Optimization Design of Subsea Christmas Tree Pipeline

Yongtian kang[#1] Menglan Duan[#2] Baoyan Chen[#3]

China University of Petroleum (Beijing) offshore Oil and Gas Research Center;No.18, fuxue Road, changping,Beijing,China 102249; Tel：13488704636；Fax：010-89731969；

China University of Petroleum (Beijing) offshore Oil and Gas Research Center;No.18, fuxue Road, changping,Beijing,China 102249; Tel：010-89731689；Fax：010-89731969；

China University of Petroleum (Beijing) offshore Oil and Gas Research Center;No.18, fuxue Road, changping,Beijing,China 102249; Tel：15117974981；Fax：010-89731969；

[1]kang402@126.com

[2]mlduan@cup.edu.cn

[3]zhanfeng.1234567@163.com

***Abstract*— Subsea Christmas tree is one of the most important equipments in the subsea production system. The easily damaged pipelines should have stress analysis according to the standards. In this paper, authors establish pipeline optimization design model under the conditions of water depth and temperature, and then use ABAQUS software for finite element calculation of stress. By comparing with the different kinds of design results, the best one for the Christmas tree pipeline design is chosen. Results shows that the use of optimization design method can reduce cost.**

***Keywords*— Christmas tree, pipeline, optimization design, constrained optimization ,finite element calculation**

I. INTRODUCTION

At present, the research and development of our country's offshore oil equipments is in the initial stage. The equipments of subsea production system such as subsea Christmas tree, manifold, jumper, plet and umbilical cables have played a key role in the offshore petroleum development, some surface equipments of oil and gas exploration such as ships, platforms and some other equipments can be researched and developed independently[1]. But because our offshore engineering started late, subsea production system equipments can't be domestic, the optimization design of offshore oil equipment has not yet begun in China and needs further study.

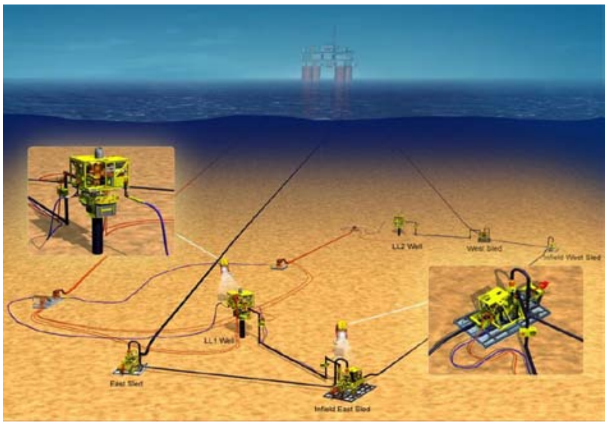

Fig.1 subsea production system

As shown in Figure 1, the subsea Christmas tree is one of the most important devices in the subsea production system, and the design of subsea Christmas tree in our country has just begun. Structural components of subsea Christmas tree are complex, which include safety clamp, top blocking device, tree cap, valves, pipelines and so on[2]. Pipeline is an important component of subsea Christmas tree, which is mainly used for transporting crude oil.

Fig 2 Structure of subsea Christmas tree pipeline

According to the research of the subsea Christmas tree structure abroad, as shown in Figure 2, different subsea Christmas trees have different pipeline structures. Optimization methods can be used for speeding up the design of subsea Christmas tree pipeline, to meet the modular design, different structures and short-cycle supply of subsea Christmas tree[3].The optimization design of subsea Christmas tree pipeline sets foundation for subsea Christmas tree design, and provides technical support for development of other subsea production equipments.

II. OPTIMIZATION DESIGN METHODS

Mechanical optimization design methods include one-dimensional search method, unconstrained optimization, constrained optimization, linear programming, and multi-objective optimization method. All optimization methods have design variables, objective function and constraint condition. Establish the mathematical model of design problem, select design variables，make the objective function, and list the constraint condition. The objective function is the functional relationship between optimal solution and design variables.

Design variables: Optimization design variables are the parameters used in the process of optimization design, and the design variable can be independent each other. During the optimization design process, design variables can be optimized to achieve optimal value. The number of design variables is the dimensions of optimization design.

Objective function: Objective function shows the relationship between design variables, and objective function include single-objective function and multi-objective function according to the objective of optimization design, it can give a direct response to the results of optimization design.

Constraint condition: Constraint conditions in design process are the constraint relations of design variables themselves, which mean that the constraints of design variables in design process. They include the boundary constraints and using constraints, and they can be expressed by using the equations or inequalities [4].

A.One-dimensional search method

One-dimensional search method is the basic method in mechanical optimization methods. One-dimensional search is needed in all optimization iteration calculation. Start from the selected $X^{(0)}$, along the decline direction $S^{(0)}$ of function value,and get the extreme value $X^{(1)}$ of objective function in this direction,then look upon $X^{(1)}$ as the starting point, and get the new extreme value $X^{(2)}$ along the decline direction of objective function value. Iterate untill getting the optimal solution $X^{(k+1)}$ which meets iteration termination. That is to say,in an iterative calculation process, when starting point $X^{(k)}$ and direction $S^{(k)}$ are known, solving the objective function minimum then becomes one-dimensional problem which solve the optimal value $a^{(k)}$ of a variable step length a.

$$f(X^{(k)}+a^{(k)}s^{(k)})=\min f(X^{(k)}+as^{(k)})$$

$$X^{(k)}+a^{(k)}s^{(k)}=X^{(k+1)}$$

This method is called one-dimensional search optimization method that gets a’s optimal solution $a^{(k)}$ to make $f(X^{(k)}+as^{(k)})$ minimum.

B. Unconstrained optimization method

Unconstrained optimization method is that there are no restrictions with the scope of design variables in the process of solving the objective function minimum.

The form of unconstrained multi-dimensional optimization problem:

$$x = [x_1, x_2 ... x_n]^T$$
$$\min f(x), x \in E^n$$

There is no restriction with X in solving Function value, however, in the actual engineering, unconstrained problems are few. But unconstrained optimization problem is still one of the basic solutions of optimal design, because the constraint problems can translate into unconstrained optimization problems through the manipulation of the constraint condition.

C. constrained optimization method

The majority of mechanical optimization problems are the constrained optimization problems, and the mathematical model is

$$\min f(x) = f(x_1, x_2 ... x_n)$$
$$g_j(x) = g_j(x_1, x_2 ... x_n) ? 0(j \quad 1, 2..., m)$$
$$h_k(x) = h_k(x_1, x_2 ... x_n) = 0(k = 1, 2..., l)$$

The process of solving the equations above is the method of constrained optimization[5].

D. Multi-objective function optimization method

Multi-objective function optimization method is a method that composed by multi-objective function and compositely solve optimal value. The optimal solution of $f_1(x), f_2(x), f_3(x),. f_n(x)$ is interconnected. But as the objective function may conflicting, adjusting the optimal solution of each objective function is needed, then we can get the optimal solution of the whole or the optimum scheme. The common mathematical model expression of multi-objective function is:

$$X = [x_1, x_2 ... x_n]T \square E^n$$
$$\min f_1(x)$$
$$\min f_2(x)$$
$$.$$
$$.$$
$$\min f_p(x)$$
$$g_u ? 0(u \quad 1, 2..m)$$

Contrast the above several optimization methods,we can know that all kinds of optimization methods have differences in design variables, objective function and constraint condition, as shown in table I:

TABLE II

THE COMPARISON BETWEENOPTIMIZATION METHODS

Optimization method	**Design variables**	**Objective function**	**Constraint condition**
one-dimensional search	ingle variable	one-dimensional objective function	no
unconstrained optimization	multi-variabls, unlimited	a multi-dimensional objective function	no
constrained optimization	multi-variabls, limited	a multi-dimensional objective function	yes
multi-objective function optimization	multi-variabls, limited	Several multi-dimensional objective function	yes

III. OPTIMIZATION DESIGN OF PIPELINE

The optimization design of subsea Christmas tree pipeline must follow API 17D, pressure vessels and other relevant norms, and should meet the requirements of corrosion and expansion bends. According to the special requirements of Christmas tree pipeline, constrained optimization design method should be chosen.

Constrained optimization design method is the method which the range of design variable values is limited， and the minimum of constraint problem's objective function satisfies the constraint condition, that is to say,it is in the feasible region defined by constraint condition[6].

The conditions that the constrained optimization problem can be derived are:

Objective function and constraint function are continuous and differentiable function,and there's a bounded feasible region F;

the feasible region should be a nonvoid set,which exists point range that satisfies the constraint condition:

$$X^{(k)}(k=1,2...)$$

The solving process of constrained optimization problem is:

design variables:

$$X^{*}=[x_1,x_2...x_n]^T, X \;\square$$

The objective function will get minimum value under the conditions of constraint equation below:

$$h_v = 0, (v = 1, 2, ..., p)$$

$$g_u = 0, (u = 1, 2, ..., m)$$

objective function:

$$f(x)\ ?\ \min f(x) \quad f(x^*)$$

Then we get x^* by solving the objective function,and x^* is the optimum constraint point.

Subsea Christmas tree pipeline can have different kinds of structures according to the different using conditions and different connection types of Christmas tree. On the basis of design methods, we can use the following process to optimize the design of subsea tree pipeline.

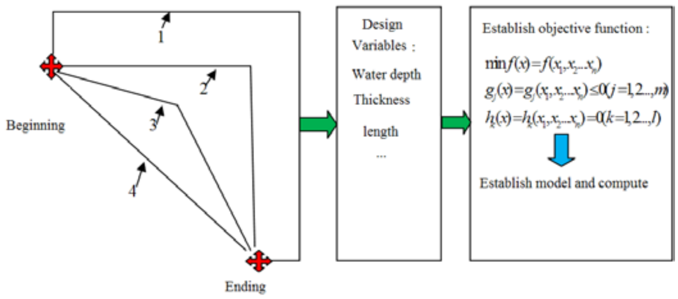

Fig.3 The process of optimization design

First, the initial data of the subsea Christmas tree pipeline can be determined according to the usage. Second, according to the standards and norms of subsea Christmas tree,the design variables, constraints, objective function of pipeline can be determined. Third, computational analysis should be completed according to the results, to check whether the results fit the design requirements[7].

Table II

THE INITIAL DATA OF SUBSEA CHRISTMAS TREE PIPELINE DESIGN

Length/m	3.2
Vertical height/m	1.2
Oil temperature/°C	52
Depth/m	300
ID/m	0.103
Initial end connection forms	Flange connection
End pipe connection forms	HUB
End pipe connection forms	90°

According to the initial data of subsea Christmas tree pipeline, the pipeline design variables can be determined as wall thickness t, corrosion allowance x, three elbows, length L, inside diameter d, and outside diameter D.

$$X=[T,x,3,L]$$

Constraint conditions according to the standards and design requirements

wall thickness T:

T>0

$$T>\frac{PR}{\sigma^{t}\varphi - 0.6p}$$

T - wall thickness, mm; P - design pressure, MPa; R - inside radius of cylinder, mm; σ - allowable stress, MPa; φ - Weld coefficient.

Corrosion allowance x:

$$0 \le x \le 4$$

ID:

$$d = 103mm$$

OD:

$$D = d + 2T + 2x$$

Establish objective function

$$\min W = \rho \cdot L \quad \pi(\frac{D^2}{4} - \frac{d^2}{4})$$

W-weight, kg; L - length of the pipeline, m; d - inside diameter of cylinder, mm; D - outside diameter of cylinder

Design data of Pipeline according to design calculation are as follows:

Table Ⅲ

THE DESIGN DATA OF SUBSEA CHRISTMAS TREE PIPELINE

Length/m	3.2
3.2	1.2
Vertical height/m	1.2
ID/m	0.103
OD/m	0.137
Corrosion allowance/mm	3
Bend Angle/º	90º
Number of Elbows	3

IV. ANALYSIS OF THE OPTIMIZATION RESULTS

By using the mechanical optimization design method, the structure of subsea Christmas tree pipeline can be obtained. This Christmas tree pipeline has three expansion bends, left end flange connection, and right end connected with the vertical hoop seat. Through the finite element analysis of the subsea Christmas tree pipeline, this subsea Christmas tree pipeline not only meet production requirements, but also meet the mechanical requirements in mechanical properties. Compared with optimization design and conventional design, optimization design has advantages on product performance, and it reduces the costs of subsea Christmas tree[8].

The pipeline OD in this optimization design is 137mm,and the wall thickness is 12mm,so it can be regarded as a thin wall container. Make stress analysis of optimized pipeline using GB150《Steel pressure vessel》[9]. The pipeline stress is shown in Figure 4:

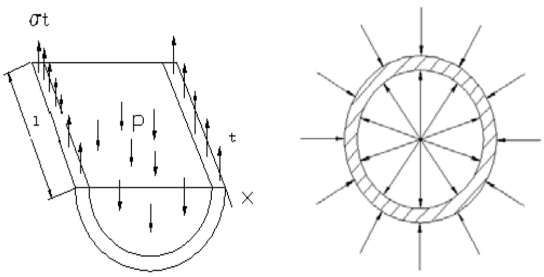

Fig.4 The pipeline stress distribution under internal pressure

The circumferential force of optimized pipeline is σ_t, axial force is σ_x, P is internal and external pressure difference,and D is pipeline OD,δe is the effective wall thickness of pipeline,according to the balance equation,we can get:

$$\sigma_t = \frac{PD}{2\delta_e}$$

$$\sigma_x = \frac{PD}{4\delta_e}$$

TableⅣ

PIPELINE STRESS OF 300m WATER DEPTHS

Depth/m	Differential pressure between the inside and outside（MPa）	Stress（MPa）

300	31.5	199.2

The thermal stress produced in pipeline because of temperature difference change is shown in Table Ⅴ

$$\sigma = \alpha E \Delta T$$

α is linear expansion coefficient of materials, E is elasticity modulus of materials,and ΔT is the change of temperature difference[10].

Table Ⅴ

PIPELINE THERMAL STRESS OF 300m WATER DEPTHS

Depth/m	Oil temperature difference(℃)	Thermal stress （MPa）
300	41	107.6

We can get that the total stress of pipeline is the sum of stress and thermal stress:

$$\sigma = 306.8 \text{ MPa}$$

The authors make the finite element analysis of the subsea Christmas tree pipeline by using ABAQUS software. The material is 42CrMo, and its material properties is shown in Table 3.In the process of analysis, the boundary conditions of pipeline both ends is fixed according to the service conditions of pipeline. By imposing fluid load on the inner part， with the fluid pressure is 34.5Mpa,and the temperature of pipeline steps from 11 ^{o}C of seawater up to 52 ^{o}C of the oil, the pressure of the subsea Christmas tree pipeline can be calculated.

Table Ⅵ

MATERIAL PROPERTIES OF 42CrMo

Yield strength Mpa	Elastic modulus Gpa	Poisson ratio	Density kg/m^3	Thermal expansivity α/(10-6℃)
930	210	0.3	7850	11.2

According to the optimization design results of subsea Christmas tree pipeline, combined with the engineering practice,the finite element analysis model of subsea Christmas tree pipeline is established. Verify the optimization design of pipeline from the aspects of the strength,and judge whether the optimization design is reasonable according to the comparison between yield strength of material and pipeline stress. If the pipeline stress is less than the yield strength of materials, the optimization design results is reasonable, otherwise, it's not reasonable[11].

The calculation results is shown in figure 5. Results shows that the subsea Christmas tree pipeline stress is 259.5Mpa,which is less than the yield strength of materials,therefore the optimization results is available.

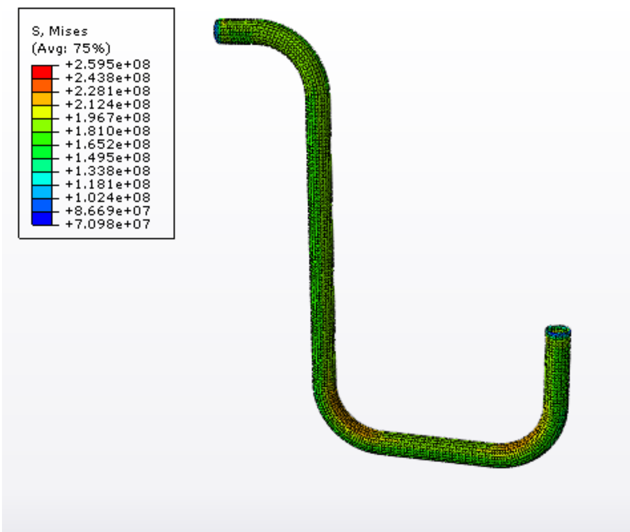

Fig.5 Finite element calculation results of pipeline design

V.CONCLUSION

The optimization design of subsea Christmas tree pipeline limits the mechanical properties and the geometric size of the subsea Christmas tree, according to relevant specification requirements under the conditions of constant environment and load. The design requires researchers to choose proper design variables, and establish the appropriate objective function by using constrained optimization method to get the optimal value of objective function. This approach applies not only to subsea Christmas tree pipeline, but also uses into other submarine production facilities according to the objective function, design variables and constraints. Therefore this method extends the service life of subsea Christmas tree pipeline and reduces its cost.

REFERENCES

[1] Gilles Barnay. Girassol: *The Subsea Production System Presentation and Challenges[C]*. OTC 14170, 2002.

[2] K.A. Aarnes,J.Lesgent,J.C.huber, *Thermal Design of a Dalia SPS Deepwater Christmas Tree - Verified by Use of Full-Scale Testing and Numerical Simulations[C]*. OTC 17090, 2005.

[3] Eric D. Larson, P.E. and Kevin G. Keosoff. *Marginal Subsea Development with Existing Subsea Trees[C]*. OTC 16533, 2004.

[4] D.X. Yang, *"Mechanical design optimization method and evaluation."J*. index Journal of Changchun University of Science and Technology (Comprehensive version)，June.2006,(in Chinese)

[5] W.S. Liu, *Mechanical optimization design*, Tsinghua university press, 1994.

[6] Huibo He, *Optimal Design of a Tilling Machine Reduction Gearbox Using Matlab.* INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING. Vol. 10, No. 2, pp. 63-66

[7] Y.S. Liu, X.B. Xu, and M.Yang, *"The optimization design of petroleum machinery in 21st centrury. " J*. Petroleum Machinery, Sep.1999, (in Chinese)

[8] Christer AH. *A review of delay time analysis for modelling plant maintenance.* In: Osaki S, editor. Stochastic models in reliability and maintenance. Berlin: Springer; 2002. p. 89–117.

[9] GB150 [M]. State Bureau of Quality Technical Supervision.1998.

[10] Y.T. Kang, H,P, Tian, X,L, Luo, M,L, Duan, J,K, Feng, *"subsea Christmas tree pipeline stress calculator", oil field equipment* 2011,40:33-36, (in Chinese)

[11] ISO 13268-1, Petroleum and natural gas industries —Design and operation of subsea production systems —Part 1: *General requirements and recommendations[S]*. 2005.