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Reliability analysis of marine oil hose fatigue testing machine

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ABSTRACT

The reliability analysis is one of the most important procedures in the design of the oil hose fatigue testing machine. In this study, the reliability of fatigue testing machine was calculated using the finite element and probability method. In this process, the most dangerous point was confirmed using static analysis and transient analysis of finite element, the equivalent stress mean and standard deviation were worked out by radius vector method, the reliability of fatigue testing machine was calculated by probability method. The results showed, this fatigue testing machine can meet the safety and reliability requirements.

KEYWORDS

Fatigue testing machine; Reliability; Marine oil hose; Radius vector method; Probability method.

INTRODUCTION

Marine oil hose fatigue testing machine is engineering equipments of carrying out fatigue test to marine oil hose, which is subjected to bending load as well as tensile load. Its reliability directly affects the test results of marine oil hose, so the reliability analysis should be as an important procedure in the design of marine oil hose fatigue testing machine.

At present, there are many research methods about the reliability of fatigue testing machine. LING Jing, GAO Zhen-tong proposed two-dimensional model of stress-strength interference based on one-dimensional interference model, which was used to analyzed fatigue reliability of mechanical structure[1]. JIANG Xiang-hua etc presented a numerical approach of calculating fatigue reliability of mechanical structure[2]. XIONG Jun-jiang etc analyzed structure fatigue reliability of mechanical structure under high frequency and low load using two-dimensional model of stress-strength interference[3]. ZHANG Yu etc posed a new calculating method of fatigue life based on P-S-N curse[4]. GUO Sheng-jie etc built stress intensity factor model of structure components fatigue reliability through analyzing material instantaneous crack length and distribution of stress intensity factors[5]. Wellstream company established a horizontal fatigue test equipment in outdoor, verified its reliability through the experiment[6]. Shanghai Jiao

Tong University built the horizontal riser fatigue test device in 2011, this device completed a full scale fatigue test of top tensioned riser commissioned by CNOOC during the period of "11th Five-Year Plan ", which verified reliability of experiment equipment[7]. Tang De-yu developed full-scale fatigue testing machine for marine pipeline and studied reliability by finite element analysis (FEA) software, This testing machine can finish coordination test of three or four points bending fatigue and internal pressure fatigue[8].

This paper analyzed the reliability of fatigue testing machine under multiaxial stress state based on Goodman stress diagram and the fourth strength theory.

THE PRINCIPLE OF RELIABILITY ANALYSIS OF FATIGUE TESTING MACHINE BASED ON FEA

Establishment of finite element model

SOLIDWORKS software was chosen to complete modeling and virtual assembly of main components in the establishment of marine oil hose fatigue testing machine model, after completing static interference check, model was incorporated into ANSYS software by special interface between SOLIDWORKS and ANSYS and analyzed by ANSYS software[9]. In order to ensure the correctness of FEA results, the finite element model must conform to the actual situation of fatigue testing machine as far as possible.

Determination of the most dangerous point and the maximum stress through the finite element static analysis

The dangerous points in the model were determined through the finite element static analysis; then transient dynamics analysis of fatigue testing machine in a cycle was carried out, the equivalent stress of the danger point varying with time was got; at last, the most serious point of stresses variation in the dangerous points was confirmed, which was the most dangerous point; so maximum stresses of this point $\sigma_{\max}$、 $\sigma_{\min}$、 $\tau_{\max}$、 $\tau_{\min}$ were obtained.

Calculation of the mean and standard deviation of equivalent stress radius of the most dangerous point

The average stress σ_m、 τ_{m} and stress amplitude σ_{a}、 τ_{a} were calculated according to the maximum stress of the most dangerous point, and the mean and standard deviation of average stress and stress amplitude were got according to the formula (1)-(4).

$$\bar{\sigma}_m = \frac{\bar{\sigma}_{\max} + \bar{\sigma}_{\min}}{2} \quad S_{\sigma_m} = \frac{\sqrt{S^2_{\sigma_{\max}} + S^2_{\sigma_{\min}}}}{2} \tag{1}$$

$$\bar{\tau}_m = \frac{\bar{\tau}_{\max} + \bar{\tau}_{\min}}{2} \quad S_{\tau_m} = \frac{\sqrt{S^2_{\tau_{\max}} + S^2_{\tau_{\min}}}}{2} \tag{2}$$

$$\bar{\sigma}_a = \frac{\bar{\sigma}_{\max} - \bar{\sigma}_{\min}}{2} \quad S_{\sigma_a} = \frac{\sqrt{S^2_{\sigma_{\max}} + S^2_{\sigma_{\min}}}}{2} \tag{3}$$

$$\bar{\tau}_a = \frac{\bar{\tau}_{\max} - \bar{\tau}_{\min}}{2} \quad S_{\tau_m} = \frac{\sqrt{S^2_{\tau_{\max}} + S^2_{\tau_{\min}}}}{2} \tag{4}$$

The mean and the standard deviation of equivalent stress of the most dangerous point can be calculated by the formula (5)-(6):

$$\bar{\sigma}_{me} = \sqrt{\bar{\sigma}^2_m + 3\bar{\tau}^2_m} \quad S_{\sigma_{me}} = \sqrt{\frac{\bar{\sigma}^2_m S^2_{\sigma_m} + \left(\sqrt{3}\bar{\tau}_m\right)^2 \left(\sqrt{3}S_{\tau_m}\right)^2}{\bar{\sigma}^2_m + \left(\sqrt{3}\bar{\tau}_m\right)^2}} \tag{5}$$

$$\bar{\sigma}_{ae} = \sqrt{\bar{\sigma}^2_a + 3\bar{\tau}^2_a} \quad S_{\sigma_{ae}} = \sqrt{\frac{\bar{\sigma}^2_a S^2_{\sigma_a} + \left(\sqrt{3}\bar{\tau}_a\right)^2 \left(\sqrt{3}S_{\tau_a}\right)^2}{\bar{\sigma}^2_a + \left(\sqrt{3}\bar{\tau}_a\right)^2}} \tag{6}$$

where S_{σ_m}、S_{τ_m}、S_{σ_a}、S_{σ_a} is respectively standard deviation of the average stress σ_m、τ_m and stress amplitude σ_a、τ_a of the most dangerous point.

According to the formula (5), (6), the reference[10], The mean and standard deviation of stress radius of the most dangerous point can be got:

$$\bar{\sigma}_R = \sqrt{\bar{\sigma}^2_{me} + \bar{\sigma}^2_{ae}} \quad S_{\sigma_R} = \sqrt{\frac{\bar{\sigma}^2_{me} S^2_{\sigma_{me}} + \bar{\sigma}^2_{ae} S^2_{\sigma_{ae}}}{\bar{\sigma}^2_{me} + \bar{\sigma}^2_{ae}}} \tag{7}$$

The mean and standard deviation of fatigue limit radius vector of fatigue testing machine

Marine Oil hose fatigue testing machine is under bending load at one end, the other end is under tensile load, so its actual stress is a simple asymmetrical cycle form, average stress has obvious influence on fatigue life, the fatigue strength at a given fatigue life often was showed by equal life curve, which was gained by fatigue test with much loading cyclic characteristics R. Because lacking 45 steel equal life curves now, simplified equal life curve-Goodman curve (as shown in Figure 1) was adopted[10].

Cyclic stress characteristics R of each dangerous point of fatigue testing machine under actual work load were adjusted as follows:

$$R_i = \frac{(\sigma_{\min})_i}{(\sigma_{\max})_i} \quad tga = \frac{\sigma_a}{\sigma_m} = \frac{1 - R_i}{1 + R_i} \tag{9}$$

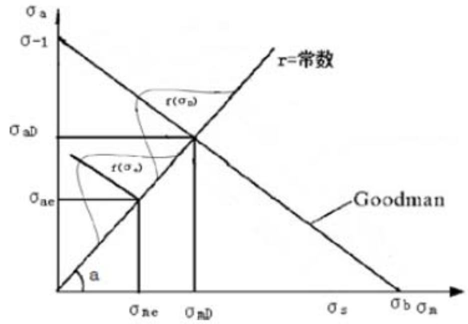


Figure 1: Equal life curve and stress- strength interference relationship

In Figure 1, Strength limit average value $\overline{\sigma}_b$ and standard deviation S_{σ_b}, fatigue limit average value $\overline{\sigma}_{-1D}$ and standard deviation $S_{\sigma_{-1D}}$ of 45# steel can be gained by literature[11], the average value and standard deviation of mean stress $\overline{\sigma}_{mD}$、the average value and standard deviation of stress amplitude can be worked out according to the Goodman curve model[12]:

Let $k = \dfrac{1+R_i}{1-R_i} = \dfrac{1}{tga}$ **(10)**

$$\overline{\sigma}_{aD} = \frac{\overline{\sigma}_{-1D}\,\overline{\sigma}_b}{\overline{\sigma}_b + k\overline{\sigma}_{-1D}} \quad \overline{\sigma}_{mD} = k\overline{\sigma}_{aD} \tag{11}$$

$$S_{\sigma_{aD}} = \frac{\sqrt{\overline{\sigma}_b^4 S^2_{\sigma_{-1D}} + k^2 \overline{\sigma}_{-1D}^4 S^2_{\sigma_b}}}{\left(\overline{\sigma}_b + k\overline{\sigma}_{-1D}\right)^2} \quad S_{\sigma_{mD}} = \frac{\overline{\sigma}_{mD} - k(\overline{\sigma}_{aD} - 3S_{\sigma_{aD}})}{3} \tag{12}$$

Mean stress、stress amplitude and standard deviation of 45# steel in formula (11), (12) were worked out using standard sample, the influence of factors such as effective stress concentration, surface processing quality and geometrical size on the fatigue limit of the most dangerous point in actual part and machine must be considered.

The effective stress concentration coefficient k_f、surface quality coefficient β and geometry dimension coefficient ε were in line with normal distribution, their mean and standard deviation were checked by literature[10], the mean and standard deviation of comprehensive effect coefficient can be calculated using these coefficients.

Fatigue limit average value $\overline{\sigma}'_{-1D}$、the mean $\overline{\sigma}'_{aD}$ and standard deviation $S'_{\sigma_{aD}}$ of stress amplitude、the $\overline{\sigma}'_{mD}$ and its standard deviation $S'_{\sigma_{mD}}$ of mean stress of fatigue testing machine taken into account comprehensive effect coefficient were respectively:

$$\overline{K}_f = \frac{\overline{\varepsilon}\overline{\beta}}{\overline{k}_f} \quad \overline{k}_f = 1 + \mu_q(k_t - 1) \tag{13}$$

$$\overline{\sigma}'_{-1D} = \overline{\sigma}_{-1D}\overline{K}_f \quad \overline{\sigma}'_{aD} = \frac{\overline{\sigma}'_{-1D}\,\overline{\sigma}_b}{k\overline{\sigma}'_{-1D} + \overline{\sigma}_b} \quad \overline{\sigma}'_{mD} = k\overline{\sigma}_{mD} \tag{14}$$

$$S'_{\sigma aD} = \frac{\sqrt{\bar{\sigma}_b^4 S^2_{\sigma_{-1D}} + k^2 \bar{\sigma}'^4_{-1D} S^2_{\sigma_b}}}{\left(\bar{\sigma}_b + k\bar{\sigma}'_{-1D}\right)^2} \quad S'_{\sigma mD} = \frac{\bar{\sigma}'_{mD} - k(\bar{\sigma}'_{aD} - 3S'_{\sigma aD})}{3} \tag{15}$$

where： $\bar{\varepsilon}$ --average value of Size coefficient

$\bar{\beta}$ --average value of surface quality coefficient

k_t --theoretical stress concentration coefficient

$\bar{k}_f$ --average value of effective stress concentration coefficient

μ_q --average value of sensitivity coefficient

$\bar{K}_f$ --comprehensive influence coefficient

The mean and standard of fatigue testing machine fatigue limit radius vector were as follows:

$$\bar{\sigma}'_{RD} = \sqrt{\bar{\sigma}'^2_{mD} + \bar{\sigma}'^2_{aD}} \quad S'_{\sigma RD} = \sqrt{\frac{\bar{\sigma}'^2_{mD} S'^2_{\sigma_{mD}} + \bar{\sigma}'^2_{aD} S'^2_{\sigma_{aD}}}{\bar{\sigma}'^2_{mD} + \bar{\sigma}'^2_{aD}}} \tag{16}$$

Reliability of fatigue testing machine

According to reliability definition, reliability was not only related to strength and average value of stress, but also was related to strength and dispersion of stress, dispersion of stress obviously decreased the machine reliability. According to stress-strength interference model, calculation formula of reliability coefficient was:

$$Z_R = \frac{\bar{\sigma}'_{RD} - \bar{\sigma}_R}{\sqrt{S'^2_{\sigma_{RD}} + S^2_{\sigma_R}}} \tag{17}$$

Reliability R of the most dangerous point was got by normal distribution table[10] and Z_R, safety and reliability analysis of marine oil hose fatigue testing machine was judged according to reliability value of the most dangerous point.

THE PRACTICAL CALCULATING EXAMPLE

The finite element model of fatigue testing machine

Marine oil hose fatigue load for each fatigue wave sea state is derived for the entire riser length as the mean and dynamic range of tension, as well as mean and range of curvature. These fatigue load were forces acting on oil hose fatigue testing machine when machine was at work which were as follows: tension (thrust) of bending hydraulic cylinder、tension (thrust) of stretching hydraulic cylinder、gravity of testing machine、gravity of oil hose and internal liquid. Fatigue testing machine structure model was shown in Figure 2, fatigue loads were shown in TABLE 1.

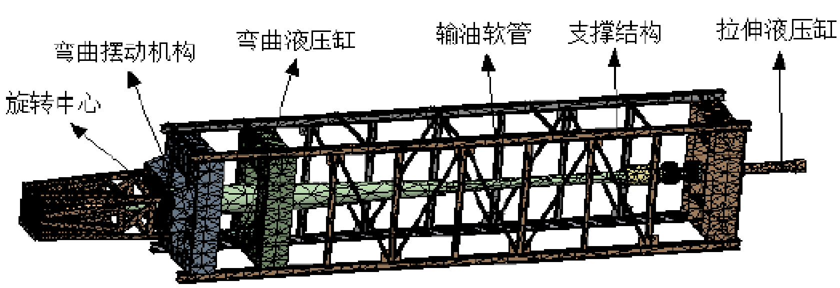


Figure 2: Structure model of fatigue testing machine

TABLE 1: Loads

cycle number	Tension (thrust) (KN)	Tension (KN)	gravity of hose (KN)	Gravity (KN)	rotation Angle（·）
155520	803	798.52	20	277.3	±19.19

Determination of the dangerous points and maximum stress by static analysis

In this static analysis, structure material is 45 steel, oil hose is Q195, these material property can be found out by literature[13], The boundary conditions and loads were set in accordance with the actual situation setting. Three points of the maximum stress were shown in Figure 3 through static analysis. The first point was on the nut between conversion head and stretching hydraulic cylinder; the second point was on the nut connecting oil hose with conversion head; the third point was on the bearing in the center of rotation. In order to verify location of three dangerous points, mesh was more elaborate, their stress was shown in TABLE 2.

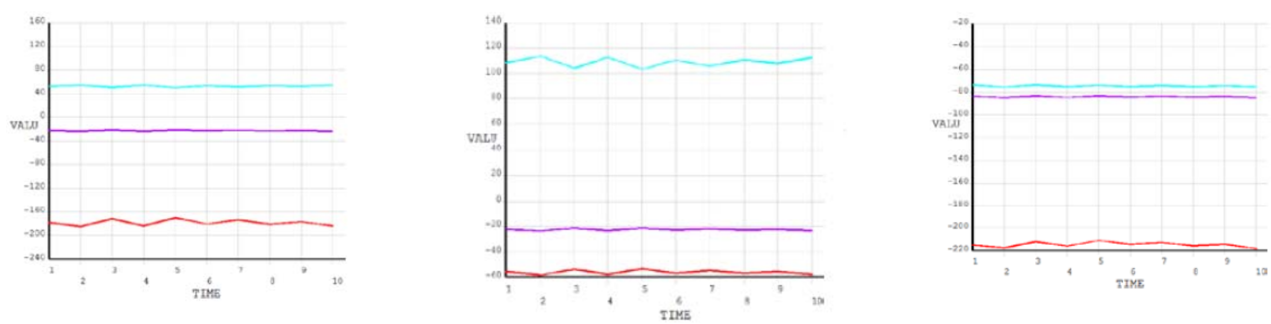
Figure 3: Three dangerous points of fatigue testing machine by static analysis

TABLE 2: Principal stress of the dangerous points

dangerous points	1	2	3
The first principal stress（MPa）	23.219	54.744	-51.676
The second principal stress（MPa）	-19.882	-2.9978	-62.903
The third principal stress（MPa）	-112.91	-51.123	-146.49

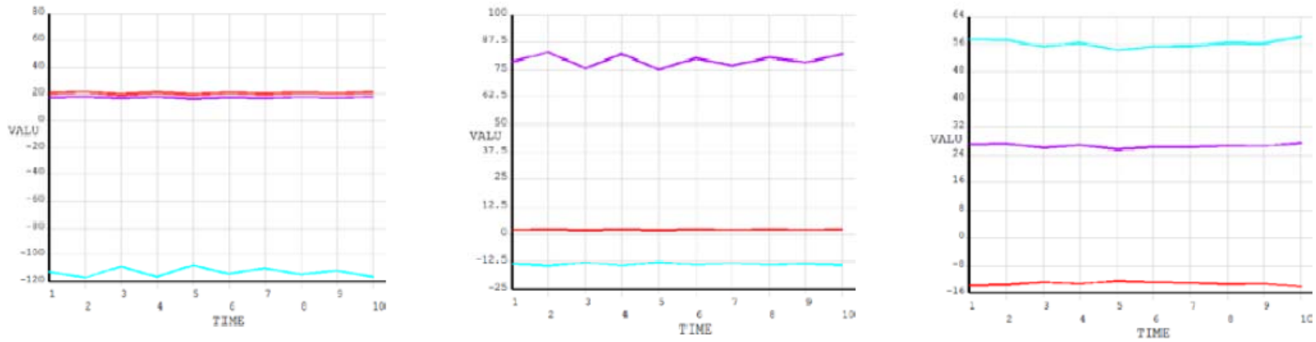
The mean and standard deviation of equivalent stress radius of dangerous points

After three dangerous points was obtained by static analysis, transient dynamics analysis was carried out in ANSYS, principal stress and shear stress curve varying with time were got and shown in Figure 4-5.



(a) The dangerous point 1 **(b) The dangerous point 2** **(c) The dangerous point 3**

Figure 4: Principal stress curve of three dangerous points



(a) The dangerous point 1 **(b) The dangerous point 2** **(c) The dangerous point 3**

Figure 5: Shear stress curve of three dangerous points

According to Figure 4, equivalent stress of the dangerous point 2 showed alternating characteristics in three dangerous points, also the dangerous point 2 had the biggest mean stress and stress amplitude, so in order to calculate reliability of fatigue testing machine, only computed fatigue reliability of the dangerous point 2. its average value of maximum stress was : $\overline{\sigma}_{\max} = 114.3MPa$、$\overline{\sigma}_{\min} = 103.2MPa$、$\overline{\tau}_{\max} = 83.1MPa$、$\overline{\tau}_{\min} = 75.1MPa$. according to formula (1) - (6), the mean and standard deviation、stress amplitude and standard deviation of the dangerous point 2 were as follows :

Average stress of primary stress $\sigma_m : (\overline{\sigma}_m, S_{\sigma_m}) = (108.8, 0.329)MPa$

Stress amplitude of primary stress $\sigma_a : (\overline{\sigma}_a, S_{\sigma_a}) = (5.6, 0.329)MPa$

Average stress of shear stress $\tau_m : (\overline{\tau}_m, S_{\tau_m}) = (79.1, 0.24)MPa$

Stress amplitude of shear stress $\tau_a : (\overline{\tau}_a, S_{\tau_a}) = (4, 0.24)MPa$

Average stress of equivalent stress $\sigma_{me} : (\overline{\sigma}_{me}, S_{\sigma_{me}}) = (175, 0.385)MPa$

Stress amplitude of equivalent stress $\sigma_{ma} : (\overline{\sigma}_{ma}, S_{\sigma_{ma}}) = (8.9, 0.384)MPa$

The mean and standard deviation of stress radius of the most dangerous point 2 can be calculated by formula（7） :

$$\overline{\sigma}_R = 175.23MPa \quad S_{\sigma_R} = 0.385MPa$$

The mean and standard deviation of fatigue limit radius vector of fatigue testing machine

According to actual loads of the most dangerous point 2, theory and actual stress of this point were respectively: $\sigma_{\max} = 135.5MPa$ 、 $\sigma_{\min} = 45.7MPa$,

According to formula (9)、(10): $R_2 = 0.34 \quad tga = 0.49 \quad k = 2.04$.

Based on the literature[11], the mean and standard deviation of 45 steel strength limit $\overline{\sigma}_b = 833.6MPa$ and $S_{\sigma_b} = 8.336MPa$ 、 the mean and standard deviation of fatigue limit $\overline{\sigma}_{-1D} = 279.5MPa$ and $S_{\sigma_{-1D}} = 8.169MPa$. Based on the formula（11） -（12）, the mean and standard deviation of the average stress 、 the mean and standard deviation of stress amplitude of fatigue limit of 45 steel were calculated:

Fatigue limit average stress of 45 steel $\sigma_{mD} : (\overline{\sigma}_{mD}, S_{\sigma_{mD}}) = (338.6, 6.03)MPa$

Fatigue limit stress amplitude of 45 steel $\sigma_{aD} : (\overline{\sigma}_{aD}, S_{\sigma_{aD}}) = (166, 2.96)MPa$

Because the fatigue testing machine was under tension or compression bending loading, ultimate strength $\sigma_b = 710MPa$, each coefficient value was obtained according to literature[9]: $\overline{\varepsilon} = 0.73$、$S_\varepsilon = 0.04188$, $\overline{\beta} = 0.9668$, $S_\beta = 0.04188$, $\mu_q = 0.7332$, $S_q = 0.0317$, $k_t = 2$

The following values were calculate by taking these coefficient into formula（13）-（15）：

Comprehensive influence coefficient：$\overline{K}_f = 0.41$

Fatigue limit average value of fatigue testing machine：$\overline{\sigma}'_{-1D} = 114.6MPa$

Fatigue limit mean stress of fatigue testing machine $\sigma'_{mD} : (\overline{\sigma}'_{mD}, S'_{\sigma_{mD}}) = (182.6, 10.2)MPa$

Fatigue limit stress amplitude of fatigue testing machine $\sigma'_{aD} : (\overline{\sigma}'_{aD}, S'_{aD}) = (89.5, 4.99)MPa$

The mean and standard deviation of fatigue limit radius in the most dangerous point 2 of fatigue testing machine were calculated by formula (16)：

$\overline{\sigma}'_{RD} = 203.4 \quad S'_{\sigma RD} = 9.4$

Reliability of fatigue testing machine

According to formula (17), reliability coefficient was:

$$Z_R = \frac{\overline{\sigma}'_{RD} - \overline{\sigma}_R}{\sqrt{S'^2_{\sigma_{RD}} + S^2_{\sigma_R}}} \frac{203.4 - 175.23}{\sqrt{9.4^2 + 0.385^2}} = 2.994$$

Reliability of the most dangerous point 2 can be obtained by normal distribution table [8]: $R = 0.998605$. Because this point was the most dangerous point in marine oil hose fatigue testing machine, and the reliability R>0.99, judged by these facts, Fatigue testing machine is reliable.

CONCLUSIONS

The paper illustrated the theory of calculating fatigue testing machine reliability using the finite element and probability method, and got the reliability of fatigue testing machine by combining the two methods. The result showed that the structure of the marine oil hose fatigue testing machine is reasonable and reliability is high, so this fatigue testing machine can meet the safety requirements.

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