Prediction of Stress Level of Offshore Windmill Tower Based on the Grey Theory

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Abstract

In the actual working process, the tower of wind power generation system mainly bears the deadweight and the wind loads. It's necessary to determine the actual stress level of tower structure in order to make sure the safety. As there is error when estimating the stress of tower with deterministic methods and it's very difficult to carry out real-time monitoring under high sea state, it has engineering significance to predict the stress level of the tower applying grey theory. Through monitoring the stress level of tower structure under low sea state in actual working process, a series of relationship between stress amplitude and wind power as well as wind direction can be obtained, and the influence of deadweight on the stress is determined. Meanwhile, data are collected and the stress level under high oceanic condition is predicted based on grey predicting model——GM (1, 1) model. The safety condition of tower is also estimated, which provides the experimental data for analyzing the design methods and rules of tower henceforth.

Key words: Grey predicting; windmill tower; stress level; GM(1,1)model.

1 Introduction

Recently, the CNOOC (China National Offshore Oil CORP.) built the first windmill system on sea in China. It is very important to determine the actual stress level of tower structure in order to ensure the safety and meet the needs of the subsequent tower structure design. As there is error in estimating the stress of the tower with deterministic methods and it's very difficult to carry out real-time monitoring under high sea condition, it is necessary to predict the stress level of windmill tower in the high wind conditions according to the monitoring results under common wind conditions. A new method to assess the stress level of tower based on the grey theory is presented in this paper, aiming at the characteristics of windmill tower and the requests of structural testing.

2 The synopsis of Grey Theory

Grey system is a kind of system in which some information is clear but some is unknown. From the perspective of the system, it aims at studying the relationship between all kinds of information and finding the way of revealing the unknown information applying the information known. With the ideas and methods of Grey Theory, nonobjective phenomena and factors can be quantized and the data can be analyzed, then the quantitative prediction and decisions will be made. Thereby, the objects with vague information can be predicted and analyzed systemically.

3 The characteristics of tower

The main support structure of the windmill at sea system is the central ribbed cone shell with variable cross-section. The cause of structure destruction is that the total profile stresses of the cone shell excesses its ultimate stress.

The relationship between the stress level of tower and the external loading is dependent on many factors such as sea conditions, weight of the windmill, geometric size of structure, initial defection in manufacture, mechanical performance of materials, and how these factors affect the stress is unknown. That is to say, it is with grey characters. Therefore, it is hard to get the effective calculation formulas of stress level in the model of mathematics or mechanics.

In view of the features above, the Grey Theory can be adopted to predict the stress level in high sea condition through the relationship between the stress level and external loads in low sea condition, which can get the results fast and easily.

4 Analysis of the tower stress under low sea conditions

In the actual working process, as an important part of predicting the stress level, it is necessary to monitor the main supporting structure's stress level in order to get the relationship between the stress level and the external loads in the low sea condition.

Based on the theoretic analysis and finite element calculating results, there are three regions in tower structure where the stress is great: (1) the bottom joint with the base(2) the middle part of the tower (3) the top joint with the windmill. Strain gauges are placed on the tower and the data of them are recorded with signal acquisition and analysis equipments, and the sea conditions are recorded when the windmill is in operation.

As the temperature has great influence on the stress gauges, the recorded data do not reflect the real stress level within the structure, but the stress amplitude still can reflect the real dynamic response of structure. Considering the longitudinal stress on structure caused by the deadweight of the windmill is of the main part, which contains both tensile and compressive stresses, the real stress can be obtained through adding the greatest stress amplitude and the deadweight effects after considering the unfavorable effect of actual work condition. As the following formula shows:

$$\sigma_{\text{total}} = \sigma_{\text{deadweghit}} + \sigma_{\text{stress amplitude}} \text{.}$$

Take the measured stress data from the mid part of tower for example, the change of stress amplitude in the mid of tower structure with time is shown in figure 1.

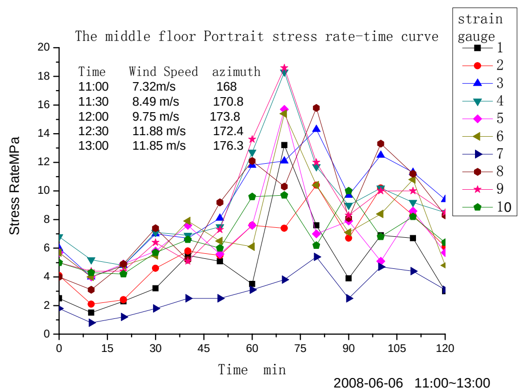

Figure 1: the change of stress amplitude in the mid of tower

The greatest stress amplitude in the mid of tower structure at every time can be obtained from fig. 1.

The influence of windmill's deadweight on stress level of tower can also be obtained through measuring, which is showed in fig. 2.

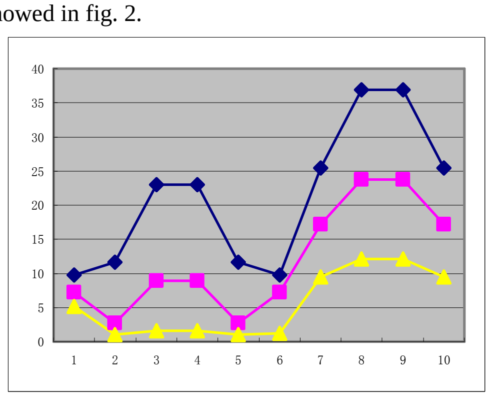

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Figure 2: the influence of windmill's deadweight on stress level

The maximum data caused by the deadweight in above three segments above is showed in the Table 1.

No.	max data （MPa）
bottom	36.9
mid	23.8
top	12.1

Table1: The max data caused by the deadweight

Meanwhile, the wind conditions are recorded in Table2.

time (min)	wind speed (m/s)	wind angle
0	7.32	168^{o}
30	8.49	170.8^{o}
60	9.75	173.8^{o}
90	11.88	172.4^{o}
120	11.85	176.3^{o}

Table2: Table of wind conditions

The relationships between the stress amplitude in the mid of the structure and the wind conditions are shown in Table 3.

Time (min)	0	30	60	90	120
Wind Condition	7.32	8.49	9.75	11.88	11.85
Stress Amplitude	6.8	7.4	9.4	13.6	10.0

Table 3: Relation of wind condition—stress amplitude

5 The formulation of Grey prediction model

5.1 Known condition

Take the data in table3 as known, unequidistant GM (1, 1) model will be set up based on Grey Theory to predict stress level in mid of tower.

5.2 Modeling

For convenience, take x_i as the equivalent stress amplitude. The $\left\{x^{(1)}(k_i)\right\}$ series (1-AGO) can be calculated according to equivalent stress sequence $\left\{x^{(0)}(k_i)\right\}$ .The results of (1-AGO) is shown in Table 4.

Number	1	2	3	4	5
k_i	7.32	8.49	9.75	11.85	11.88
$x^{(0)}(k_i)$	6.80	7.40	9.40	10.0	13.6
$\Delta(k_i)$	0.00	1.17	1.26	2.10	0.03
$x^{(1)}(k_i)$	6.80	15.46	27.30	48.30	48.71

Table 4 The results of (1-AGO)

According to the 1-AGO series, whitened differential equations is established as follows:

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = u$$

The estimating equation of parameter $\hat{a}$ is obtained by the least square method as follows:

$$\hat{a} = \begin{bmatrix} a \\ u \end{bmatrix} = (B^T B)^{-1} B^T Y_N$$

Where $Y_N = [x^{(0)}(k_2), x^{(0)}(k_3), x^{(0)}(k_4), x^{(0)}(k_5)]^T$

And $B = \begin{bmatrix} -\frac{1}{2}(x^{(1)}(k_2) + x^{(1)}(k_1)) & 1 \\ -\frac{1}{2}(x^{(1)}(k_3) + x^{(1)}(k_2)) & 1 \\ -\frac{1}{2}(x^{(1)}(k_4) + x^{(1)}(k_3)) & 1 \\ -\frac{1}{2}(x^{(1)}(k_5) + x^{(1)}(k_4)) & 1 \end{bmatrix}$.

Parameters $\hat{a}$ can be calculated according to the data in the table 5.1:

$$\hat{a} = \begin{bmatrix} a \\ u \end{bmatrix} = \begin{bmatrix} -0.1451 \\ 5.7891 \end{bmatrix}$$

The respond function is as follows:

$$\hat{x}^{(1)}(k_i) = \left[x^{(0)}(k_1) - \frac{u}{a} \right] e^{-a(k_i - k_1)} + \frac{u}{a}$$

Substituting a and u into the equation, one gets

$$\hat{x}^{(1)}(k_i) = 46.6973e^{0.1451(k_i - 7.32)} - 39.8973$$

That is the basic formula of the GM (1, 1) model.

6 Prediction of stress level of structure

The reducing sequence is as follows:

$$\hat{x}^{(0)}(k_{i+1}) = \frac{1}{\Delta k_{i+1}}\left(1 - e^{a\Delta k_{i+1}}\right)\left[x^{(0)}(k_i) - \frac{u}{a} \right] e^{-a(k_{i+1} - k_1)}$$

According to the reducing sequence above and the calculating results $\hat{x}^{(1)}(k_i)$ as well as its reducing results $\hat{x}^{(0)}(k_i)$ of GM（1，1）model, the errors at each point can be obtained through comparing and analyzing the predicted and measured stresses of the structure shell, which are presented in table 5.

Similarly, the predicted results and models in other floors can also be obtained in the same way.

Input the wind condition that once met in 50 years into the calculating model and predict the stress amplitude in this condition. The maximum data can reach 28.71MPa in the middle of the structure. Combining with the deadweight of the windmill, the total stress can be obtained:

$$\sigma_{\text{total}} = 28.71 + 23.8 = 52.51MPa$$

Multiply the safety coefficient and compare with the ultimate stress of the material:

$$\sigma_{\text{total}} = 52.51 << 0.7\sigma_s = 241.5MPa$$

As the process above, analyzing the data of the stress gauges in other floors, each stress of them can be found through their GM（1，1）models: On the bottom, which is 50.21MPa, on the top is 46.44MPa. Compared with the yield limit of the material, the tower structure is safe under this sea condition

Number	1	2	3	4	5
k_i	7.32	8.49	9.75	11.85	11.88
$x^{(0)}(k_i)$	6.80	7.40	9.40	10.0	13.6
$\Delta(k_i)$	0.00	1.17	1.26	2.10	0.03
$\hat{x}^{0}(k_i)$	6.80	7.39	8.92	11.90	14.00
Δx	0.00	0.01	0.48	1.90	0.04
$\frac{\Delta x}{x^0(k_i)}\%$	0.00	0.10	5.10	1.90	0.20

Table5: The calculated results and the error analysis

7 Conclusions

1) Grey Theory is effective and feasible to predict the stress level of the tower, which can avoid the use of ideal modeling of deterministic methods and too much mathematical calculation.

2) Based on the monitoring data in low sea condition, it shows that it is safe for the wind power generation system to run in high sea conditions. Moreover, there is much margin stress. Therefore, the tower structure design can be adjusted to decrease the deadweight of tower henceforth.

3) In applying the Grey Theory to predict the stress level of the tower structure, it is very important to monitor the

stress in low sea condition. The closer the monitored stress approaches to the goal stress, the better the precision is.

References

[1] DENG Julong. *Grey Control System* [M].Wuhan: Huazhong University of Science and Technology Publishing House, 1993(in Chinese).

[2] LIU Sifeng, DANG Yaoguo, FANG Zhigeng. *Grey system theory and its applications* [M].Beijing: Science Press, 2004(in Chinese).

[3] JI Peirong, HUANG Weifeng, HU Xiangyong. *Grey forecast model characteristics* [J]. Systems engineering theory and practice, 2001(in Chinese).

[4] HU Bing, ZENG Xuegui. *An Unequal Interval Gray Forecast Model* [J]. Journal of northern Jiao tong university, 1998(in Chinese).

[5] LI Tianjun, XIONG Wei, WANG Ping, ZHENG Yanshuang. *A Gray Forecasting Method for Non-Collapsing Test on Structures* [J].Journal Huazhong University of SCI.&TECH,1995(in Chinese).