Fatigue Analysis Method of Steel Containment of Floating Nuclear Power Plant

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Abstract. Floating nuclear power plant (FNPP) is a movable nuclear power plant built on the floating platform, which can provide clean and stable power for remote coastal areas, and are currently a hot research topic in the field of nuclear power. The steel containment is located in the reactor compartment of the FNPP and it is an important safety guarantee structure. Fatigue and fracture have been an important issue for ship and offshore structures for a long time. Fatigue failure of containment will have serious consequences.

In order to research the fatigue life analysis method of steel containment of the first FNPP in China, the paper adopts miner linear cumulative damage theory and spectral analysis method, based on the American Society of Mechanical Engineers (ASME) standards and relevant standards of China Classification Society (CCS), and uses AQWA to analyze Wave load of FNPP. The hydrodynamic calculation results are imported into finite element model to analyze the structural response of each point of containment, and calibrate the transfer function data of each key point by using the linear system theory and regular wave periodic evaluation method. The fatigue analysis of each point is carried out according to the transfer function and the wave dispersion diagram drawn by the forty years monitoring sea conditions of the working sea area of the FNPP. The result shows that the fatigue life of steel containment is superior and meets the service requirements.

Keywords: Floating nuclear power plant · Containment vessel · Fatigue analysis · Transfer function · Regular wave simulation method

1 Introduction

With the continuous adjustment and optimization of China's energy structure and the continuous promotion of the strategy of strengthening the country through the sea, it is increasingly difficult for traditional fossil energy sources as well as emerging energy sources such as wind, wave and solar energy to meet the energy demand brought by the development of coastal oil and gas resources and islands. Offshore floating nuclear power plant refers to a movable floating marine platform equipped with nuclear reactor and power generation system, which is a product of the organic combination of mobile small nuclear power plant technology and ship and marine engineering technology. As

C. Liu (Ed.): PBNC 2022, SPPHY 283, pp. 1046–1059, 2023.
https://doi.org/10.1007/978-981-99-1023-6_88

early as in the 1970 s, researchers in the United States proposed the idea of floating nuclear power plants [1], and the world's first floating nuclear power plant 'Akademik Lomonossov' was also launched in Russia in 2016 [2]. In floating nuclear power plants, a sealed steel containment structure is usually installed to wrap around the reactor and other auxiliary power generation equipment structures to protect the reactor from normal operation as well as to protect the external environment. Compared to traditional onshore containment, the environment and loads on the small steel containment and support structure of an offshore floating nuclear power plant are very different, especially because the complexity of the marine environment leads to more complex loads on the containment and support structure.

The alternating loads caused by these complex sea conditions may cause fatigue damage to the structure and generate cracks, which in turn threaten the safety of the floating nuclear power plant structure and cause the structure to fracture when the cracks expand to a certain extent, resulting in serious accidents. Floating nuclear power plants. However, there are few studies on the fatigue of floating nuclear power plant containment. Therefore, in order to ensure the operational safety of floating nuclear power plants and protect the surrounding personnel and external environment from nuclear radiation, it is important to carry out research on the fatigue assessment method of floating nuclear power plant steel containment in marine environment to ensure the safe operation of floating nuclear power plants during the design life and reduce economic losses.

The current fatigue assessment methods for marine structures can be divided into, simplified algorithm [4], design wave method [5] and direct calculation of spectral analysis method, among which spectral analysis method has the advantages of high accuracy and can reflect the specific structural details of the ship is widely used in the field of marine engineering, previously Hadi and Yang et al. used spectral analysis method for fatigue reliability analysis of marine platforms [6, 7], Zhang et al. used the spectral analysis method to evaluate the fatigue strength of a small waterline surface catamaran [8]. In contrast, in the study of nuclear power system pressure-bearing equipment, the transient method is usually used to assess its fatigue damage because its stress response time course is easily accessible [9, 10].

In this paper, based on the above research, the fatigue reliability study of a type of floating nuclear power plant containment is carried out by combining the spectral analysis method commonly used in marine engineering with the fatigue strength analysis of floating nuclear power plant containment, while referring to ship-related codes and ASME-related codes [11], using the regular wave simulation method.

2 Fatigue Strength Spectrum Analysis Method

2.1 Spectrum Analysis Method

The FNPP has a complex working environment and is subjected to the combined action of wind, wave and current. The main part of the fatigue load that causes the fatigue failure of the containment structure of the FNPP is the wave load. The key points of evaluating the fatigue strength of the containment of FNPP are the selection of wave spectrum, the calculation of transfer function and the calculation of fatigue damage.

Spectrum analysis method is a commonly used method in ship and ocean engineering to study load and structural response. Its theoretical basis is the linear system transformation in random process theory. The method firstly obtains the power spectral density function (PSD) of the structural stress response, after that establishes the relationship between the stress response power spectral density function and the rain flow stress range distribution, and then selects a suitable S-N curve and Miner cumulative damage theory to calculate the fatigue damage of the structure (Fig. 1).

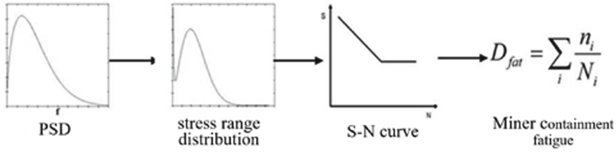


Fig. 1. Fatigue analysis flow

The FNPP can be regarded as a typical dynamic system in ships and offshore engineering structures. The wave process a acting on the hull is the input of the system, and the alternating stress B caused by the wave action in the structure is the response of the containment. In general, the relationship between the response process of the containment and the wave load input process of the FNPP can be written as:

$$X(t) = L[\eta(t)] \tag{1}$$

where, B represents the operator that transforms C into D. When e is a linear operator, the system is linear.

In the fatigue analysis of ship structure, the calculation of wave load and structural response are based on linear theory. Under this condition, if the wave is a stationary random process, the alternating stress obtained by transformation is also a stationary random process. According to the random process theory, there is the following relationship between the power spectral density functions of two stationary random processes:

$$G_X(\omega) = |H(\omega)|^2 \cdot G_\eta(\omega) \tag{2}$$

In function (2), $H(\omega)$ is a transfer function or frequency response function of linear dynamical system. $|H(\omega)|^2$ is response amplitude operator (RAO).

The physical meaning of $H(\omega)$ is the ratio of the amplitude of the response process to the amplitude of the input process when the linear dynamic system vibrates with a circular frequency of ω.

2.2 Wave Spectrum

For the spectral analysis method for fatigue assessment of ship structures, since the FNPP is located in a shallow water depth and the wave dispersion diagram is the joint distribution of meaningful wave height and spectral peak period, the improved JONSWAP spectrum is selected for analysis, and its expression is as follows:

$$S(f) = \beta_J H_{\frac{1}{3}}^2 T_P^{-4} f^{-5} \exp[-\frac{5}{4}(T_P f)^{-4}]\gamma^{\exp[-(\frac{f}{f_P}-1)^2 / 2\sigma^2]} \tag{3}$$

In function (3):

$$B_J = \frac{0.06238}{0.23 + 0.0336\gamma - 0.185(1.9 + \gamma)^{-1}}[1.094 - 0.01915 \ln \gamma]$$

γ is the crest factor, mean value is 3.3.

σ is the peak shape parameter. When the frequency is on the left side of the maximum value point, it is taken as 0.07, and when the frequency is on the right side of the maximum value point, it is taken as 0.09.

2.3 Regular Wave Simulation Method

The transfer function is determined by the system through experiments under the action of rule input or random input, or by the system's theoretical analysis of rule input. Based on the regular wave test method in the pool test, we propose the regular wave simulation method, that is, using the wave load calculation program to obtain the response of the ship motion and external hydrodynamic pressure of a series of regular waves arranged according to a certain initial phase interval under the heading angle and circular frequency. The external hydrodynamic pressure and various inertial forces related to the motion of the hull are applied to the finite element model of the hull structure to obtain the stress response. For the stress response of a series of regular waves under the heading angle and circular frequency, the maximum stress response at the point is fitted by Fourier transform, and the stress amplitude of the heading angle and circular frequency can be obtained. The value of the transfer function under the heading angle and circular frequency can be obtained by comparing the obtained stress amplitude with the wave amplitude.

2.4 Fatigue Cumulative Damage Calculation and S-N Curve

After obtaining the damage caused by each cycle, the selection of a suitable fatigue accumulation damage theory is also one of the core elements of fatigue calculation. The S-N curve and the fatigue cumulative damage analysis method of linear cumulative damage theory are commonly used to evaluate the fatigue of structures in the codes of classification societies of various countries.

When the fatigue load spectrum is expressed as a continuous probability density function corresponding to a certain period of time, the fatigue cumulative damage degree can be expressed as

$$D = \int_L \frac{dn}{N} = \int_0^\infty \frac{N_L f_S(S) dS}{N} = N_L \int_0^\infty \frac{f_S(S) dS}{N} \tag{4}$$

S is the stress range, is the probability density function of the stress range distribution, is the number of cycles required to achieve fatigue failure under a single cyclic load with a stress range of, is the total number of cycles of the internal stress range during the whole time period considered, is the number of cycles of the included stress range, and represents the integral of the whole time interval considered. According to the cumulative damage theory, when the damage degree is accumulated, the fatigue failure of the structure will occur.

The S-N curve is often used to reflect the relationship between the stress range S and the number of cycles required for the structure to achieve fatigue failure under a single cyclic load at the level of the stress range, i.e. the fatigue life n. It is generally obtained by fitting the fatigue test results. A large number of research results show that under a given stress range s, the discrete type of the parameter m is small and can be regarded as a certain value, the fatigue life n and parameter a should be treated as random variables, and it is generally considered that n obeys lognormal distribution. Expressed as

$$NS^m = A \tag{5}$$

Take logarithm on both sides of the equation

$$\lg N + m \lg S = \lg A \tag{6}$$

Equation (6) is a commonly used double log-linear model of the S-N curve. The small steel containment material studied in this paper is Steel-SA-738Gr.b. Therefore, the parameters are referred to the appendix of ASME BPVC Volume III [11].

The tensile strength of Steel-SA-738Gr.b is 585-705mpa. According to the S-N curves, the S-N curve of the material can be obtained by interpolation. The curve is transformed into a double logarithmic linear form, taking m = 3 and a = 11.464.

3 Containment Fatigue Strength Analysis

3.1 Hydrodynamic Analysis

The structural hydrodynamic model is shown in Fig. 2. The right-hand rectangular coordinate system is used. The origin is taken at the intersection of the intersection line of the longitudinal section and the middle transverse section of the platform and the base plane. The X axis is the longitudinal axis, and the point from the tail to the head is positive; Y-axis is the transverse axis, and it is positive from the centerline to the port; The z-axis is the vertical axis, and upward from the base is positive.

For model hydrodynamic analysis, AQWA software is used for hydrodynamic analysis of FNPP. During frequency domain hydrodynamic calculation, the minimum frequency of each wave direction is set at 0.01592 Hz and the maximum frequency is set at 0.27 Hz, with a total of 50 frequency points.

The frequency response curve of the longitudinal bending moment of the middle hull cross-section (x = 0.328 m cross-section) of the reactor bay at 0° wave incidence angle is shown in the following Fig. 3:

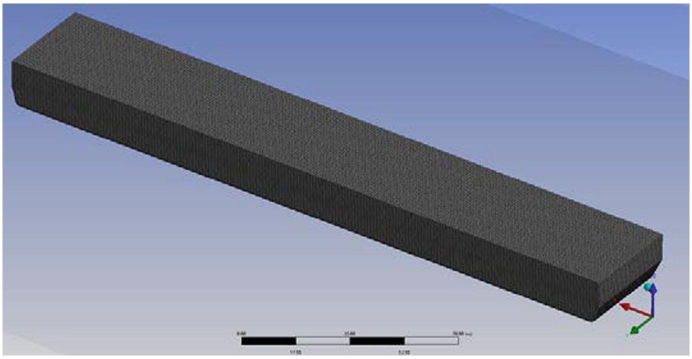


Fig. 2. Hydrodynamic model of FNPP.

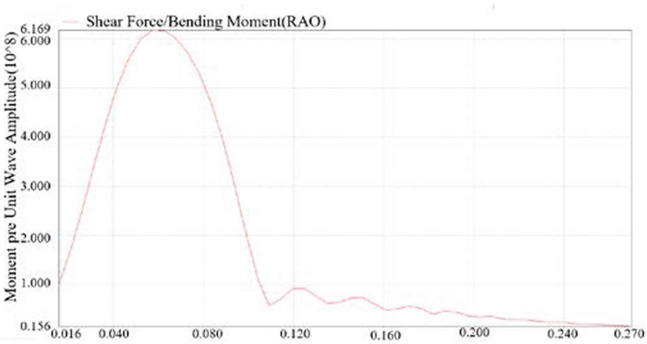


Fig. 3. Frequency response curve of longitudinal bending moment (0° wave incidence angle)

Taking 0° wave incidence angle as an example, it can be seen from the calculation results that the peak longitudinal bending moment in the transverse section of the hull in the middle of the stack is about $6.169*10^8$ N*m under 0° wave incidence angle and unit wave amplitude, and the corresponding wave frequency is 0.0574 Hz. Another longitudinal bending moment value at the waistline is $3.425*10^8$ N*m corresponding to the wave frequency of 0.03147 Hz, and the longitudinal bending moment value is $3.035*10^8$ N*m corresponds to a wave frequency of 0.0937 Hz.

3.2 Selection of Fatigue Damage Assessment Points

The finite element model of the FNPP structure is constructed with shell181 and beam188 elements. The mesh size of the bottom and supporting parts of the containment is 0.1 M, the mesh size of the upper part of the containment is 0.2 m, and the mesh size of the rest parts is 0.8 m. The total number of elements on the ship is about 1.56 million. The finite element model of the containment is shown in Fig. 4.

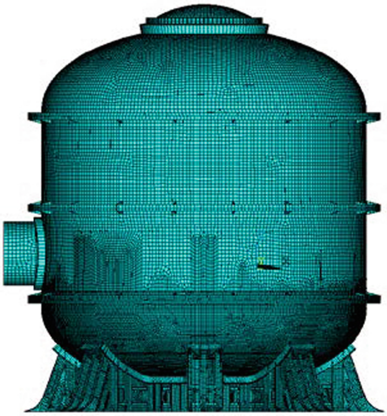


Fig. 4. Structural finite element model.

Since the spectrum analysis method needs to superimpose all working conditions and the number of structural finite element nodes is very large, according to the hydrodynamic calculation results and the longitudinal bending moment diagram, the wave load files of 0.03147 Hz, 0.0574 Hz and 0.0937 Hz in all wave directions are selected to be loaded on the whole ship finite element model of the FNPP without preload and hydrostatic pressure, and the calculation results are obtained. Select the stress concentration node as shown in Table 1:

A local refinement of the grid near the evaluation point of the model is shown in Fig. 5.

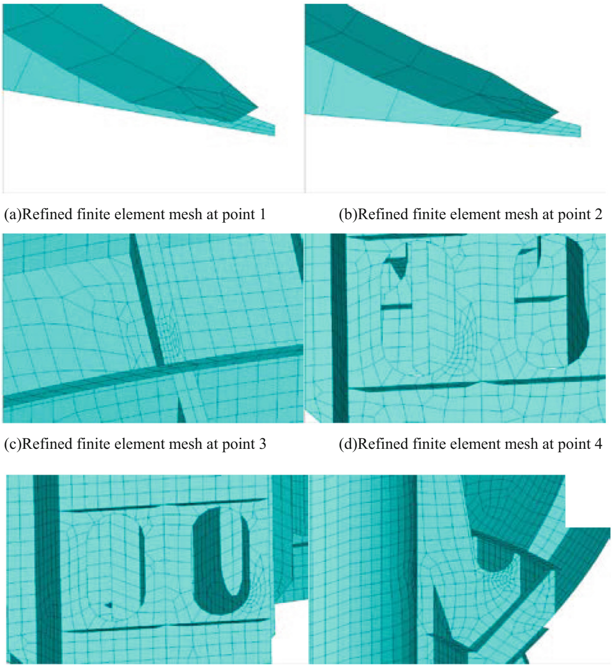
3.3 Fatigue Life of Containment

Wave scatter diagram is a common method to describe the marine environment in ship and ocean engineering. Table 2 shows the monitoring data of the nearby platform in the sea area where the floating nuclear power plant works. In the table, H_s denotes the meaningful wave height and T_p denotes the spectral peak period.

The long-term distribution of the stress range within the design life of the FNPP containment can be obtained from the short-term distribution combined with the distribution of various sea conditions that may be encountered in operation. In a given sea state, the ship may sail in any course. In the calculation, several courses are divided, and it is assumed that the probability of each course is equal.

The FNPP can set a course every 15° from 0° to 360° in the marine environment. There are 24 courses in total, and the probability of each course angle is 1/24. In order to simplify the calculation, the FNPP, as a symmetrical structure, can simplify the structural response caused by the symmetrical course. Therefore, in the actual calculation, take a course every 15° from 0° to 180°, a total of 13 courses, of which the probability of 0° and 180° is 1/24, and the probability of other courses is 1/12 (Fig. 6).

Therefore, in the regular wave experimental simulation method, AQWA software is used to calculate the response of hull motion and external hydrodynamic pressure



(a)Refined finite element mesh at point 1 (b)Refined finite element mesh at point 2

(c)Refined finite element mesh at point 3 (d)Refined finite element mesh at point 4

(e)Refined finite element mesh at point 5 (f)Refined finite element mesh at point 6

Fig. 5. Finite element refinement mesh

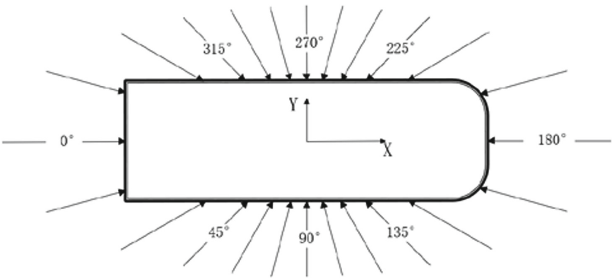


Fig. 6. Schematic diagram of wave incidence angle.

of a series of regular waves with unit wave amplitude of 1 at each heading angular circular frequency arranged at a certain initial phase interval, the phase is taken as 0° to 360° with 45° interval, 8 regular waves at each wave direction frequency, and the wave load file is extracted. The wave load is the wave surface pressure, and the wave surface pressure is mapped to the wet surface of the hull to calculate the structural response. The structural response is the response of the structure under the action of unit wave amplitude. The maximum stress value at each calculation point acting on the top of the FNPP containment is extracted and fitted using the fast Fourier transform (Fig. 7), and the stress response transfer function is obtained by dividing the magnitude of the two trigonometric functions.

Since the unit wave amplitude is 1, the fitted resulting amplitude is the stress response transfer function.

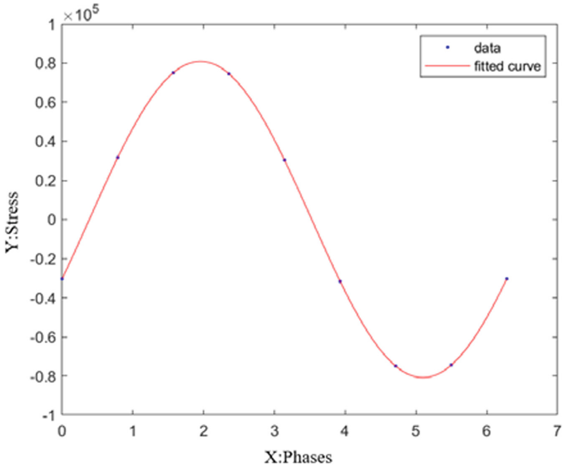


Fig. 7. Fitted curve of stress response of evaluation point 4 at 0° wave direction 0.26451 Hz.

Under the above conditions, the long-term distribution of the stress range can be expressed as a weighted combination of short-term distributions, and its distribution function is Eq. (7)

$$F_S(S) = \frac{\sum_{i=1}^{n_s}\sum_{j=1}^{n_H} v_{ij}\cdot p_i \cdot p_j \cdot F_{s\theta ij}(S)}{\sum_{i=1}^{n_s}\sum_{j=1}^{n_H} v_{ij}\cdot p_i \cdot p_j} = \sum_{i=1}^{n_s}\sum_{j=1}^{n_H} r_{ij}\cdot p_i \cdot p_j \cdot F_{s\theta ij}(S) \tag{7}$$

In Eq. (7),n_S is the total number of sea states in the sea state distribution data, n_H is the total number of divided courses, p_i is the probability of occurrence of the i-th sea state, which can be obtained according to the frequency of occurrence of each sea state in Table 3;p_j is the frequency of occurrence of the j-th heading. v_{ij} is the average zero crossing rate of stress alternating response under the i-th sea state and the j-th heading.v_0 is the total average zero crossing rate of stress response considering all sea conditions and heading.

$$v_0 = \sum_{i=1}^{n_s}\sum_{j=1}^{n_H} v_{ij}\cdot p_i \cdot p_j \tag{8}$$

Table 1. Fatigue damage point calculation number and location.

Evaluation point	Location
1	Containment bottom support
2	Containment bottom support
3	T-section at bottom of containment
4	Containment bottom support
5	Containment bottom support
6	Containment pressurizer reinforcing rib

3.4 Containment Fatigue Life Correction

In addition to the influence of marine environmental load on the structure, the marine environmental conditions also have a great impact on the fatigue performance of materials, mainly in the form of corrosion. *Fatigue strength guide for hull structures (2021)* of CCS [12] stipulates that for the normal bending stress of hull girder during simplified stress analysis and the hot spot stress under overall load conditions during finite element stress analysis, the corrosion correction factor $f_{cl} = 1.05$;

For the bending normal stress under lateral load in simplified stress analysis and the hot spot stress under local load in finite element stress analysis, the corrosion correction factor $f_{cl} = 1.1$.

In the direct calculation method of fatigue assessment, the fatigue safety factor needs to be superimposed for calculation. In this regard, *GUIDELINES FOR FATIGUE STRENGTH ASSESSMENT OF OFFSHORE ENGINEERING STRUCTURES (2013)* of CCS provides relevant provisions [13].

Fatigue failure criteria can be based on fatigue damage or fatigue life. When based on fatigue damage, the fatigue strength of the calculated point shall meet Eq. (9)

$$D \leq \frac{1.0}{S_{ftg}} \tag{9}$$

D-- Fatigue damage degree;

S_{ftg}-- Fatigue strength safety factor.

The fatigue safety factor of the small steel containment of the FNPP is selected by reference to the fixed floating structure. The fatigue damage assessment location is accessible for inspection and maintenance in a dry environment, and the failure consequences are serious. Considering the special nature of the small steel containment of FNPP, we select 5 as the fatigue safety factor. Therefore $D \leq 0.2$.

See Table 4 for the cumulative fatigue damage degree and the corrected fatigue life of the final six fatigue assessment points of the containment.

T_1 is fatigue life considering corrosion correction factor/year.

T_2 is the fatigue life considering the fatigue safety factor and corrosion.

Table 2. Wave Dispersion

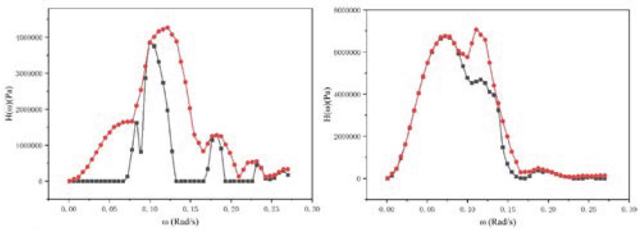
Spectral Peak period – Tp(s)															
Hs(m)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15
0.0–0.5	0.094 (1)	1.836(2)	6.383(3)	11.998(4)	1.508(5)	0.665(6)	0.290(7)	0.018(8)	0.005(9)	0.002(10)	0.005(11)	0.012(12)	0.014(13)	0.018(14)	0.026(15)
0.5–1.0	0	0	0	7.584(16)	27.675(17)	4.405(18)	1.220(19)	0.144(20)	0.003(21)	0	0	0	0	0	0
1.0–1.5	0	0	0	0.193(22)	6.793(23)	10.673(24)	2.290(25)	0.043(26)	0.008(27)	0.001(28)	0	0	0	0	0
1.5–2.0	0	0	0	0.005(29)	0.119(30)	3.580(31)	4.138(32)	0.248(33)	0.003(34)	0	0	0	0	0	0
2.0–2.5	0	0	0	0	0.020(35)	0.112(36)	2.874(37)	0.933(38)	0.002(39)	0	0	0	0	0	0
2.5–3.0	0	0	0	0	0	0.021(40)	0.452(41)	1.566(42)	0.028(43)	0	0	0	0	0	0
3.0–3.5	0	0	0	0	0	0	0.012(44)	0.740(45)	0.253(46)	0	0	0	0	0	0
3.5–4.0	0	0	0	0	0	0	0	0.132(47)	0.426(48)	0.012(49)	0	0	0	0	0
4.0–4.5	0	0	0	0	0	0	0	0.004(50)	0.164(51)	0.135(52)	0	0	0	0	0
4.5–5.0	0	0	0	0	0	0	0	0	0.008(53)	0.054(54)	0.004(55)	0	0	0	0
5.0–5.5	0	0	0	0	0	0	0	0	0	0.013(56)	0.024(57)	0	0	0	0
5.5–6.0	0	0	0	0	0	0	0	0	0	0.002(58)	0.009(59)	0	0	0	0
6.0–6.5	0	0	0	0	0	0	0	0	0	0	0.001(60)	0.001 (61)	0	0	0
6.5–7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3. Fatigue cumulative damage results.

Evaluation point	Cumulative fatigue damage	Fatigue life/years
1	0.009708	4120
2	0.003918	10209
3	0.02289	1747
4	0.08070	496
5	0.01025	3903
6	0.05275	758

Table 4. Fatigue cumulative damage results after correction.

evaluation point	Cumulative fatigue damage	T_1/years	T_2/years
1	0.01292	4120	619
2	0.005215	7670	1534
3	0.03047	1747	263
4	0.1074	496	74
5	0.01364	3903	587
6	0.07021	758	114



(a) evaluation point 4 (b) evaluation point 6

Fig. 8. Comparison of transfer function results

4 Conclusion

Based on the spectral analysis method and regular wave simulation method, this paper analyzes the small steel containment vessel of FNPP. It is concluded that the maximum fatigue cumulative damage is at No. 8 calculation point, the fatigue cumulative damage degree is 0.1074, and the fatigue life is 74 years. It is located at the bottom support, which meets the design requirements of FNPP. At the same time, the parameters are conservative and the fatigue life is short.

For the regular wave simulation method, take the evaluation point 4 and evaluation point 6 with short fatigue life as an example. Figure 8 shows the transfer function plots of evaluation point 4 and evaluation point 6 at 45° wave direction. The black curve is the simplified theoretical analysis method, and the red curve is the regular wave experimental simulation method. It can be concluded from the figure that the regular wave simulation method has a smoother and more accurate curve, although the calculation is more complex.

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