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Fatigue Life Prediction of Mooring Chains for a Floating Tidal Current Power Station

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Abstract: As a kind of clean and renewable energy, tidal current energy is becoming increasingly popular all over the world with the shortage of energy and environmental problems becoming more and more severe. A floating tidal current power station is a typical type of tidal current power transformers which can sustain the loads of wind, waves, and current, and even the extreme situation of a typhoon. Therefore, the mooring system must be reliable enough to keep the station operating normally and to survive in extreme situations. The power station examined in this paper was installed at a depth of 40 m. A 44 mm-diameter R4-RQ4 chain was chosen, with a 2 147 kN minimum break strength and 50 kN pretension. Common studless link chain was used in this paper. Based on the Miner fatigue cumulative damage rule, S-N curves of chains, and MOSES software, a highly reliable mooring system was designed and analyzed. The calculation results show that the mooring system designed is reliable throughout a 10-year period. It can completely meet the design requirements of American Petroleum institution (API). Therefore, the presented research is significant for advancing the design of this kind of power station.
Keywords: floating tidal current power station; mooring system; mooring chain; fatigue analysis
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1 Introduction

With the decreasing supply of land-based oil and gas, more and more attention is paid to the wide ocean energy. The ocean not only provides mankind with a shipping channel, aquatic products, and mineral resources, but also holds enormous energy. Theoretically, the ocean contains 76.6billion kW of renewable energy, including about 64million kW of available energy (Zhang, 1987; Krock, 1989; NERL, 1997), according to the Non-Nuclear Energy Program (1996) supported by the European Commission. Tidal current energy as a kind of clean, non-polluted, and renewable ocean energy has become a hot topic worldwide. The development of tidal current energy offers a way to solve the problem of energy shortage.

Based on different supporting platforms, the tidal current power station (TCPS) can be classified as a floating station, semi-submersible station, and submersible tidal current power station. In China, Zhejiang province is rich in tidal current energy, but the sea depth is deep and the seabed is composed mostly of stones, so the floating system is preferable, as shown in Fig.1. One of the factors that restrict the development of the TCPS is the reliability and viability of the mooring system. During the whole life of the TCPS, the power station will suffer the loads of wind, waves, and current, and possibly even the extreme situation of typhoons, so the mooring system must be reliable enough to keep the station operating normally.

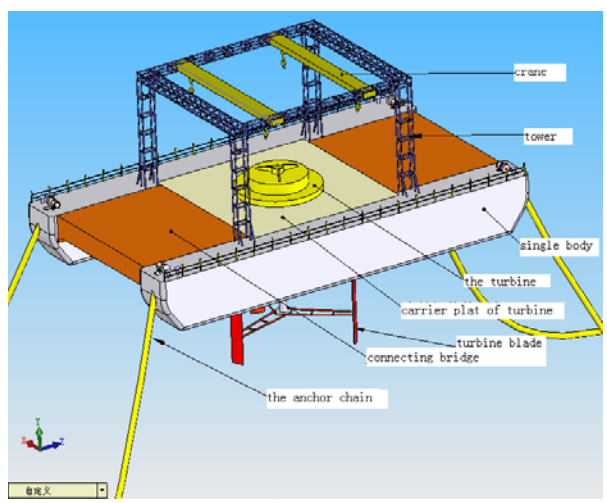

Fig.1 Floating tidal current power station

Larsen and Mathisen (1996) used reliable-based fatigue analysis method to analyze the mooring line. The result show that the method is effective to get the safety cycle number. Geir and Moan (1997) used the reliable-based fatigue analysis method which considered the uncertainty of the load to analyze the mooring line. Vazquez-Hernandez *et al.*(1998) studied the fatigue life of a floating production system (FPS)

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with different method. Gao and Moan (2006) studied the combined fatigue damage due to the low-frequency and wave-frequency tension. Liu *et al.*(2006) applied the spectral method to the fatigue analysis which can help engineers platform spectral fatigue analysis quickly and accurately. Zhang *et al.*(2012) studied a nonlinear restoring effect study of mooring system and its Application. Cao (2007) give some predietions on the Project of 130 kW TCPS mooring system.

In recent years, most research on the mooring system is concentrate in the hydrodynamic aspect. Rarely of them pay enough attention to the fatigue performance. For TCPS, the fatigue performance is a very important factor to predict its serve life. The TCPS should be running as much as possible to ensure its economical efficiency. A high-efficiency mooring system with a high reliability is contrived in this paper for a floating tidal current power station. There are three kinds of mooring systems used in ocean engineering – catenary mooring, taut mooring, and tension leg mooring. The traditional catenary mooring is studied in this paper.

Based on the Miner fatigue cumulative damage rule, the strength of the mooring system is analyzed. A chain-only mooring system is wearable, and has an appropriate breaking strength, so it is chosen in this paper. The pre-tension T_0=50 kN is set for the project and the equipment. In order to begin the calculation, full data is needed, including the depth of the water, the characteristics of the waves, wind, current, length, and characteristics of the mooring chain. With all data integrated, MOSES is used to calculate the fatigue life of the mooring system. The method used in this paper would cover both time and frequency domain calculation. Compared with the life of a 10-year power station, the fatigue life of the mooring system will be longer based on a safety coefficient – 3, which means 30 years. The calculation results show that the reliability of the mooring system is satisfactory. In a 10-year period, the fatigue strength is more than adequate for what is needed. It can completely meet the design requirements. This research is very important for the design and application of floating tidal current energy.

2 Basic theories of the fatigue analysis of the mooring chain

Many parts may fail in service due to fatigue failure caused by repeated cyclic loading. In practice, loads significantly below static limits can cause failure if the load is repeated a sufficient number of times. Characterizing the capability of material to survive the many cycles that a component may experience during its lifetime is the aim of fatigue analysis (Ma and Li, 1996).

2.1 Miner fatigue cumulative damage theory

The recommended procedure of fatigue analysis by API (API RP 2SK, 2005) is as follows:

1) The probability of each condition should be given. Usually, 8-12 relative directions can indicate the long-term environment direction distribution well. The number of sea conditions needed is 10-50.

2) Wave frequency tension and low frequency tension is calculated by the position of the mooring system working under the mean load.

3) M, the slope of the S-N curve and *K,* and the intercept of S-N curve can be gotten from API RP 2SK.

4) The annual fatigue damage caused by wave frequency tension and low frequency tension under one condition can be calculated by the method recommended in API RP 2SK.

5) Repeat step 4, calculate all the data that is needed by formulae (2) and (3).

The S-N equation applied:

$$NR^M = K \tag{1}$$

where N is the number of cycles; R the ratio of tension range to nominal breaking strength; M the slope of S-N curve which is 3 here; K the intercept of S-N curve which is 316 here.

This equation can be used for calculating the nominal tension failure lives of the chain.

The anchor chain’s fatigue life is evaluated through the long-periodic cycle load working on the anchor chain and the ability to resist fatigue damage to the anchor chain. The time-domain method and frequency-domain method are combined to handle the fatigue caused by the wave frequency tension and low frequency tension. Normally, fatigue design may be carried out by methods based on fatigue tests (S-N data) and estimation of cumulative damage (Palmgrens-Miner rule). The S-N curves are obtained from tests in this method. The expression of the cumulative fatigue damage ratio calculated by the Miner fatigue cumulative damage rule is:

$$D = \sum \frac{n_i}{N_i} \tag{2}$$

where n_i is the number of cycles within the tension range interval ***I***; N_i the number of cycles to failure in a tension range i as given by the appropriate S-N curve.

Designed fatigue life (1/D) must be longer than the given serving life multiplied by the security factor. The previous fatigue damage should be considered if the second-hand anchor chain is used. Annual fatigue damage D is the cumulative result of the cyclic loading working on the chain i. The expression is:

$$D = \sum_i^n D_i \tag{3}$$

where D_i is the annual fatigue damage ratio of the chain under the sea state i.

If the annual fatigue damage from one environment condition

(one sea-state in one direction) due to both low frequency and wave frequency tension is computerized, three methods can be considered for combining fatigue damage due to the low-frequency and wave-frequency tension, as follows:
1) Simple summation method.
2) Combined spectrum.
3) Time domain cyclic counting.

Method 3 is considered to be more precise but is not an efficient approach for design. Method 1 will generally give an acceptable estimate of fatigue life. However, this method may underestimate fatigue damage when low-frequency tension and wave-frequency tension have a significant contribution to the fatigue damage. Method 2 is always conservative and may significantly overestimate the actual fatigue calculation. There is a method that improves method 2 with a factor. But it still overestimates the actual fatigue damage when low-frequency tension has a significant effect.

A simple summation method is introduced in this paper:

Wave-frequency and low-frequency fatigue damage are estimated by Eq.4, which is based on Rayleigh Distribution of tension peaks.

$$D_i = \frac{n_{Wi}}{K}\left(\sqrt{2}R_{W\sigma i}\right)^M \cdot \Gamma\left(1+M/2\right) + \frac{n_{Li}}{K}\left(\sqrt{2}R_{L\sigma i}\right)^M \cdot \Gamma\left(1+M/2\right) \tag{4}$$

where, D_i is the annual fatigue damage from wave frequency and low-frequency tensions; n_{wi} the number of wave frequency tension cycles per year; $R_{w\sigma i}$ the ratio of RMS wave frequency tension range to a reference breaking strength. The RMS tension range should be taken as twice of the RMS tension; Γ the Gamma function; n_{Li} the number of low-frequency tension cycles per year; R_{Li} the ratio of the RMS low-frequency tension range to a reference breaking strength. The RMS tension range should be taken as twice the RMS tension.

The condition number i must be given in detail to avoid serious mistakes. Usually, 8-10 relative directions can perform the long-term environment direction distribution very well. The condition number that is needed will be 10–50. Each condition should contain the size and direction of the wind, waves, and flow in order to calculate the response amplitude operators (RAO) of the mooring system. In addition, the probability of each condition (P_i) must be known. The fatigue life of the mooring system is calculated as follows:

$$L=1/D(\text{year}) \tag{5}$$

Annual fatigue damage of a single condition is calculated as follows:

$$D_i = \frac{n_i}{K} E\left[R_i^M\right] \tag{6}$$

M and K are given by API RP 2SK, n_i is the annual number of cycles under condition i; R is the ratio of tension range to nominal breaking strength. Where $E\ [R_i^M]$ is the expected value of the R_i^M under the condition i.

Under each condition, the annual cycle number of tension is:

$$n_i = v_i \cdot T_i = v_i \cdot P_i \cdot 3.15576\times 10^7 \tag{7}$$

where v_i is the zero up-crossover frequency of the combined spectrum; T_i the total time of condition i; P_i the probability of condition i.

Repeated with the formulas elaborated above, the fatigue life can be obtained by considering of the safety factor of 3 as defined which also considered the safety margin. According to previous research literature (API Recommend Practice 2SK, 2005), when chosing 3 as the factor of the S-N curves, calculated with the simple summation method, the result is acceptable according to reliable research.

As for the tension bending of a chain, the portion of the mooring line in direct contact with a fairlead is inspected and shifted to avoid constant bending. The diameter of the fairlead is also large enough.

2.2 MOSES introduction(MOSES Users Manual, 1989)

MOSES is used to analyze the fatigue damage of the mooring system in this paper. Before MOSES, most marine problems were considered in two steps: a simulation followed by a stress analysis. Two different programs were required. Since MOSES performs both of these analyses, one needs only a single program to investigate all aspects of the problem. Also, with MOSES, the operator is spared the agony of transferring files and of learning the idiosyncrasies of several programs.

Fatigue is a particularly complex topic, as there are several components to consider:
1) The SN curve defines the number of cycles of a given maximum stress that the material can withstand without breaking;
2) The Stress Concentration Factors (SCF) define maximum stresses in terms of the nominal ones;
3) The duration defines the lifetime history of the environment to which the structure has been exposed.

Normally the result of interest is a Cumulative Damage Ratio (CDR). This is simply a sum of the ratio of the fraction of the life used for all stress ranges. Sometimes, however, one wishes to view the loading history independently of the SN curve. Thus, MOSES has the capability for counting either load cycles or stress cycles sorted into bins. The fatigue (or cycles) can be computed for beams, plates, tubular joints, and mooring lines, and the details will vary with type. In general, one can compute fatigue in either the time or frequency domains.

3 Fatigue numerical model of the TCPS

During the process of mooring system design, the response of the operation condition and the extreme condition should be taken into account. Also, the displacement of the power station should range in a specified value. Under extreme conditions, the mooring system could ensure the survival of the power station. There are many islands around the power station. So the sea states would be very sheltered. The design in sea states is shown in Table 1.

Table 1 The environmental conditions

Condition	Wind speed /(m·s^{-1})	Wave	Current speed /(m·s^{-1})
Operating	15	Significant wave height 2 m Average period 5 s	2.0
Extreme	30	Significant wave height 4 m Average period 10 s	3.0

The depth of the water h is 40 m in the working area. The maximum tidal range Δh is 4 m. The benthal composition is bedrock. Therefore, a gravity anchor is chosen.

Considering the sea states of the power station, distribution of the mooring system is designed as seen in Fig.2.

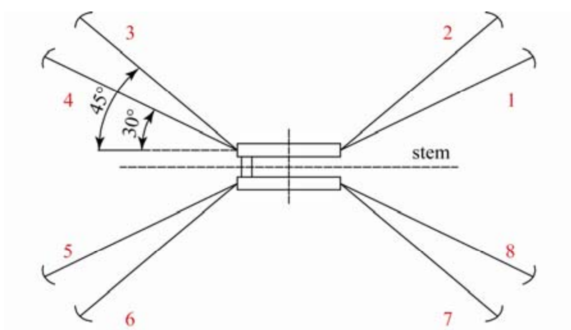

Fig.2 The distribution of the mooring system

According to the normal rule of marine engineering (API Recommend Practice 2P, 1987), the offset of the floating structure should be less than 15% of the depth of the water in operating conditions.

The limitation of tension on the anchor chain can be expressed by a percent of the minimum break strength (MBS) of the component of the anchor chain. Table 3 shows the maximum tension and the safety factor in different conditions. The extreme max tension in the mooring line is about 520 kN in operating situations, far less than the breaking strength. But when one of the mooring lines is broken, the extreme max tension will be about 1300 kN.

According to research literature (Ma and Li, 1996), when the depth of the water ranges from 25–50 m, the ratio of the length of the chain and the depth of the water will be about 3.

Table 2 The tension limitation and safety coefficient

Condition	Method	Tension limitation (%MBS)	Equivalent safety coefficient
Full	Quasi-static	50	2.0
Full	Dynamic	60	1.67
Breaking	Quasi-static	70	1.43
Breaking	Dynamic	80	1.25

There is no anchor windlass on the power station, so a pre-tension that is applied in practical engineering could not be gained. The pre-tension T_0=50 kN is decided due to the project that has been designed and the equipment that has been chosen. A 44mm chain diameter is chosen according to the environment load that has been calculated. The R4-RQ4 anchor chain is chosen due to vryhof anchor manual 2005(API Recommend Practice 2P,1987). The parameters decided on are shown as Table 3.

Table 3 Parameters of the mooring system

Type	Length /m	Diameter /mm	Degree /(°)	Pre-tension /kN	Break strength /kN
R4-RQ4	200	44	30/45	50	2147

The model that is established in MOSES is shown as Fig.3.

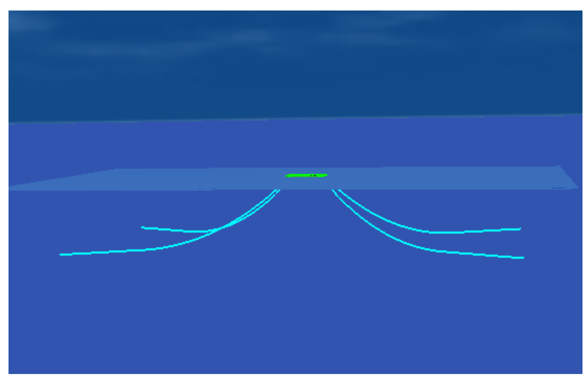

Fig.3 The model of the mooring system

Because the power station is symmetrical, only the 90, 135, 180 degrees of the wave will be taken into account when the fatigue damage is analyzed.

According to the design requirement, the life of the floating tidal current power station is about ten years, so the mooring system's life should be longer than 10 multiplied by the safety coefficient. Considering the environment data, the safety coefficient would be 3, and the time of the fatigue analysis would be 30 years. According to the actual environment load conditions, 30 sea states would be used. The specific parameters and the duration of each sea state can be seen in Table 4. The wave spectrum selected during calculation is the Jonswap wave spectrum.

Table 4 Sea states set in MOSES

Sea states	Duration /day	Direction /(°)	Significant Wave /m	Period /s
env1	0.03	180	3	7.6
env2	0.03	180	4	10
env3	0.03	90	3.8	9
env4	0.03	90	4	10
env5	0.06	135	3.2	7.8
env6	0.06	135	4	10
env7	0.07	180	2	6.4
env8	0.08	90	1.8	5.6
env9	0.1	180	1.5	5.3
env10	0.12	90	2.2	6.4
env11	0.16	135	3	7.6
env12	0.18	180	1.9	5.7
env13	0.22	90	1.5	5.3
env14	0.25	135	1.6	5.4
env15	0.42	180	1.3	5
env16	0.44	135	1.6	5.4
env17	0.5	90	1	4
env18	0.77	180	2.3	6.1
env19	0.91	90	2.2	6
env20	1.01	135	3.2	7.8
env21	1.5	180	1.6	5.4
env22	1.78	90	2.8	7
env23	1.86	135	2.5	6.8
env24	3.63	135	2.8	7
env25	4.54	180	1.5	5.9
env26	5.38	180	1.2	4
env27	5.4	90	1	4.2
env28	6.39	90	0.8	2
env29	11.01	135	0.6	3.2
env30	13.03	135	0.5	3

4 Analysis results and discussion on the fatigue life of the TCPS

According to the calculation result from MOSES, the cycle number of the tension working on each anchor chain of the mooring system in 30 years is shown in Fig.4.

Fig.4 shows the result. According to this result, the designers could calculate the fatigue life of the mooring chain. This should be an important aspect of the design of the serving time and the mooring system design.

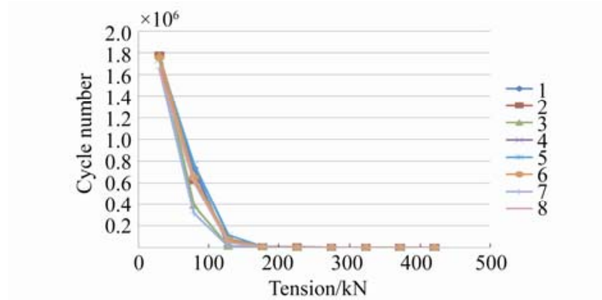

Fig.4 The cycle number of the tension

It is shown in Fig. 4 that the largest cycle number of the tension appears when the amplitude is in the range of 0 to 50 kN in every chain. Along with the amplitude increasing, the cycling times decrease.

In this project, the cumulative damage ratio D of each anchor chain during 30years operation are: 1.83×10^{-1}, 1.72×10^{-1}, 1.62×10^{-1}, 1.74×10^{-1}, 1.82×10^{-1}, 1.76×10^{-1}, 1.48×10^{-1}, 1.68×10^{-1}. Based on the damage ratio results and Eq.(3), it is concluded that the fatigue life of chain number 1 is: 30/0.183=164 (years), which is considered infinite; the same is true of the other chains. Up to this, the result indicate that the design is rational.

This paper regards the S-N curve method as reliable in predicting the fatigue life of TCPS' mooring chain according to API RP 2SK. Therefore, the fatigue life of this TCPS' mooring system completely meets the design requirements.

5 Conclusions

Fatigue failure has been an important issue for offshore structure for a long time. Certainly, it is important to TCPS' mooring system, which determines the life of the TCPS. Method used in this paper recommended by API RP 2SK could be regarded as a reliable method.

Based on the Miner fatigue cumulative damage rule, the chosen mooring system was analyzed using MOSES software in this paper. According to the rules of API RP 2SK, the fatigue life of the mooring system calculated completely meets the design requirements.

The fatigue life of the mooring system should be 3 times longer than the life of the TCPS according to the factor of safety given by the API Recommend Practice 2SK(API Recommend Practice 2SK, 2005). The reliability of the mooring system is of significance to the TCPS. This research is very important for the design and application of a floating tidal current power station.

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