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Structural Reliability Analysis of Microsphere Focused Logging Tool Based on Response Surface Method

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Abstract: The push-pull system of microsphere focused logging tool is an important moving mechanism of this type of logging tool. The push-pull system will periodically bear large loads under working conditions and is prone to stress concentration. The structural strength reliability of the push-pull system is related to the logging accuracy and even the success or failure of the logging task. Based on ANSYS workbench software, this paper first conducts modeling and static simulation on the push-pull system of microsphere focused logging tool under working conditions, then conducts sensitivity analysis and experimental design on the basis of this analysis, and then conducts response surface analysis on the key stressed components of the push-pull system according to the analysis results. Finally, six sigma module is used to analyze the reliability of the push-pull system, and the structural strength reliability of the push-pull system is given by the probability distribution table obtained from the analysis. The analysis results show that the maximum equivalent stress occurs on the link arm of the push-pull system under working condition. The strength reliability of the link arm of the push-pull system under current working condition is high, and it can meet the daily logging requirements. However, there is still room for further design optimization.

Keywords: Push-back system; Response surface analysis; six sigma module; Reliability analysis.

1. Introduction

Microsphere focused logging instrument is a very important oil logging equipment in the field of oil logging, and its push-pull system is a key system installed on the microsphere focused logging instrument to assist the microsphere focused logging instrument to complete downhole logging tasks[1]. When the push system is working, it will be subject to periodic load, and the load is large, which is easy to produce stress concentration, resulting in failure and failure. .

At present, the research on the push-back system of microsphere focused logging tool mostly focuses on the design optimization of push-back system, the wear resistance design of push-back pad and the application of new materials. Based on the poor wear resistance of the push-back pad of microsphere focused logging tool, Dou Jinai improved the material and manufacturing process of the original pad, so that the wear resistance and insulation of the pad are better than that of conventional rubber pad[2]. Aiming at the minimum fluctuation between the transmission Angle of the main transmission mechanism and the root mean square of the expected transmission Angle, Ren Tao optimized the transmission performance and the motion stability of the push and lean system[3].

The microsphere focused logging tool push system is subject to a large periodic load in the working process, which is easy to produce stress concentration and lead to system failure and failure. The failure mode is usually that the structural strength of the link arm is not enough, so it is necessary to analyze the structural strength reliability of the microsphere focused logging tool push system. At present, there are few researches on this kind of analysis. Yang Baiqing discussed and analyzed the mechanical properties of the single-arm push-back device. By analyzing the working conditions of the push-back device and the movements of each mechanical arm, he established a theoretical basis for designing high-quality push-back devices[4]. Aiming at the reliability problems of logging instruments in the process of petroleum development, Zhang Guangzhou conducted specific research on the reliability design methods of logging instruments from multiple perspectives, and proposed that the framework strength and anti-impact reliability of instruments should be paid attention to in the design[5].

Based on the statics analysis of the microsphere focused logging tool push-pull system, the position of the maximum equivalent stress in the system is obtained, and the Six Sigma analysis module is used to analyze the reliability of the push-pull system, which provides a reference for further optimization of the push-pull system.

2. Introduction of Microsphere Focused Logging Tool Push-pull System

The push-pull system of microsphere focused logging tool mainly includes: motor, self-locking device of transmission system, centripetal ball bearing group, push-pull upper arm, push-pull inner wall, push-pull pad, link arm and push-pull main body. The working state structure diagram of push-pull system is shown in Figure 1.

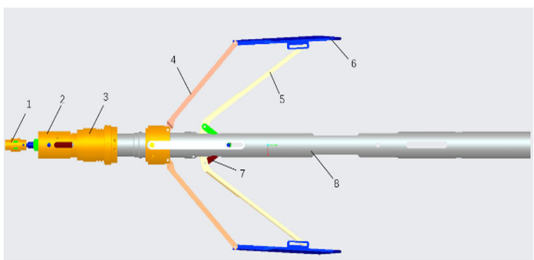


Figure 1. Structure diagram of the working state of the microsphere focused logging tool push-pull system

Note: 1- Motor; 2- transmission system self-locking device; 3- radial ball bearing group; 4- Push the upper arm; 5- Push against the inner wall; 6- Push the pad; 7- Link arm; 8- Push on the subject

During logging, the motor drives the thrust rod and thrust plate to move forward in a straight line through the lead screw, thus compressing the spring and opening the push arm, thus driving the push plate to move until the pad is attached to the well wall[6]. When the pad is completely attached to the well wall, the motor is powered off, and the spring provides the push force of the pad.

3. Statics Analysis of Microsphere Focused Logging Tool by System

3.1. Model Import and setting

According to the actual working conditions, the push-pull system of the microsphere focused logging tool was modeled and assembled in CREO modeling software. In order to reduce the amount of calculation, this paper only modeled the upper arm of unilateral push-pull, inner wall of push-pull, pad of push-pull and link arm, and imported the simulation model into ANSYS workbench simulation software. The simulation model of microsphere focused logging tool push-on system is shown in Figure 2.

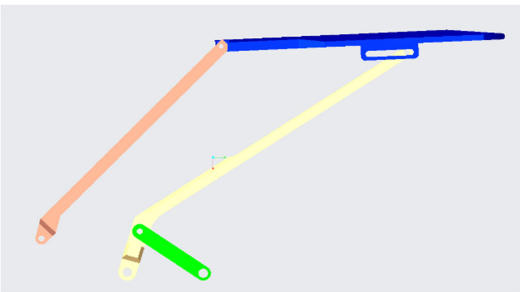


Figure 2. Simulation model of microsphere focused logging tool push-pull system

3.2. Grid Division

Tetrahedral method was used to divide the grid of the pushing system, the overall mesh size was set to 2mm, and the whole model was refined by Body Sizing. The number of grid units, nodes and grid quality after processing were shown in Table 1.

Table 1. The number of model grid elements, nodes and grid quality

Name	Number of elements	Number of nodes	Mesh quality
Push against upper arm	79128	122432	0.8341
Push against inner arm	98426	147887	0.8391
Push against plate	202911	295535	0.8474
Link arm	7789	12756	0.8259

3.3. Add contact and load

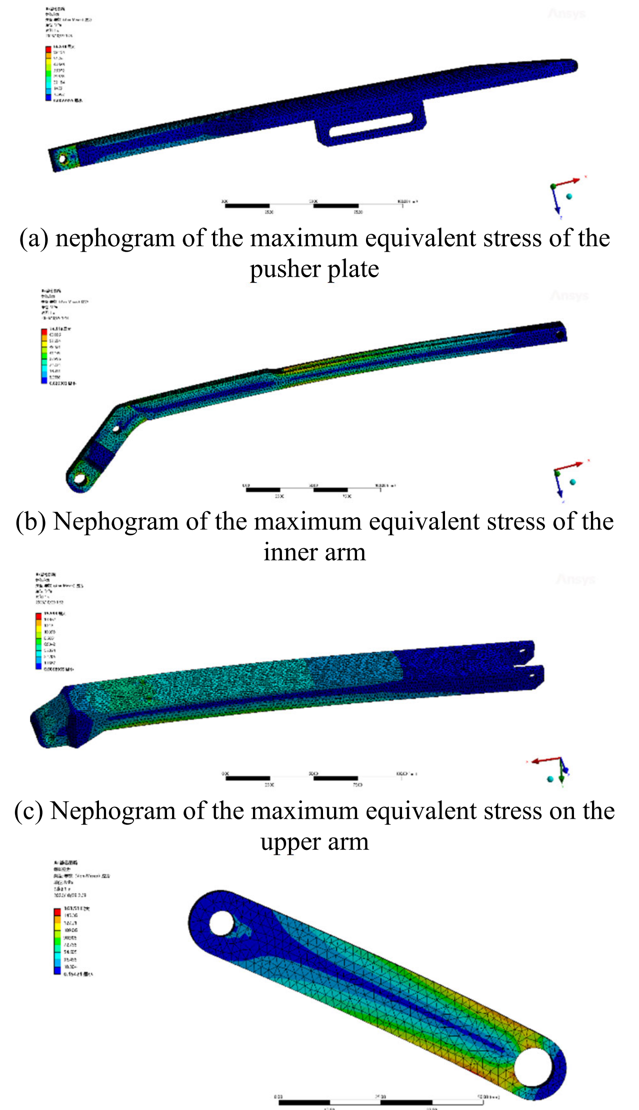
The connection mode of the moving pairs between the parts of the push-pull system is consistent with the actual connection mode, as shown in Table 2. According to the actual working conditions and reference 7, the load added to the push-back system is as follows: the driving force of the pin hole at the lower part of the link arm is 225N, and the wall pressure on the upper surface of the plate is 240N.

Table 2. Connection information table of the moving pair of the microsphere focused logging tool push-pull system

Number	Kinematic pair type	part 1	part 2
1	Moving pair	Link arm	ground
2	Rotating pair	Link arm	Push against inner arm
3	Rotating pair	Push against inner arm	ground
4	Moving pair	Push against inner arm	Push against plate
5	Rotating pair	Push against plate	Push against upper arm
6	Rotating pair	Push against upper arm	ground

3.4. Analysis of simulation results

The maximum equivalent stress and deformation cloud diagram of each part of the statics simulation of the microsphere focused logging tool under the loading condition of the system are shown in Figure 2 (a) -(d).



(a) nephogram of the maximum equivalent stress of the pusher plate

(b) Nephogram of the maximum equivalent stress of the inner arm

(c) Nephogram of the maximum equivalent stress on the upper arm

(d) Cloud map of the maximum equivalent stress of the link arm

Figure 3. The maximun equivalent stress and deformation cloud map of each part

The simulation results of each part of the push system are shown in Table 3.

Table 3. Maximum equivalent stress of each component of the microsphere focused logging tool push-back system

Name	Maximum equivalent stress (MPa)
Push against upper arm	66.548
Push against inner arm	74.118
Push against plate	15.593
Link arm	163.51

It can be seen from Table 3 that under working conditions, the equivalent stress on the link arm is the largest, which is 163.51MPa, while the equivalent stress on the other parts is much less than that on the link arm, among which the equivalent stress on the upper arm of the push is the least, which is 15.593MPa. Therefore, the strength of the link arm should be considered and the strength reliability analysis of the link arm should be carried out when designing the microsphere focused logging tool push-in system.

4. Reliability Analysis of Link Arm Strength Based on Response Surface Method

4.1. Link arm strength reliability analysis process

Link arm strength reliability analysis steps are divided into the following two points:

1) Parameter response surface analysis

Response surface method is an optimization method that integrates experimental design and mathematical modeling. It fits the functional relationship between design variables and output results within the global scope through local test point regression, and has the characteristics of fewer test times, high precision and good prediction performance[8]. In this paper, Kriging method is used to fit the response surface. Kriging model can be regarded as an interpolation model, which combines non-parametric random process with parametric linear regression model[9,10]. The expression of the model is as follows:

$$G(x) = \Gamma(\beta, x) + z(x) = f^T(x)\beta + z(x) \quad (1)$$

Type: $f^T(x) = [f_1(x), f_2(x), \ldots, f_p(x)]^T$, β is the regression coefficient vector, $\beta = [\beta_1, \beta_2, \ldots, \beta_p]^T$, $\Gamma(\beta, x)$ Is a polynomial regression model, $z(x)$ is a random Gaussian process with variance σ^2 and mean zero. Classical Kriging model Common functional models include Gaussian model, exponential model, spline model, linear model, etc. The most commonly used one is Gaussian model (y) :

$$\mathbb{R}(x_i, x_j; \theta) = \prod_{m=1}^{M} \exp[-\theta_m (x_i^m - x_j^m)^2] \quad (2)$$

Type: m first M-delements for the input vector, θ for the parameter vector, $\theta = [\theta_1, \theta_2, \ldots, \theta_m]^T$, M for total dimension of input vector.

Define the correlation matrix $R(x_i, x_j; \theta)_{N0 \times N0}$, then the estimated values of β and σ^2 are:

$$\hat{\beta} = (F^T R^{-1} F)^{-1} F^T R^{-1} G \quad (3)$$

$$\hat{\sigma}^2 = argmax(-N_0 \ln(\hat{\sigma}^2) - \ln(|R|)) \quad (4)$$

At this time, the variance and mean of the predicted value of the prediction point x are:

$$\begin{cases} \mu_{G(x)}(x) = \hat{\beta} + r(x)R^{-1}(G - \hat{\beta}F) \\ \sigma_G^2(x) = \sigma^2(x)(1 - \mu^T(x)(F^T R^{-1} F)^{-1}\mu(x) - r^T(x)R^{-1}r(x)) \end{cases} \quad (5)$$

Type: r(x)= $[\mathbb{R}(x\ \ , x_1; \theta, x\ \ , x_2; \theta, \ldots, x\ \ , x_{N_0}; \theta)]$, $\mu_{G(x)}(x)$is treated as the predicted value of point X.

2) Reliability analysis

The calculation of strength reliability is usually based on the stress-strength interference model[11], and its schematic diagram is shown in Figure 4:

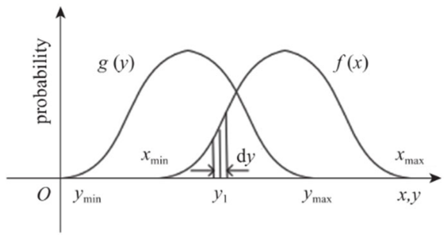


Figure 4. Schematic diagram of interference model

Its functional functions are:

$$G(z) = f(x) - g(y) > 0 \quad (6)$$

Type：f(x) is the strength of the part, and g(y) is the stress on the part. If f(x) and g(y) both follow a normal distribution, then:

$$R = \frac{1}{\sqrt{2\pi}\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{z-\mu_z}{\sigma_z}\right)^2\right] \quad (7)$$

Then the reliability can be expressed as:

$$R = P(z > 0) = \int_0^{\infty} \frac{1}{\sqrt{2\pi}\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{z-\mu_z}{\sigma_z}\right)^2\right] dz \quad (8)$$

If $\mu = (z - \mu_z)/\sigma_z$, then:

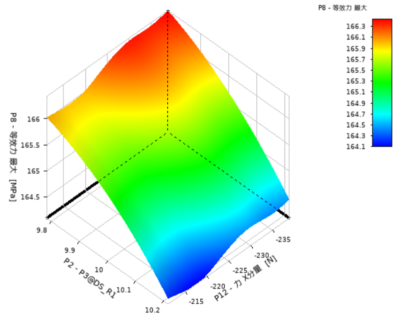
$$R = P(z > 0) = \int_0^{\infty} \frac{1}{\sqrt{2\pi}\sigma_z} \exp\left[-\frac{1}{2}u^2\right] du = \phi(\beta) \quad (9)$$

$$\beta = \frac{\mu_z}{\sigma_z} = \frac{\mu_0 - \mu_u}{\sqrt{\sigma_0^2 - \sigma_u^2}} \quad (10)$$

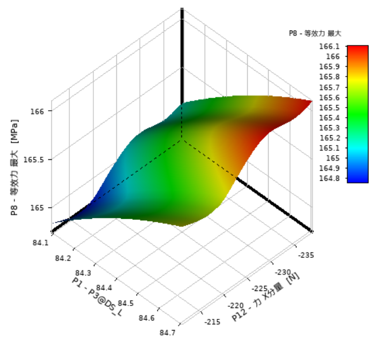
Type：β is the strength reliability index, μ_u and σ_u are the mean and standard deviation of input variables, and μ_0 and σ_0 are the mean and standard deviation of output variables.

4.2. Parameter response surface analysis

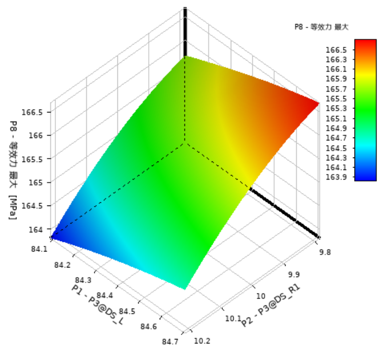
Taking the maximum equivalent stress of the link arm of the microsphere focused logging tool pushing system as the output variable, the three parameters of link arm rod length (p1), pin hole diameter at the lower end of link arm (p2) and the x-axial force on the pin hole at the lower end of link arm (p12) were selected as the input variables, and the rod length, pin hole diameter and load on the link arm were selected as the input variables. The influence of input variables on output variables is shown in Figure 5:



(a) p2, p12 and p8 response surfaces



(b) p1, p12 and p8 response surfaces



(c) p1, p2 and p8 response surfaces

Figure 5. Response surface of random variables to output parameters

It is easy to see from the response analysis diagram of the maximum equivalent stress that the above three random variables have different degrees of influence on the maximum equivalent stress of the link arm. The length of the link arm (p1) is negatively correlated with the maximum equivalent stress of the link arm, while the diameter of the pin hole at the lower end of the link arm (p2) and the x-axial force on the pin hole at the lower end of the link arm (p12) are positively correlated with the maximum equivalent stress of the link arm. The maximum equivalent stress is minimum when the length of the link arm is minimum and the diameter of the pin hole at the lower end of the link arm and the axial force of the pin hole X are maximum.

4.3. Reliability Analysis

In the Six Sigma module of ANSYS Workbench, the probability value corresponding to a certain fixed value can be intuitively obtained by analyzing the probability distribution table. The probability distribution table of the maximum equivalent stress of the link arm is shown in Figure 6.

	A	B	C
1	P8 - 等效应力 最大 (MPa)	概率	西格玛水平
2	177.83	0.99993	3.8106
3	176.85	0.9995	3.2889
4	175.88	0.99903	3.0991
5	175	0.9981	2.8948
6	173.94	0.99389	2.5055
7	172.97	0.9868	2.2203
8	171.99	0.97498	1.9597
9	171.02	0.9529	1.6736
10	170.05	0.91708	1.3857
11	169.08	0.86317	1.0947
12	168.11	0.7896	0.80503
13	167.13	0.69531	0.51097
14	166.16	0.58299	0.20956
15	165.19	0.4666	-0.083832
16	164.22	0.35688	-0.36681
17	163.25	0.25779	-0.65016
18	162.27	0.17484	-0.93522
19	161.3	0.11187	-1.2166
20	160.33	0.063551	-1.5256
21	159.36	0.035639	-1.8037
22	158.39	0.018257	-2.0912
23	157.42	0.0089689	-2.3669
24	156.44	0.0033283	-2.7135
25	155.47	0.0012886	-3.0141
26	154.5	0.00048142	-3.3012
27	153.53	0.00019027	-3.5532
28	152.56	6.9312E-05	-3.8106
*			

Figure 6. Table of maximum equivalent stress distribution of link arm

It can be seen from Figure 6 that the probability that the maximum equivalent stress of the link arm is less than 177.83MPa is 0.99993. According to the experience, the design maximum allowable stress of the link arm is 175MPa, and the strength reliability of the link arm is 0.9981. Take the variation coefficient of the maximum equivalent stress of the link arm as 0.02, and bring it into equation (9) and (10) to calculate $\beta=1.946$, $R=0.99813$, which is basically consistent with the corresponding probabilities in the probability sub-table, indicating that the simulation results are correct.

4.4. Closing remarks

Aiming at the microsphere focused logging tool push-pull system, this paper conducts static analysis of the push-pull system under working conditions, and on this basis carries out uncertainty analysis. Based on the analysis results, reliability analysis is carried out and the maximum equivalent stress probability distribution table of the link arm of the push-pull system is obtained. The research shows that:

1. The maximum equivalent stress occurs in the link arm of the microsphere focused logging tool push-back system under working condition;

2. When the maximum allowable stress is 175MPa, the strength reliability of the link arm is 0.9981, indicating that the strength reliability of the link arm is high and can meet the current logging requirements, but there is still much room for improvement.

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