Reliability Analysis on Subsea X-tree Tubing Hanger

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Abstract-**As a vital component of Subsea X-tree, the tubing hanger has a significant impact on the safety level of Subsea X-tree. The reliability of the tubing hanger directly determines the service life of the tree. Among all the factors such as the design level, human error and the validity of the control system that would probably influence the reliability of the tubing hanger, the reliability of structural strength is the basis of normal production. In this paper, the probability design system of ANSYS based on the response surface method is used to calculate the reliability of the tubing hanger main body which is used in the water 300-meter deep. Finally, several important variable parameters in the proposed model of tubing hanger are discussed.**

Keywords-Structure Reliability; Tubing Hanger; Response Surface Method; Subsea X-tree

I. INTRODUCTION

With the increase of water depth in offshore oil development, subsea production system development model has become a hot off-shore oil and gas field development direction. Meanwhile the world's major oil companies regularly provide a large injection of cash into the design and fabrication of subsea production system. As a new development model, subsea production system faces a variety of challenges among which the most concerned one is the safety and reliability issues. Subsea system must be manufactured of such a quality that it can withstand long-term exposure to seawater and extreme pressure over their lifespan of two decades or more. In recent years the offshore oil accidents occurred frequently, in which case it not only caused huge economic losses, but also brought a serious threat to the marine environment and human health. As a result, the safety and reliability issues become a concern that scholars are committed to address.

Subsea X-tree, one of the key equipment of subsea production system, has a substantial influence on the running state of the whole system[12]. It forms the connection between the production channel from the well below and the flow line, as well as an essential barrier on top of the well and the outside environment. The major function of subsea X-tree includes controlling the pressure of the well head, regulating the flow of the oil (gas), and injecting chemical reagent. At the same time the subsea X-tree plays an important role in particular works like acidify, fracturing, injecting water and testing, etc. Of all the functions, controlling the pressure of the well head and regulating the flow of the oil (gas) are the two main control objectives of subsea X-tree.

II. PARAMETER ANALYSIS OF TUBING HANGER

The vital component of the tree is the tubing hanger whose function is to hanger the tubing string, seal the annular space between the tubing string and the production casing, control and regulate the pressure between the tubing string and production casing, bear the pressure in the tubing string as well as the load of the tubing string. Therefore, it can also be used in workover process. To evaluate the strength reliability of tubing hanger, the following parameters should be considered.

(1) Water depth

The deep sea environment exhibits extremely high external pressure. In the design of subsea tubing hanger, the collapse pressure must be considered. The deep sea environment also makes the validity of control system and the repair work more difficult.

(2) Oil pressure

Internal pressures derived from the petroleum reservoir could result in the collapse of the tubing hanger. So, a relatively thick wall tubing hanger is required for deep sea applications.

(3) Impact load

Impact load mostly appears at the installation phase. It can result in shock waves propogating through the elements with possible serious consequences.

(4) Corrosion

The corrosion of tubing hanger can result in leakage, which is a major cause of catastrophic events. The main hazard associated with corrosion is H_2S, chemical agent and hydrocarbon.

(5) Tubing load

One of the major functions of tubing hanger is to hang the tubing string with the weight of hundreds of tons. It requires high reliability of the structure of tubing hanger as well as the connection method.

III. PROBABILISTIC RELIABILITY THEORY

The term reliability means the probability that a component part, equipment, or system will satisfactorily perform its intended function under given circumstances, such as environmental conditions, limitations as to operating time, and frequency and thoroughness of maintenance for a specified period of time[3]. If there is a visible deformation, or the structure to withstand the force exceeds the ultimate strength of the material, the structure would fail.

The performance function is used in the probabilistic reliability theory. Suppose there are N random variables affecting the structure of the working state, the structure of the performance function can be written as $Z = g(X_1, X_2, \cdots X_n)$. The performance function corresponds to the different work states of the structure:

$Z = g(X_1, X_2, \cdots X_n) > 0$，Reliable state;

$Z = g(X_1, X_2, \cdots X_n) = 0$，Limit state;

$Z = g(X_1, X_2, \cdots X_n) < 0$，Failure state.

Random variable $X_i (i = 1, 2, \cdots, n)$ that characterized the uncertainty information regularly appears in the structure design, such as the randomness of the material parameters, the geometric dimensions, the load and so forth. The function of the random variable is $f_x(x_1, x_2, \cdots x_n)$ .The probability expression of the structure reliability based on the performance function $Z = g(X_1, X_2, \cdots X_n)$ can be written as:

$$P_s = P(Z = g(X_1, X_2 \cdots X_n) > 0) = \iint\limits_{Z>0} \cdots \int f_x(x_1, x_2, \cdots x_n) dx_1 dx_2 \cdots dx_n \tag{1}$$

With the above expression, the failure probability which is the supplementary set of the above equation can be obtained:

$$P_f = P(Z = g(X_1, X_2 \cdots X_n) < 0) = \iint\limits_{Z<0} \cdots \int f_x(x_1, x_2, \cdots x_n) dx_1 dx_2 \cdots dx_n \tag{2}$$

On the foundation of stress-strength interference theory, the performance function which characterizes the structure reliability can be[4]:

Z=R-S

The probability of failure is expressed as:

$$P_f = \int_{-\infty}^{0} f_z(z) d_z = \int_{-\infty}^{0} \frac{1}{\sqrt{2\pi}\sigma_z} \exp\left[-\frac{(z-\mu_z)^2}{2\sigma_z^2} \right] dz \tag{3}$$

If $t = \frac{z-\mu_z}{\sigma_z}$, then the probability of failure will be:

$$P_f = \int_{-\infty}^{\frac{\mu_z}{\sigma_z}} \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{t^2}{2} \right] dt = \Phi(-\beta) \tag{4}$$

Where $\beta = \frac{\mu_z}{\sigma_z} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$ is recognized as reliability index。

The relationship between reliability and reliability index is:

$$P_s = 1 - P_f = 1 - \Phi(-\beta) = \Phi(\beta) \tag{5}$$

It turns out that the larger β , the smaller P_f . Consequently, β described as a reliability indicator of the system reliability, can give judgment on structure[5].

IV. RESPONSE SURFACE METHOD

For a large model which involves a huge number of elements, the Monte Carlo method will encounter the problem of compute-intensive and time-consuming. Therefore the Response Surface Method (RSM) provides an access to solve these problems. The response surface function or the response surface is then used instead of the performance function or the limit state function. The reliability analysis work will be done if the response surface is fitted by a series of sample points. In recent years, lots of scholars have been commiting themselves to the research of response surface method. For example, Faravelli[6] proposed an approximation method based on experiments. However, a large amount of experiments are required in the method. Several researchers[7] proposed a response surface method in which the correlation between variables is considered. Nevertheless, the number of collocation points should be at least two times the number of unknown coefficients of the random polynomial. An improvement method was recommended by D.L. Allaix[8] for the reason that it solved the calculation error problem caused by the improper fit of response surface polynomial and sample points. Some researchers[9,10] proposed a method that combines the response surface method with neural network, in which case the real limit state function was fitted by a neural network model so as to get the reliability of the structure.

g(X) is recognized as the response surface, so the g(X) can be written as a polynomial like:

$$g(X) = a_0 + \sum_{i_1=1}^{n} a_{i_1} x_{i_1} + \sum_{i_1=1}^{n}\sum_{i_2=1}^{n} a_{i_1 i_2} x_{i_1} x_{i_2} + \sum_{i_1=1}^{n}\sum_{i_2=1}^{n}\sum_{i_3=1}^{n} a_{i_1 i_2 i_3} x_{i_1} x_{i_2} x_{i_3} + \cdots \tag{6}$$

Where $a_0, a_{i_1}, a_{i_1 i_2}, a_{i_1 i_2 i_3}$ are the unknown coefficients which can be evaluated based on a large number of sample points.

In the PDS model of ANSYS, the sampling points are chosen by the way of experimental design which includes three approaches: (1) Central Composite Design(CCD); (2) Box-Behnken Matrix (BBM); (3) User-Defined Sampling. As a result, the CCD method is used in this paper, and the sample center is corrected by linear interpolation so as to get a high precision result. Then the Monto Carlo method is adopted to simulate the response surface again and again. In this case, the calculation speed is efficiently improved, so does the accuracy of the reliability value.

V. RELIABILITY CALCULATION OF THE TUBING HANGER MAIN BODY BASED ON THE PDS MODEL

As one of the powerful reliability analysis softwares, the PDS (probability design system) in ANSYS can evaluate the failure probability of the system and the non-determinacy of the output parameters as well as the sensitivity of the input parameters.

A. *System Description*

There are many variables that affect the reliability of the tubing hanger main body. For example, the diameter of the oil channel, the screwed depth of the tubing string, the weight of the tubing string, the oil pressure, the elastic modulus and so forth. The length of the tubing hanger main body is approximately 2000mm. Along with the axial direction, there are almost ten cylinders whose diameter are different from each other. In the paper, the model is simplified to three cylinders (see Fig.1) with the reason that the diameter of the cylinders is not a critical factor to the structure reliability. There are five through holes in the tubing hanger, namely the production channel, power line channel of the down hole safety valve, the injection channel of the chemical agent, and two cable channels. Among these the production fairway is the major part of the load. Specifically speaking, the internal channel bears the oil pressure of 34.5MPa. Meanwhile, the lower part of the channel bears the weight of the oil string 150t.

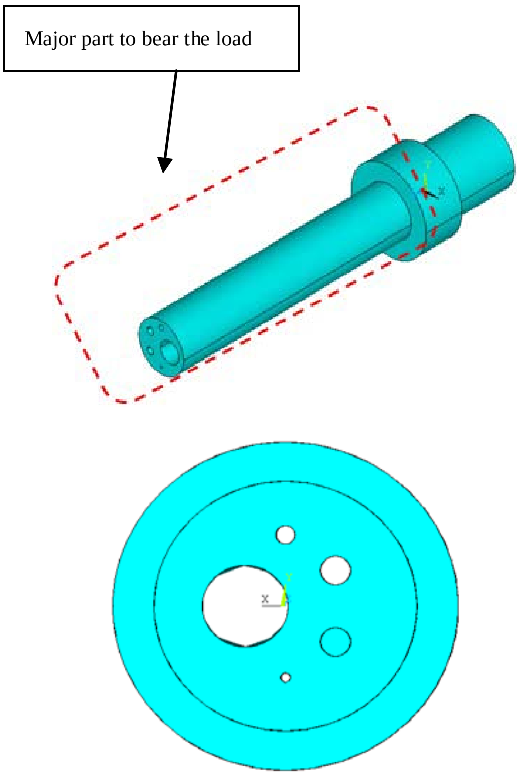

Fig. 1 The main body of the tubing hanger

B. Determination of the Load and the Boundary Condition

The lifecycle of the tubing hanger mainly includes the lowering phase, the installation and commissioning phase, the production phase and the recycle phase. Once failure occurs in the production phase, maintenance and repair probably involve recycling and reinstallation, in which case the cost will be extremely high. So, the production phase is chosen in this paper. The middle cylinder whose diameter is larger than the other two sits at the inside of the tree body. Then the tubing hanger will not bear the outside water pressure. Consequently, the dangerous part is the production channel. According to the difference of the applied load, the channel is divided into two parts. The upper part bears only the oil pressure of 34.5MPa while the lower part bears not only the oil pressure but also the weight of the tubing string which is 150t in the axial direction. The finite element result shows the force mainly distributed in the dashed area in Fig.1. And the chemical injection channel has a minimal effect on the structure reliability. So the model of the tubing hanger main body can be simplified as Fig.2.

The load and boundary condition (BC) is shown in Fig.3 in which the surface of the top cylinder is restrained on all degrees of freedom.

Fig. 2 The model after simplified

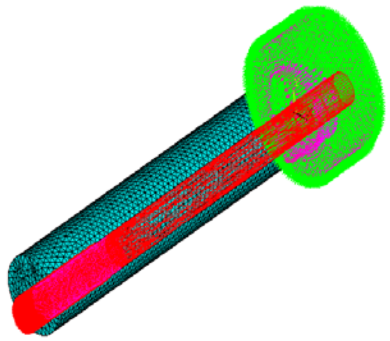

Fig. 3 The finite element model with load and BC

The mechanical parameters of the tubing hanger main body are shown in Table.1.

TABLE I MECHANICAL PARAMETERS

Density [Kg/m^3]	Elastic modulus [GPa]	Poisson ratio	yield strength [MPa]
7.75×10^3	210	0.3	372

C. The Failure Criteria of the Tubing Hanger

According to the Mises yield criterion, failure occurs when the equivalent stress at any point of the tubing hanger exceeds the yield strength. So the failure criterion is:

$$\sigma_{\max} \geq \sigma_s \tag{7}$$

Where $\sigma_{\max}$ is the largest stress in the main body of the tubing hanger;

σ_s is the yield strength of the material.

The limit state function is

$$Z(X) = \sigma_s - \sigma_{\max} \tag{8}$$

If Z(X)≤0, the structure failed, where X is the vector composed of uncertainty.

TABLE II THE CHARACTER OF THE INPUT RANDOM VARIABL

Name	Symbol	mean value	standard deviation	Distribution
The diameter of the oil channel[mm]	D	114.3	6.858	normal
Screwed depth[mm]	H	400	24	normal
Internal pressure[MPa]	P	34.5	2.07	normal
The gravity of the tubing string[N]	T	196000/H	5.5437	normal
elastic modulus	E	210000	12600	normal
Yield strength[MPa]	S	372	22.32	normal

D. *Random Variables and Their Distribution*

A large number of statistical data indicate that the strength of the material, most of the load and geometric dimension obey the normal distribution[11], such as the axial force, internal pressure, density and so on.

The coefficient of variation in engineering is mainly between 0.03-0.1[12]. The 0.06 is taken in this paper.

The screwed depth H which is the depth that the tubing string screwed in the tubing hanger is considered as a variable. The 150t force is applied to the nodes of the contact face. The number of the nodes is related to H, so does the force T. The linear density of the nodes is 7.5, then $T = \frac{F}{7.5H}$, where F is the weight of the tubing string. Both F and H obey to the normal distribution. The mean and standard deviation are $\mu_F = 1470000$, σ_F=88200 μ_H=400 σ_H=24 . As a result, the force T also obeys the normal distribution with the mean and the standard deviation is:

$$\mu_T = \frac{\mu_F}{7.5\mu_H} = \frac{196000}{\mu_H} \tag{9}$$

$$\sigma_T = \frac{\sqrt{\mu_F^2\sigma_H^2 + \mu_H^2\sigma_F^2}}{7.5^2\,\mu_H^2} = 5.5437 \tag{10}$$

The character of the random variables is listed in Table.2.

E. *Result Analysis*

(1) The probability density functions and cumulative distribution functions are shown in Fig.4 to 9.

(2) Reliability in different Z value

The Monte Carlo simulation was executed for 10000 times on the response surface. The reliability of the tubing hanger main body changes with Z. Some of the results are listed on Table.3.

Histogram plots and cumulative distribution function plots of the random output parameter Z are shown in Fig.10 and Fig.11 whose curve is smooth enough to achieve the required precision.

It is obviously in the two figures above that, the value of Z is bigger than 0, which means the structure of the tubing hanger main body is reliable enough. From the distribution of Z, another conclusion can be seen: the structure design of tubing hanger is too conservative, in which case the material and production cost are increased.

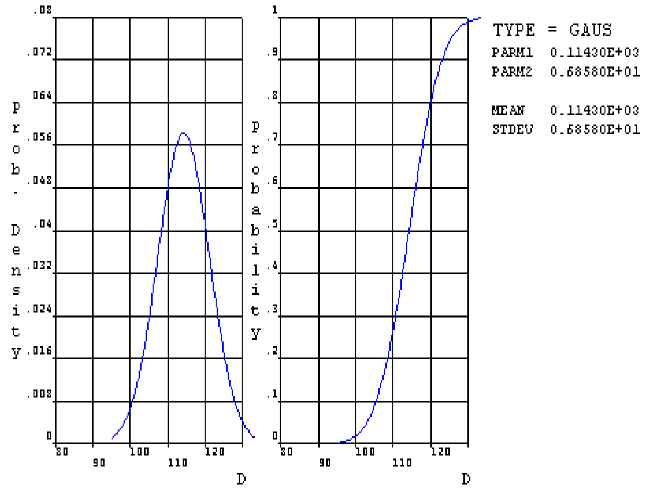

Fig. 4 PDF & CDF of input random variable D

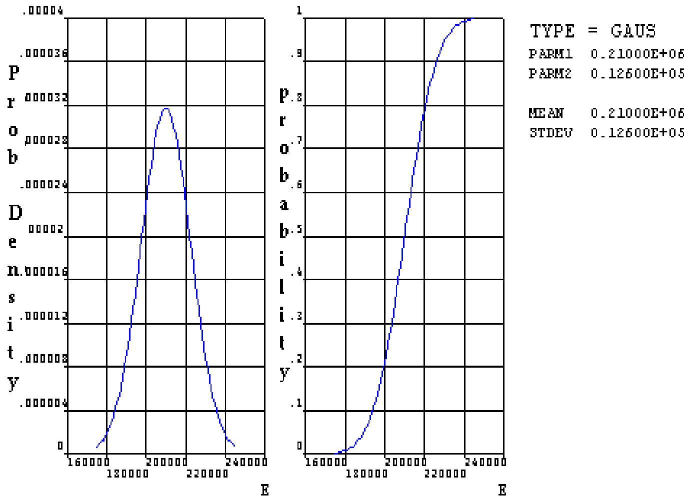

Fig. 5 PDF & CDF of input random variable E

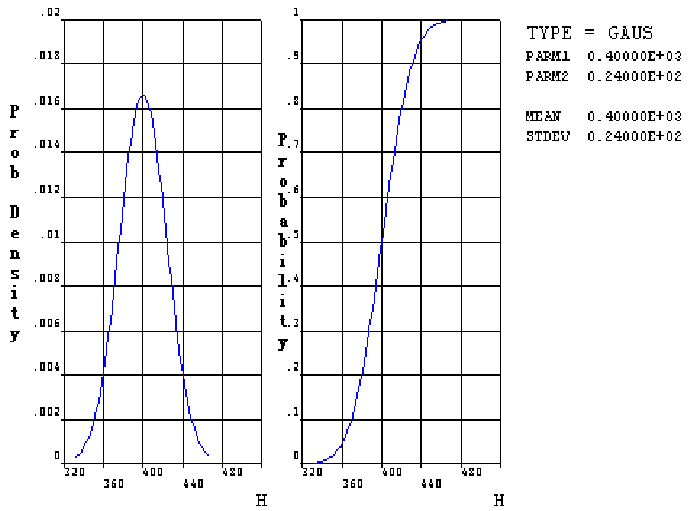

Fig. 6 PDF & CDF of input random variable H

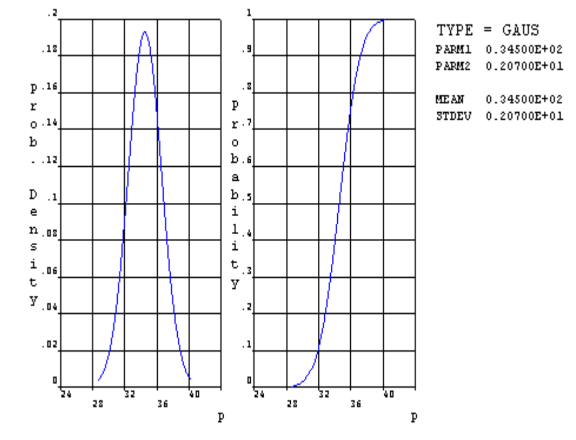

Fig. 7 PDF & CDF of Input Random Variable P

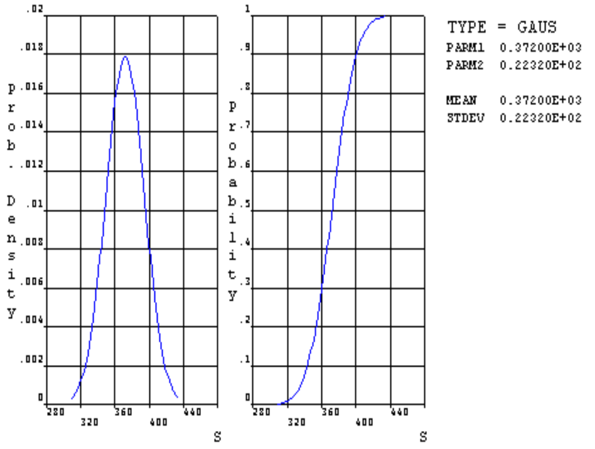

Fig. 8 PDF & CDF of input random variable S

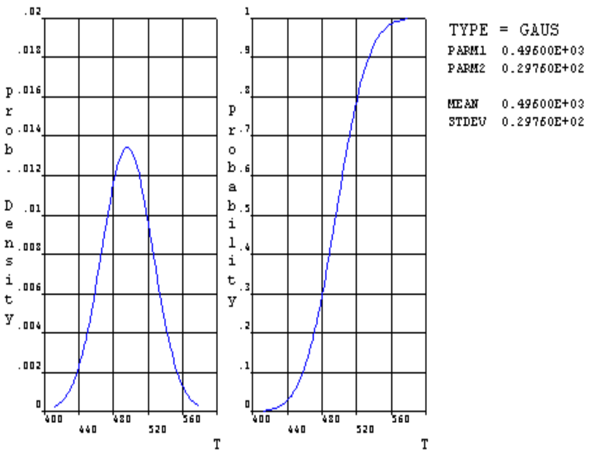

Fig. 9 PDF & CDF of input random variable T

(3) sensitivity plot of the random output parameter

Fig. 12 is the sensitivity plots in which the input parameters (D、S、T、E、H、P) affected the output parameter Z. The significant level is 2.5%, which means that the effect of the input parameters reaches limit state. The result shows that: the significant parameters are oil channel D, material strength S and force T, while the insignificant parameters are elastic modulus E, screw depth H and oil pressure. The histogram on the left presents that the material strength has a positive influence on the reliability of tubing hanger main body while the oil channel and the force T have a negative effect. It means reliability will decrease if D and P increase. The increased D will give rise to material load.

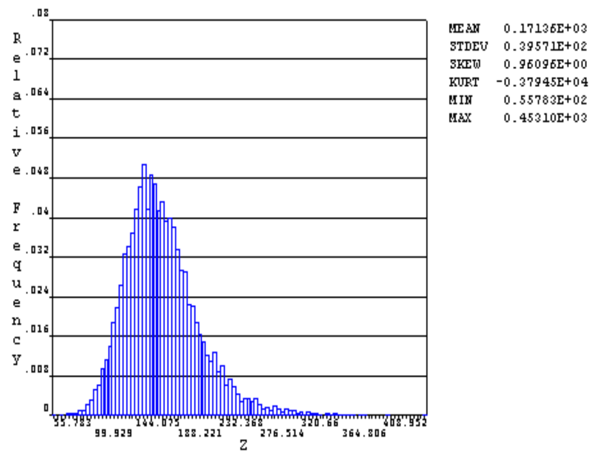

Fig. 10 Histogram of output parameter Z

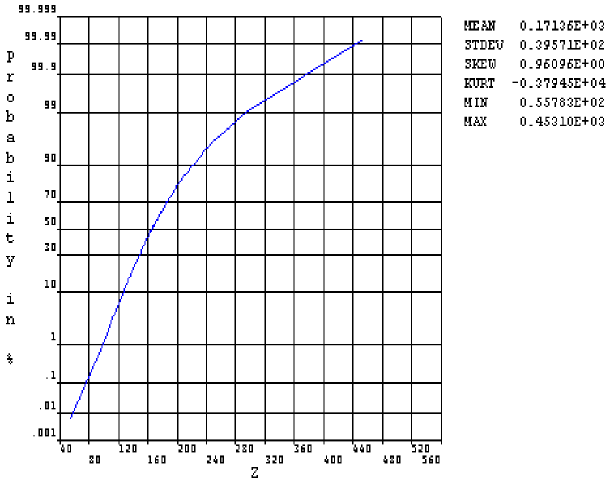

Fig. 11 CDF of output parameter Z

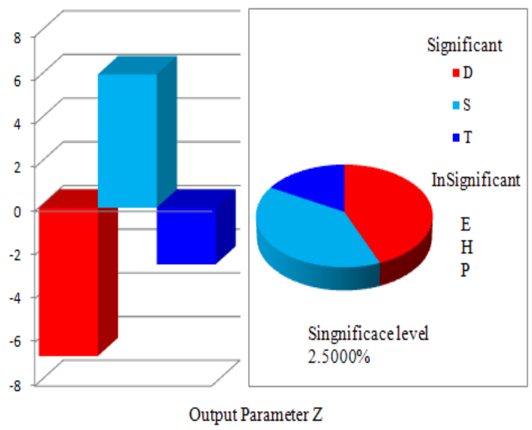

Fig. 12 Sensitivity plot

TABLE III RELIABILITY IN DIFFERENT Z VALUE

Z[MPa]	0	80	140	180	220
Reliability/%	100%	99.88%	76%	38%	10%

TABLE IV THE STATISTICAL DATA OF OUTPUT PARAMETER Z

Name	Mean	Standard Deviation	Skewness	Kurtosis	Minimum	Maximum
Z	171.4	39.57	0.9610	-3794	55.78	453.1

VI. CONCLUSIONS

The randomness of load, structural materials and geometry are considered in the paper, and a reliability method adopted for the main body of tubing hanger is established. The reliability analysis based on the mathematical statistics, probability analysis and finite element analysis make the evaluation model much more reasonable because various factors affecting the uncertainty of the model are involved in the calculation. That the risk is reduced to the minimum on the design phase provides the basis for the realization of intrinsic safety. The main conclusions are as follows:

(1) The analysis result presents that the structure design of the tubing hanger is too conservative; in which case the manufacturing costs is increased. As a result, the reliability-based structural optimization is recommended to carry out.

(2) The sensitivity analysis of each input variable is finished and that gives a significant guidance to the structural optimization of tubing hanger. It also provides a basis for the accuracy determination of each input variable. The variables whose sensitivity is high require a high degree of accuracy. Conversely, the accuracy can be reduced. It can effectively improve the following test process of data acquisition and data processing.

(3) The reliability analysis based on stochastic finite element method is established on the foundation of a large number of statistical data. Particularly for the pressure equipment like tubing hanger whose parameters have a much higher dispersion than non-Pressure Equipment's. Currently, the statistical data of the tubing hanger are in severe shortage. So the database needs to be further improved.

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