation operator based on experiments is used to redesign the genetic operators to make the algorithm more stable.

2.1 Choice of crossover operator

At present, the arithmetic crossover is most common in the real coded multiobjective evolutionary algorithm (Zhang *et al.*, 2010).

In the multiobjective optimization algorithm with real number coding, the most common is the crossover operator (Zhang *et al.*, 2010). In this paper, a simulated binary crossover (SBX) is selected, which is defined as getting two children individuals x_1 and x_2 on the two parent individuals c_1 and c_2 according to the Equations below:

$$\begin{cases} c_{1,i} = \left[(1+\beta)x_{1,i} + (1-\beta)x_{2,i}\right]/2 \\ c_{2,i} = \left[(1-\beta)x_{1,i} + (1+\beta)x_{2,i}\right]/2 \end{cases}, 1 \le i \le n \quad (1)$$

where β is a random variable, which needs to be generated in each dimension as follows:

$$\beta = \begin{cases} (2\mu)^{\frac{1}{\eta+1}}, \mu \le 0.5 \\ (2(1-\mu))^{\frac{1}{\eta+1}}, \mu > 0.5 \end{cases} \quad (2)$$

where μ represents a random number uniformly distributed in the interval (0,1), and η represents a crossover parameter, which is a constant.

2.2 Choice of variation operator

Uniform variation operation means selecting uniformly distributed random numbers in a certain range to replace the original gene, which can make individuals move freely in the search space, but is not easy for a local search in the key region.

Non-uniform variation means taking the result of random gene perturbation of the original gene values as the new genetic value. Mutation operates on every gene with the same probability, and it seems like a minor change to the vector solution in the entire solution space. Meanwhile, search processes of the optimal solution will be more concentrated in a certain key area most promising with the operation of a genetic algorithm (Srinivas and Kalyanmoy, 1994).

Non-uniform mutating from $X = x_1 x_2 \cdots x_k \cdots x_l$ to $X' = x_1 x_2 \cdots x'_k \cdots x_l$, if the genetic variation range of point x_k is $[U_{\min}^k, U_{\max}^k]$, the new value x'_k gene is determined as follows:

$$x'_k = \begin{cases} x_k + \Delta\left(t, U_{\max}^k - v_k\right), & \text{if random}(0,1) = 0 \\ x_k - \Delta\left(t, v_k - U_{\min}^k\right), & \text{if random}(0,1) = 1 \end{cases} \quad (3)$$

where $\Delta(t, y)$ is a random number non uniformly distributed in the range $[0, y]$, ($U_{\max}^k - v_k$ or $v_k - U_{\min}^k$). And with the increasing of t,

$$\Delta(t, y) = y\left(1 - r^{(1-t/T)b}\right) \quad (4)$$

where r is a random number uniformly distributed in the range $[0,1]$; T the maximum evolutionary generation; b a fixed parameter, which determines the dependence degree of evolutionary generation in the effect of random disturbance.

The main loop of INSGA-II is shown as follows:
1) Initialize the population with the size of *N*.

2) The population is sorted based on the non-domination. Selection, crossover, and mutation operators are used to create a children population. Then parent and children population are combined.

3) Fast non-dominated sorting to the result of 2), and calculate the crowding density.

4) The process of selecting the new parent population: The new parent population is formed by adding solutions from the first front till the size exceeds *N*. First of all, individuals after the abandonment of a body in the first non-dominated front F_1 are selected as the part of new parent population. Then the subsequent fronts are selected. If the size of the new parent population exceeds *N* after selecting to all of F_i, the individuals with the greater crowding density are

selected as a priority till the size of the parent population reaches *N*.

5) The new parent population includes the executed selection, crossover, and mutation operations to obtain the new children population. Upon meeting the stopping criterion, terminate the algorithm, or go to 6).

6) If the parent and children population are combined, go to 3).

3 Mathematical model of the equivalent water depth truncated system

When designing the truncated system, an overall rule is that the following two aspects should be guaranteed (Zhang *et al,*. 2009a; Zhang *et al,*. 2009b; Yang *et al.*, 2008). (i) One should strive to obtain the same motion responses of the floater as would result from the full-depth mooring. (ii) The truncated mooring system should preferably have a similarity to the physical properties of the full-depth system. In practice, the design of the test set-up may follow the following rules, given in succession of recommended priority:

(a) Model the correct total, horizontal restoring force characteristic; (b) Model the correct total, vertical restoring force characteristic; (c) Model the correct quasi-static coupling between vessel responses (such as, between surge and pitch for a moored semi-submersible); (d) Model a "representative" level of mooring and riser system damping, and current force; (e) Model "representative" single line tension characteristics (at least quasi-static).

To the extent that these requirements may not be fully obtained, the philosophy of the procedure is that the numerical simulations will take care of the effect of the deviations between the full-depth and the truncated system. In this paper, the above listed (a), (b), and (e) are mainly considered during the designing of the truncated system while (c) and (d) belong to the system of dynamic characteristics which are very difficult to quantify and their numerical value needs to be obtained through time consuming simulation in the time domain. It is obvious that (c) and (d) are not suitable for the optimal stage for times of iteration. But it cannot be controlled by selecting a proper design rule, such as keeping the number of the mooring lines and the anchor angle unchanged.

In this paper, the static characteristics of a mooring system are mainly considered. Therefore, the static characteristics between the truncated and the full depth mooring systems need to be calculated separately.

3.1 Computation of mooring system static characteristics

In this optimization design, static characteristics of the mooring line should be calculated, including the tension-displacement characteristics of a single mooring line which is the most important (Miao, 1996; Pan, *et al.*, 1997), and the horizontal and vertical restoring force displacement characteristics of the total mooring system, which can be computed according to the static characteristics of a single mooring line.

3.1.1 Static characteristics of composite single mooring line

Because different parts of the composite mooring line are made of different materials, so the density of the line is different in each part. Also, the weights in water may be positive, negative, or zero. The elastic stretching of each segment must be considered in the calculation, which could be linear or nonlinear. Nonlinear elastic stretching is too complex to calculate, so only the linear elastic stretching is considered here, as shown in Fig.1.

1) Static characteristics of each composite mooring line section**.**The Elastic tensile cable segmental catenary equation can be obtained form correcting of an inelastic tensile cable, and the inelastic tensile cable segmental catenary equation is:

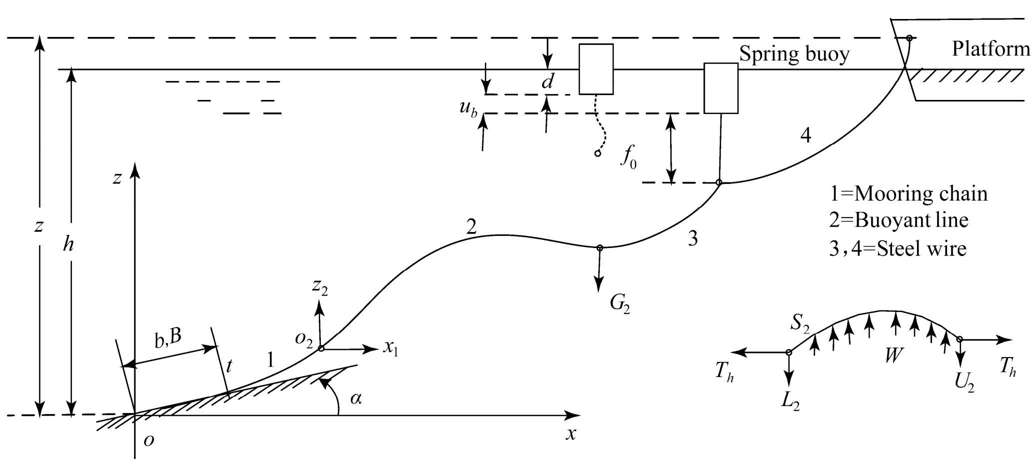


Fig.1 Mooring system and coordinate system

$$x_i = \frac{T_h}{w_i}\ln\left[\left(U_i+\sqrt{U_i^2+T_h^2}\right)/\left(L_i+\sqrt{L_i^2+T_h^2}\right)\right]$$
$$z_i = \frac{1}{w_i}\left[\sqrt{U_i^2+T_h^2}-\sqrt{L_i^2+T_h^2}\right] \tag{5}$$

where x_i is the horizontal span of section i; z_i the vertical span of section i; T_h the horizontal tension; w_i the weight of cable section i before stretching; L_i the vertical tension section near anchor; U_i the vertical tension near the buoy.

The bottom point of the cable is noted as t and it does not necessarily overlap with any end segment, b represents the unstretched length of the upper seabed cable, $b=\sum_{i=1}^{t} b_i=\sum_{i=1}^{t} S_i$, S_i represents the unstretched length of each segment.

The vertical force of end section i was revised by adding the weight of the cable which began from i to the upper:

$$\begin{cases} L_i = \sum_{j=t}^{i-1}(S_j w_j + G_j) + R \\ U_i = L_i + G_i + S_i w_i = \sum_{j=t}^{i}(S_j w_j + G_j) + R \end{cases} \tag{6}$$

where $1 \le i \le N$, G_j is the weight of the clump which hangs on the top of this section in water; R the vertical reaction force of the fixed mooring point. If the line is loose, there is some certain length of b lying on the seabed, then $R=T_h \tan\alpha$, α represents the tilt angle of the seabed. If the seabed is horizontal, then R=0.

The catenary equation of elastic stretching section i is:

$$\begin{cases} C_i = 1 + \dfrac{U_i\sqrt{T_h^2+U_i^2} - L_i\sqrt{T_h^2+L_i^2} + T_h^2 \ln \dfrac{U_i\sqrt{T_h^2+U_i^2}}{L_i\sqrt{T_h^2+L_i^2}}}{2A_iE_iw_is} \\ X_i = C_i x_i \\ Z_i = C_i z_i \end{cases} \tag{7}$$

where C_i is stretching coefficient; A_i the cross-sectional area of mooring line sections; E_i the elastic modulus of mooring line sections.

Assuming that there is a buoy on the surface of the water, and it connects to the top of the No. K section of cable, ($1<K<N$). $Z(d_b)$ represents the buoy's function relationship of buoyancy increasing and draft increasing, and it is known. Then according to the location of the buoy, formula (6) needs to be amended as follows.

$$\begin{cases} L_i = \sum_{j=t}^{i-1}(s_j w_j + G_j) + R \\ U_i = L_i + G_i + s_i w_i = \sum_{j=t}^{i}(s_j w_j + G_j) + R \end{cases} \quad 1 < i \le K \tag{8}$$

$$\begin{cases} L_i = \sum_{j=t}^{i-1}(s_j w_j + G_j) + R - Z(d_b) \\ U_i = L_i + G_i + s_i w_i = \sum_{j=t}^{i}(s_j w_j + G_j) + R - Z(d_b) \end{cases} \quad K < i \le N \tag{9}$$

Therefore, $d_b = h_1 - B\sin\alpha - \sum_{i=t}^{K} Z_i - d - f_0$ represents the draft increasing of the buoy on the surface water, where d is the draft increasing of the buoy when free-floating on the surface water; f_0>0 the vertical distance between bottom of the buoy and top segment of the No. K cable.

The span of a single composite mooring line is:

$$X = B\cos\alpha + \sum_{i=t}^{N} X_i$$
$$Z = B\sin\alpha + \sum_{i=t}^{N} Z_i \tag{10}$$

2) Computation of static characteristics of a single composite mooring line by iterative solution.

First, the evaluation function of the horizontal mooring line system when it balances should be given, which is $f(T_h) = Z_1 - B\sin\alpha - \sum_{i=t}^{N} Z_i \to 0$. Where, Z_1 is the vertical span of the line, which is known. Given the initial value of the three variables b, T_h, R, where b should be large enough. The vertical span of the total line is obtained by the equation Eq.(7)–Eq.(10). Then the value of T_h changes until the evaluation function conforms to the requirements.

In addition, it should be noted that this balance is to a specific b value, that is to say, the calculated T_h may be not equal to the given T_h so the value of b must be reduced gradually, until the calculated T_h equals the given T_h in the range of error.

3.1.2 Static characteristics of the total mooring system

The computation process is as follows. Individually give the horizontal moving distance of the upper mooring point dx, generally choose the initial static balanced position as the 0 point of the system. And, the offset distance can be taken as order −2m, −4m, −6m, −8m, ..., −50m, assuming that the range of the vertical surge offset is −50 ~ 0 m. Calculating the new horizontal span of each mooring line corresponding to each dx, and with these horizontal span, it is easy to obtain the tension of the upper endpoint, in the horizontal and vertical directions of each mooring line in the corresponding array (Zhang *et al*,. 2007b). And then, as shown in Fig.2, the horizontal tension of each mooring line is projected in the positive direction of the X axis, and then added together to get the total horizontal restoring force of the X direction of the mooring system after moving the upper mooring point. Add the vertical tension of each mooring line to get the corresponding total vertical restoring force of the Z direction of the mooring system.

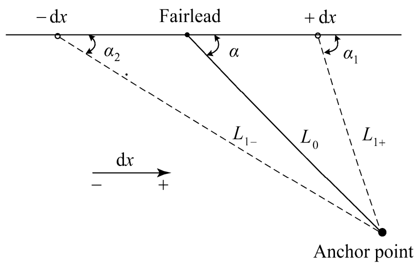


Fig.2 Calculation of the overall mooring system's static characteristic

3.2 The objective function

The object of this optimization is mainly about a minimization problem, that is, to maintain the characteristics of the truncated system consistent to the prototype one, namely "$Sc(\boldsymbol{X})_{\mathrm{Trun}} = Sc(\boldsymbol{X})_{\mathrm{Full}}$". Therefore, $\boldsymbol{X}$ is the design variable vector. However, the static characteristics of the overall system can only be made to be close as far as possible to that of the corresponding each type of mooring line in a numerical value.

The tension-displacement characteristics of the single mooring line, as well as the horizontal and the vertical restoring force-displacement characteristics of the overall system are considered in the paper. Then the objective function can be expressed by formula (11) as follows.

$$\begin{cases} F_1 = \sqrt{\sum_{i=1}^{n_p}\left(\dfrac{Fh_{(\mathrm{full})i} - Fh_{(\mathrm{trun})i}}{Fh_{(\mathrm{full})i}}\right)^2 \Big/ n_p} \\ F_2 = \sqrt{\sum_{i=1}^{n_p}\left(\dfrac{Fv_{(\mathrm{full})i} - Fv_{(\mathrm{trun})i}}{Fv_{(\mathrm{full})i}}\right)^2 \Big/ n_p} \\ F_3 = \sqrt{\sum_{i=1}^{n_p}\left(\dfrac{T_{(\mathrm{full})i} - T_{(\mathrm{trun})i}}{T_{(\mathrm{full})i}}\right)^2 \Big/ n_p} \end{cases} \tag{11}$$

where F_1 represents the difference of the horizontal restoring force-displacement characteristic similarity degree expressed in a numerical value between the truncated system and the prototype one; $Fh_{(\mathrm{full})i}$ represents the horizontal restoring force-displacement characteristic of the full depth system; $Fh_{(\mathrm{trun})i}$ represents the horizontal restoring force-displacement characteristic of the truncated depth system; F_2 represents the difference of the vertical restoring force-displacement characteristic similarity degree expressed in numerical value between the truncated system and the prototype one; $Fv_{(\mathrm{full})i}$ represents the vertical restoring force-displacement characteristic of the full depth system; $Fv_{(\mathrm{trun})i}$ represents the vertical restoring force-displacement characteristic of the truncated depth system. F_3 represents the difference of the static characteristic similarity degree expressed in numerical value of a representative single mooring line between the truncated system and the prototype one. $T_{(\mathrm{full})i}$ represents the static characteristic expressed in numerical value of a representative single mooring line of the full system; $T_{(\mathrm{trun})i}$ represents the static characteristic expressed in numerical value of a representative single mooring line of the depth system; n_p represents the number of the discrete points. Because the static characteristic is expressed by a curve, the similarity degree between the two curves can be determined by comparing the corresponding y-coordinate related to the identical x-coordinate.

In this optimization design, the similarity of the static characteristic between the truncated system and the prototype one is mainly considered. Thus the involved design variables mainly include the segment length of the mooring line, the rigidity of the axial direction, the weight in water per unit length, the breaking strength, the buoy position, and the weight in water (if a buoy exists).

Among them, the axial direction rigidity of the mooring line, the weight in water per unit length, and the breaking strength is related to the material, the diameter, and the structural of the mooring line. If the material and the structural of the mooring line are assigned, the other parameters can be uniquely determined by the diameter.

4 Numerical experiment

An inner turret mooring system FPSO which works in the water depth of 320 m is selected as the object of research. While the model scale factor λ is 80 and the truncated water depth is 80 m.

The FPSO includes the inner turret, mooring system, and risers, as shown in Figure 3. The number of the mooring line is 3×3. In this paper, the details of the risers are not given, and the corresponding optimal design of the truncated system will not involve them. Every mooring line, from top to bottom, including the end chain (RQ3), the middle steel wire (Spriral Strand), and the turret steel wire (Spriral Strand). The detail parameters of each steel wire and chain are listed in Table 1 (full scale).The pretension of every mooring line is 300 kN (full scale).

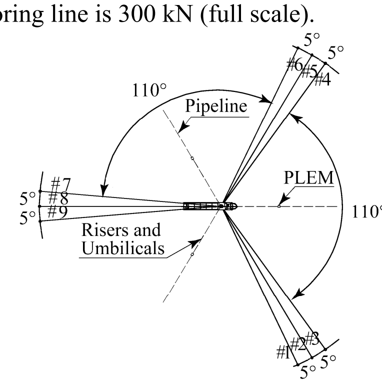


Fig.3 Plan view of the turret mooring system

4.2 The optimization results and analysis

In order to make the static characteristics of the truncated mooring system similar as far as possible to the full depth one, it should be calculated many times to determine the physical characteristics of the single mooring line.

In the experiment, it is found that dividing the original mooring system into two sections from the middle of junction of the turret to that of the submarine cable, and putting a buoy with appropriate weight on it, cause the static characteristics of the total horizontal of restoring force between the truncated system and original system to be very close, so as to the static characteristics of the single mooring line.

Therefore, the variables are adjusted accordingly as shown in Table 2, which lists the range of the variables. The parameters of INSGA-II are shown in Table 3.

Table 1 Main parameters of the mooring line of the 320m system, full scale

Particulars	Length /m	Diameter /mm	Weight in air /(kg·m^{-1})	Weight in water /(N·m^{-1})	EA /kN	Break strength /kN
End chain	600	126.0	316.4	2 700.3	164 490.0	11 362.6
Middle steel wire	320	101.6	55.2	429.6	891 805.0	8 485.8
Turret steel wire	120	101.6	55.2	429.6	891 805.01	8 485.8

Note: A buoy, whose weight in water is −20750kg, located at top of the middle steel wire.

Table 2 Upper limit and lower limit of the optimization variable

Partic-ulars	End chain		Middle steel wire, lower		Clump Weight in water /kN	Middle steel wire, upper		Buoy Weight in water /kN	Turret steel wire	
	Diameter /mm	Length /m	Diameter /mm	Length /m		Diameter /mm	Length /m		Diameter /mm	Length /m
Lower limit	30	250	76.2	20	180 000	76.2	30	−500 000	76.2	8
Upper limit	50	550	177.5	40	400 000	177.5	90	−250 000	177.5	40

Table 3 Parameters of INSGA-II

Iterations	Population size	Probability of crossover	Probability of mutation	Crossover constant	Mutation constant
300	200	0.8	0.05	5	5

On the basis of the above system, INSGA-II is put forward to get the similarity of static characteristics in the truncated depth mooring system. In order to calculate it, the author developed a computer program by using the C++ language. According to the requirement, choosing [0.0372249, 0.0426799, 0.0178204] as the optimal solution from the pareto solution which was calculated, the corresponding optimal points are [108, 15.4558, −287084，158.8, 41.4787, 376805, 177.5, 32.620 8, 33.434 5, 315.693]^{T}. Fig.4 shows the Pareto optimal surface. The Pareto optimal curve of F_1 and F_3 is shown in Fig.5; The Pareto optimal curve of F_2 and F_3 is shown in Fig.6.

The corresponded physical properties of the 80m depth truncated mooring system are listed in Table 4 (full scale). Comparison of static characteristics between the full depth and truncated mooring system are shown in Fig.7 and Fig.8. Also, the initial shape of the mooring line underwater is shown in Fig.9.

Therefore, L1-P represents the static characteristics of the representative single mooring line in the full depth system while L1-T represents that of the truncated depth system; FH-P represents the total horizontal restoring force-displacement characteristics in the full depth system while FH-T represents that of the truncated depth system; FV-P represents the total vertical restoring force-displacement characteristics in the full depth system while FV-T represents that of the truncated depth system; L1S-P represents the initial underwater shape of the single mooring line in the full depth system while L1S-T represents that of the truncated depth system.

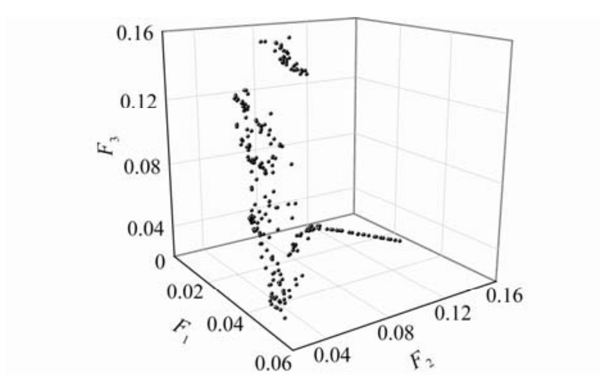


Fig.4 Pareto optimization curve of three functions

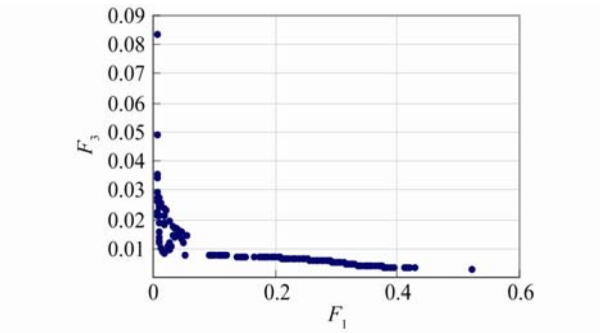


Fig.5 Pareto optimization curve of F_1 and F_3

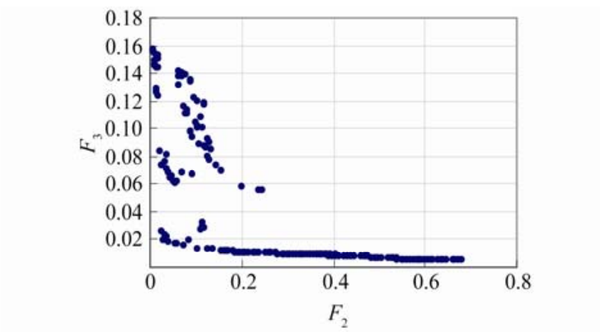


Fig.6 Pareto optimization curve of F_2 and F_3

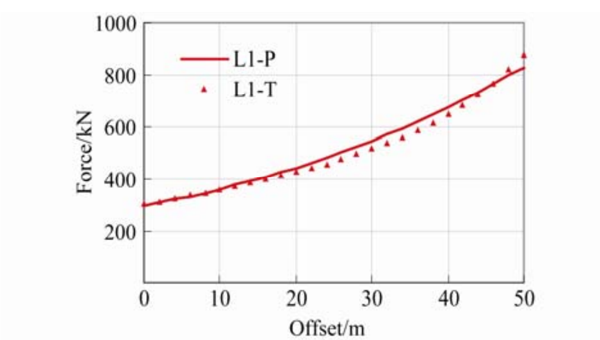


Fig.7 Tension-offset curve of the simple mooring line of the truncated & full depth mooring system

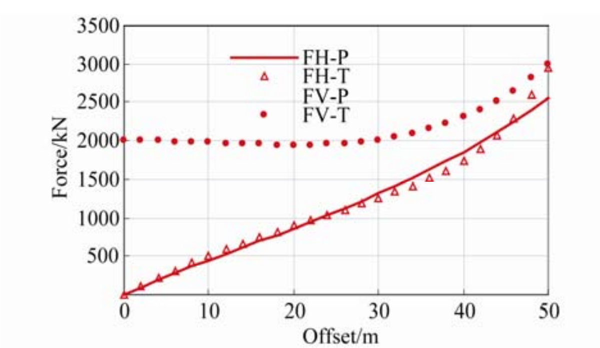


Fig.8 Over restoring force-offset curve of the truncated & full depth mooring system

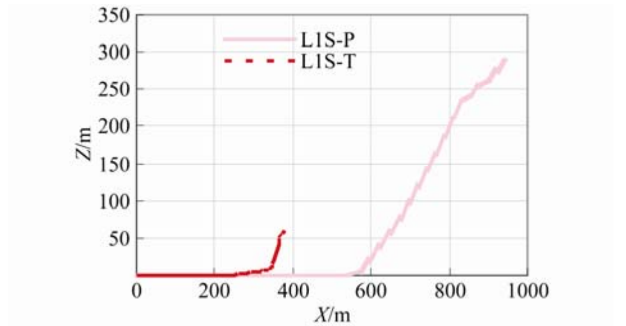


Fig.9 Initiation underwater shapes of the mooring line

As can be seen from the figures, the static characteristics of the equivalent water depth truncated mooring system are similar to the full depth system.

5 Conclusion

In this paper, the similarity degree of the static characteristics including the total mooring system's horizontal and vertical characteristics, as well as the "representative" single mooring line between the truncated and full depth system were optimized by the INSGA-II algorithm.

Considering that there are multiple objects in the paper, the algorithm should achieve a balance between them, and INSGA-II does this well. Moreover, it not only designs the equivalent water-depth truncated system as an alternative to the full depth system model test faster and more accurately, but also provides technical parameters and a scientific basis for the design of a stable and reliable floating production system. Therefore, it is very meaningful to the research of ocean engineering as well as the development of the deep sea oil and gas resources.

References

Baarholm R, Palazzo FG (2004). Hybrid verification of a DICAS moored FPSO. *Proceedings of the 14th ISOPE Conference*, Toulon, France. 307-314.

Buchner B, Wichers JEW, de Wilde JJ (1999). Features of the state-of-the-art deepwater offshore basin. *OTC 1999 Conference*, Houston, TX, USA. 10841,1-9.

Kalyanmoy D, Agrawal S, Pratab A (2000). A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization：NSGA-II. KanGAL Report 200001. R. Indian Institute of Technology, Kanpur, India.

Miao GP (1996). *Introduction to mechanics of flexible components*. Shanghai Jiao Tong University Press, Shanghai, 40-46.

Pan B, Gao J, Chen XH, Chen JD (1997). Static calculation of buoy mooring fast. *Journal of Chongqing Jiaotong University*, **16**(1), 68-73. (in Chinese)

Sheng ZB, Xiao LF (2003). Hybrid model test technique for deep sea platform. *Shanghai Shipbuilding*, (1), 12-14. (in Chinese)

Srinivas N , Kalyanmoy D (1994). Multiobjective optimization using nondominated sorting in genetic algorithms. *Evolutionary Computation*, **2**(3), 221-248.

Stansberg CT, Oritsland O, Kleiven G. (2000). Verideep: reliable methods for laboratory verification of mooring and stationkeeping in deep water. *OTC 2000 Conference*, Houston, TX, 12087, 1-11.

Stansberg CT, Yttervik R, Oritsland O, Kleiven G (2000). Hydrodynamic model test verification of a floating platform system in 3000 m water depth. *Proceedings of ETCE/OMAE2000 Joint Conference Energy for the New Millenium*, New Orleans, LA, OMAE2000/OSU OFT 4145, 1-9.

Su YH , Yang JM , Xiao LF (2007). The Experiment of a deepwater spar and its mooring system at truncated water depth. *Journal of Shanghai Jiao Tong Univeristy*, **41**(9), 1454-1459, 1464. (in Chinese)

Su YH, Yang JM , Xiao LF (2008). Multi-objective optimization design of truncated mooring system based on equivalent static characteristics. *China Offshore Platform*, **23**(1), 14-19. (in Chinese)

Yang JM, Xiao LF, Sheng ZB (2008). *Investigation on Hydrodynamic Test on Ocean Engineering*. Shanghai Jiao Tong University Press, Shanghai, 127-128.

Zhang HM, Yang JM, Xiao LF (2004). Investigation on hydrodynamic performance of a turret moored FPSO by using hybrid model test technique. *Proceedings of the 14th ISOPE Conference*, Toulon, France, 726-732.

Zhang HM, Yang JM, Xiao LF. (2007a). Investigation on hybrid model testing technique of deep-sea platforms based on equivalent water depth truncation. *China Ocean Engineering*, **21**(3), 401-416.

Zhang HM, Fan J, Yang JM (2007b). Investigation on quick computation method of the static characteristics of deep water mooring system. *Ship Ocean Engineering*, **36**(2), 64-68. (in Chinese)

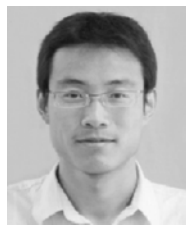
Zhang Min, Luo Wenjian, Wang Xufa (2009a). A normal distribution crossover for e-MOEA. *Journal of Software*, **20**(2), 305-314. (in Chinese)

Zhang HM, Sun ZL, Yang JM, Gao MZ (2009b). Investigation on optimization design of equivalent water depth truncated mooring system. *J. Science in China Series G*, **52**(2), 277-292.

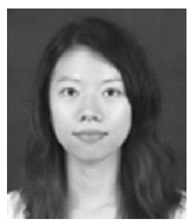
Zhang XF, Zhang HM (2010). Improved non-dominated sorting genetic algorithm II based on the elitist strategy. *Journal of China Univeristy of Metrology*, **21**(1), 52-58. (in Chinese)

Huoming Zhang was born in 1976. He is an associate professor at the College of Metrology Technology and Engineering, China Jiliang University. His current research interests include hybrid model testing technique for deep sea platforms, intelligent calculation method in engineering application, *etc*.

Wenjun Gao was born in 1985. He graduated from Changsha University of Science and Technology majoring in Automation in 2009. Now he is a master candidate at the College of Metrology Technology and Engineering, China Jiliang University. His current research interest is the design and realization of 6-DOF real-time simulation control device in the hybrid model testing technique of the active deep-sea platform.



Qiang Wang was born in 1987. He graduated from Qingdao University majoring in physics in 2009. Now he is a master candidate at the College of Metrology Technology and Engineering, China Jiliang University. His current research interests include the study on the dynamic properties of deep-water mooring lines, the modern intelligent optimization algorithm.



Juan Jiang was born in 1986. She graduated from East China Institute of Technology in 2009. Now studying for a master candidate at the College of Metrology Technology and Engineering, China Jiliang University. Her current research interest is the study on the numerical forecasting of storm surge.

Zhou Zhao was born in 1987. She graduated from China Jiliang University in 2010. Now studying for a master candidate at the College of Metrology Technology and Engineering. Her current research interest is the simulation of the offshore platform motions.