The 2022 World Congress on
Advances in Civil, Environmental, & Materials Research (ACEM22)
16-19, August, 2022, GECE, Seoul, Korea

A new fatigue assessment method for wind turbine structures considering load sequence

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ABSTRACT

Wind turbine structures are continuously subjected to variable amplitude fatigue loads during the whole life cycle, and most of the fatigue loads are low amplitude loads. In the present study, a new fatigue assessment method in the time domain for wind turbine structure is presented. A modified non-linear cumulative damage (NLCD) model is proposed based on Chaboche's work to further consider the damaging and coaxing effects of low amplitude loads. The modified rain flow counting method is used to keep the load sequence information when translating load time series to damaging events. The proposed modified NLCD model is proved to be accurate with collected fatigue test data. Lastly, the complete flow for implementing this proposed method is presented.

1. INTRODUCTION

Wind turbine support structures will be subjected to hundreds of millions of stress cycles during their service life, and most of them fall in the low-stress region (i.e., stress ranges below the fatigue limit). The structure is continuously subjected to "low-high" and "high-low" stress sequences, accompanied by contingent environmental effects (extreme winds, waves, etc.) and crew actions (yawing, braking, etc.). For the welds and bolts of wind turbine support structures, it is important to reveal their damage evolution mechanism under variable amplitude loading with typical characteristics of wind turbine and to establish an accurate and efficient fatigue cumulative damage model, which is the basis for fatigue resistant design and remaining life prediction of wind power support structures.

Currently, Miner's criterion is widely used in the fatigue design and research of wind turbine support structures, but the biggest defect of this criterion is that it ignores the influence of low-stress cycles and load sequence on fatigue damage, which leads

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to large deviations between the quantitative analysis of fatigue damage and the actual results [1-2]. For the effects of low-stress cycles and load sequence on fatigue damage, some researchers have conducted experimental studies on variable amplitude fatigue [3-4]. The results show that, unlike the constant amplitude fatigue, low-stress cycles will also contribute to fatigue damage (i.e., damaging effect) under the "high-low" time series of stress cycles. On the contrary, the low-stress cycles will increase the fatigue strength (i.e., coaxing effect) under the "low-high" time series of stress cycles. The fatigue loads of wind turbine support structures have a significant feature, that is, more than 90% of the load is the low-amplitude loads. However, few studies have explored the evolution mechanism of fatigue damage for this situation, and damage models that consider the damaging effect and the coaxing effect are not yet available.

To reveal the evolution mechanism of variable amplitude fatigue damage of welded joints and bolts of wind turbine support structure under the influence of low-stress amplitude. On the one hand, based on the nonlinear continuous damage (NLCD) model proposed by Chaboche [5], this paper improves the original model by introducing new characteristic variables to take into account the effect of a large number of low-stress cycles on damage in wind turbine structures. On the other hand, based on the traditional rain flow counting method, the defect of the load spectrum losing the load time sequence is compensated by introducing the start and end time of the load cycle, and the damaging effect and coaxing effect generated by the load sequence when multiple loads are applied is taken into account in the preparation of the load spectrum, which in turn reflects the load cycle more realistically. On this basis, a fatigue damage assessment method for wind turbine support structures is proposed, which improves the accuracy of fatigue assessment of welded joints and bolts.

2. PROPOSAL AND VALIDATION OF A MODIFIED NONLINEAR CUMULATIVE DAMAGE MODEL

2.1 Non-linear continuous damage model

The nonlinear continuous damage (NLCD) model was originally proposed by Chaboche and Lesne [5] based on continuum damage mechanics. The damage rate of the NLCD model is shown in differential Eq. (1)

$$dD = (D)^{\alpha(\sigma_{\max},\sigma_{\text{mean}})}[\frac{\sigma_a}{M_0(1-b\sigma_{\text{mean}})}]^{\beta}\,dN \qquad (1)$$

Where, β, M_0 and b are constants depend on the material, $\sigma_{\max}$ and σ_{mean} are the maximum stress and mean stress of the cycle, respectively. $\sigma_a = \sigma_{\max} - \sigma_{\text{mean}}$ is the stress amplitude. The function α can be expressed as

$$\alpha = 1 - a\left\langle \frac{\sigma_a - \sigma_1(\sigma_{\text{mean}})}{\sigma_u - \sigma_a} \right\rangle \qquad (2)$$

Where, $\sigma_1(\sigma_{\text{mean}})$ is the fatigue limit at different mean stress, and can be calculated by Eq. (3).

$$\sigma_1(\sigma_{\text{mean}}) = \sigma_{\text{mean}} + \sigma_{l_0}(1 - b\sigma_{\text{mean}}) \qquad (3)$$

Where, a and b are coefficients, σ_{l_0} and σ_u is the fatigue limit at zero mean stress and ultimate tensile strength, respectively. The symbol $\langle\ \rangle$ is defined as Eq. (4):

$$\langle x \rangle = \begin{cases} 0, & x < 0 \\ x, & x \geq 0 \end{cases} \tag{4}$$

2.2 Modified NLCD considering effects of low amplitude loads

A modified NLCD model is proposed considering the strengthening and damaging effects of low amplitude loads, Eq. (5) can be expressed as

$$dD = (D)^{\alpha(\sigma_{\max},\sigma_{\text{mean}})}\left[\frac{\sigma_a}{M_0(1-b\sigma_{\text{mean}})}\right]^{\beta} f(N,\sigma_a)dN \tag{5}$$

For fully reversed loading conditions (i.e., stress ratio $R=-1$, $\sigma_{\text{mean}}=0$), Eq. (5) can be simplified as Eq. (6).

$$dD = D^{\alpha(\sigma_{\max},\sigma_{\text{mean}})}\left[\frac{\sigma_{\text{a}}}{M_0}\right]^{\beta} f(N,\sigma_{\text{a}})dN \tag{6}$$

In the case of loadings above the fatigue limit, Integrating Eq. (6) from $D=0$ to $D=1$ (correspondingly, from $N=0$ to $N=N_f$), Eq. (7) can be expressed as

$$F(N_{\text{f}},\sigma_a) = \frac{1}{1-\alpha}\left(\frac{\sigma_{\text{a}}}{M_0}\right)^{-\beta} \tag{7}$$

Where $F(N_{\text{f}},\sigma_{\text{a}})$ is the original function of $f(N,\sigma_{\text{a}})$. To consider the influence factors of saturation cycle number with small stress amplitude below fatigue limit, When $\sigma_{\text{a}} > \sigma_1$, the following conditions should be satisfied.

$$\begin{cases} f(N,\sigma_{\text{a}}) = 1 \\ F(N_{\text{f}},\sigma_{\text{a}}) = N_{\text{f}} \end{cases} \tag{8}$$

Therefore, it is the same as the original NLCD model, Eq. (9) can be expressed as

$$Y_i = (Y_{i-1})^{\frac{(1-\alpha_i)}{(1-\alpha_{i-1})}} + \frac{n_i}{N_{\text{f},i}} \tag{9}$$

In the case of ith load below the fatigue limit, $\alpha=0$, from $D=D_{\text{i-1}}$ to $D=D_{\text{i}}$ (correspondingly, from $N=N_{i\text{-1}}$ to $N=N_i$), Eq. (10) can be expressed as

$$D_i = D_{i\text{-1}}\exp\left[F(n_i,\sigma_{\text{a}})\left(\frac{\sigma_{\text{a}}}{M_0}\right)^{\beta}\right] \tag{10}$$

Submit Eq. (10) to Eq. (9), Eq. (11) can be expressed as

$$Y_{i+1} = (Y_{i-1})^{\frac{(1-\alpha_{i+1})}{(1-\alpha_{i-1})}}\exp\left[(1-\alpha_{i+1})\frac{F(n_i,\sigma_{\text{a}})}{N_i^*}\right] + \frac{n_{i+1}}{N_{\text{f},i+1}} \tag{11}$$

where $N_i^* = (\frac{\sigma_{\text{a}}}{M_0})^{-\beta}$, $(1-\alpha_{i+1})\frac{n_i}{N_i^*}$ can be evaluated by $M_0 a^{-1/\beta}$, which is obtained by fitting the S-N data with Eq. (1). Where $F(n_i,\sigma_a)$ should be satisfied Eq. (12)

$$F(n_i,\sigma_a)=\begin{cases} n_i, & \text{for } n_i \le N_s \\ N_s, & \text{for } n_i > N_s \end{cases} \tag{12}$$

Then we consider the stress strengthening effect of low-stress cycles, Eq. (13) can be expressed as

$$Y_{i+1}=(Y_{i-1})^{\frac{(1-\alpha_{i+1})}{(1-\alpha_{i-1})}}\exp\left[(1-\alpha_{i+1})\frac{F(n_i,\sigma_a)}{N_i^*}\right]+\frac{n_{i+1}}{N_{fc,i+1}} \tag{13}$$

Where $N_{fc,i+1}$ is the fatigue life after considering the strengthening effects.

By the values of $F(n_i,\sigma_a)$, it is integrated into an explanatory formula, Eq. (14) can be expressed as

$$F(n_i,\sigma_a)=n_i\frac{1+\text{sgn}(\sigma_a-\sigma_l)}{2}+(n_i\frac{1-\text{sgn}(n_i-N_s)}{2}+N_s\frac{1+\text{sgn}(n_i-N_s)}{2})\frac{1-\text{sgn}(\sigma_a-\sigma_l)}{2} \tag{14}$$

Where $\text{sgn}\,(\,)$ is defined as Eq. (15)

$$\text{sgn}(x)=\begin{cases} -1, & x<0 \\ 1\ , & x\ge 0 \end{cases} \tag{15}$$

2.3 Validation of the modified NLCD model

To confirm that the original NLCD model does not sufficiently consider the damage effects and strengthening effects caused by low-stress cycles when targeting load sequences with a large number of low-stress cycles, two-stage loading test data from He et al. [3] were collected to verify the correctness of the proposed modified NLCD model. As can be seen from Table 1, the modified NLCD model obtained a better prediction of the tested results.

Table 1 Validation results of the damaging effects *4

σ_H/σ_L	10/1000 *2			10/5×1000			10/10000		
	N_{exp}	N_{NLCD}	$N_{M\text{-}NLCD}$ *3	N_{exp}	N_{NLCD}	$N_{M\text{-}NLCD}$	N_{exp}	N_{NLCD}	$N_{M\text{-}NLCD}$
277/225 *1	-	306	306	-	95	95	84	55	55
277/200	613	518	518	388	177	330	307	105	330
277/160	1020	1101	1101	669	507	902	910	327	902
277/140	1183	1432	1550	1611	837	1550	1342	585	1550
277/120	1609	1672	1700	1848	1259	1700	1585	992	1700
277/100	2410	1791	1736	2061	1617	1736	2208	1452	1736

*1 277/225: The high-stress amplitude is 277 MPa, and the low-stress amplitude is 277 MPa.

*2 10/1000: 10 cycles of high-stress loading and 1000 cycles of low-stress loading in one loading block.

*3 The saturation cycle numbers corresponding to low stresses of 100 MPa, 120 MPa, 140 MPa, 160 MPa, and 200 MPa are 2150, 820, 640, 1650, and 2050, respectively.

*4 σ_H/σ_L is the ratio of high-stress amplitude to low-stress amplitude, N_{exp} is the tested result, N_{NLCD} is the result of the NLCD model calculation and $N_{M\text{-}NLCD}$ is the result of the modified NLCD model calculation.

4. MODIFIED RAINFLOW COUNTING METHOD PROPOSED AND DAMAGE ASSESSMENT IMPLEMENTATION PROCESS

There are few studies on fatigue load counting methods that retain load timing information and cannot be directly applied to the NLCD model. Therefore, a new fatigue load counting method is proposed to convert the typical fatigue load time series of wind turbine support structures into fatigue load spectra that can be used for damage calculations to consider the effects of low-stress amplitude and load time series on fatigue damage. By introducing the parameters of start and end times of load cycles based on the traditional rainfall counting method to compensate for the loss of load time sequence in the load spectrum, the damage effects generated by the load sequence when multiple loads are applied are taken into account in the preparation of the load spectrum, which in turn reflects the load cycles more realistically. A step-by-step flowchart of a rain flow counting method that preserves load timing is shown in Fig. 1.

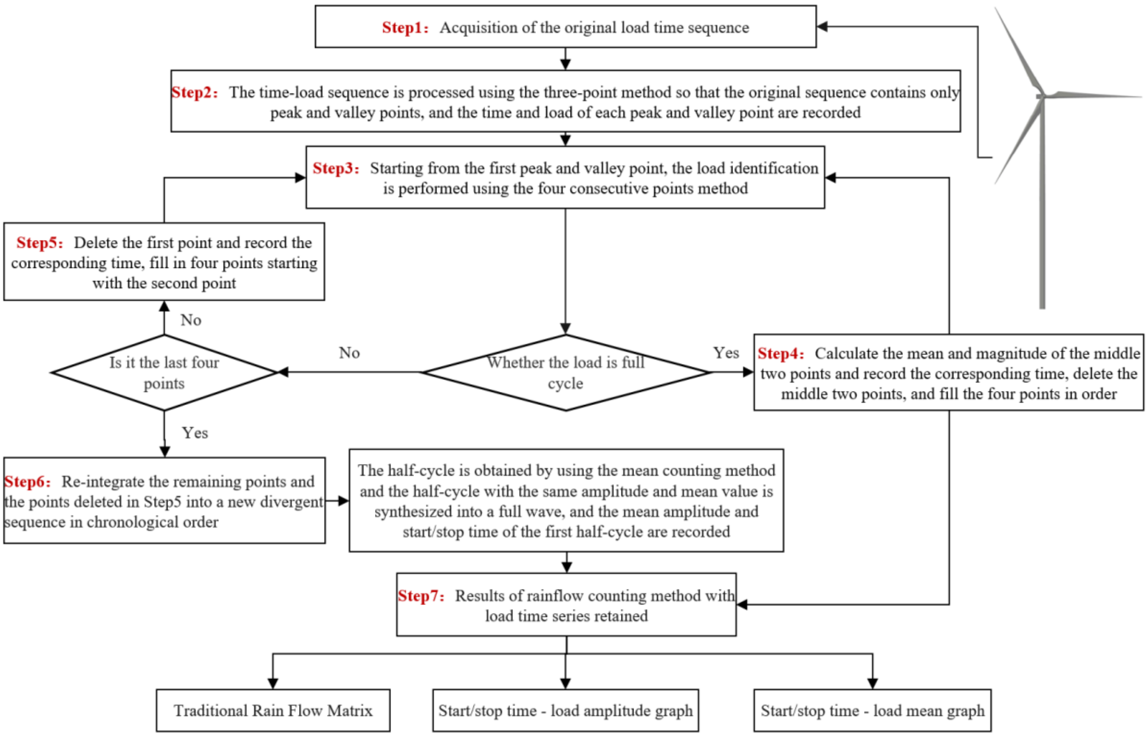

Fig. 1 A step-by-step flowchart of a rain flow counting method that preserves load timing

Taking an actual wind power support structure as an example, the fatigue load matrix calculated by the modified rainfall counting method with the retained load time series and the modified NLCD model proposed in Section 2 are combined to obtain a nonlinear fatigue cumulative damage assessment method consistent with the wind turbine support structure. The fatigue damage calculation process for a wind turbine support structure is shown in Fig. 2.

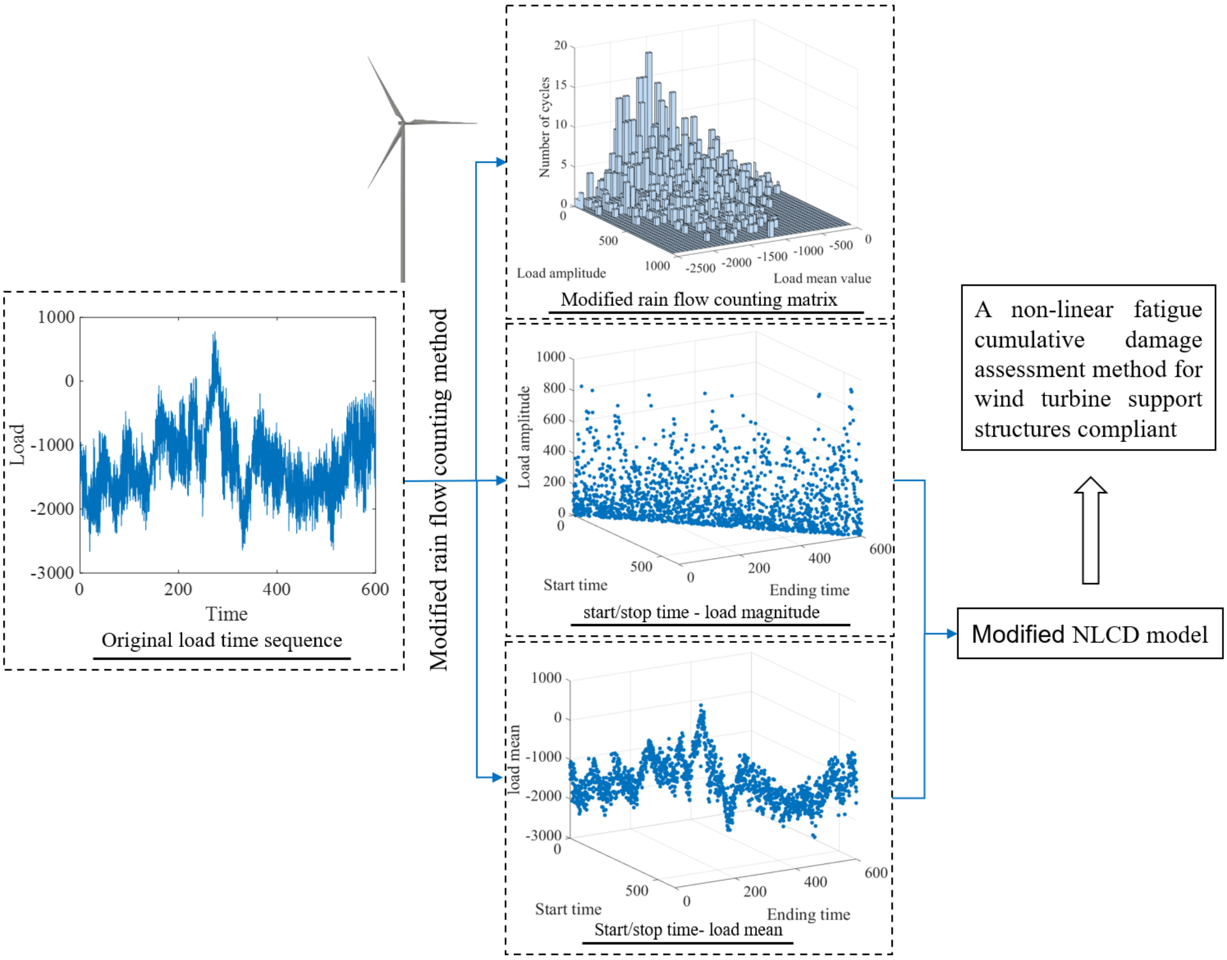

Fig. 2 Fatigue damage calculation process for a wind turbine support structure

5. CONCLUSIONS

In this paper, a fatigue assessment method for wind turbine structures considering damaging and coaxing effects of low amplitude loads is proposed, and the following conclusions were obtained:

(1) The original NLCD model does not sufficiently consider the damage effects and strengthening effects caused by low-stress cycles for load sequences with a large number of low-stress cycles, and the modified NLCD model can make better predictions of the test results, which verifies the correctness of the proposed modified model.

(2) By introducing the parameters of start and end times of load cycles based on the traditional rainfall counting method to compensate for the loss of load time sequence in the load spectrum. Using an actual wind turbine support structure as an implementation example, the modified rain flow counting method is combined with the proposed fatigue cumulative damage model to briefly introduce the process of the fatigue damage assessment method for wind power support structures.

REFERENCES

[1] Fatemi, A., Yang, L. (1998), “Cumulative fatigue damage and life prediction theories: A survey of the state of the art for homogeneous materials”. International Journal of Fatigue”, 20 (1): 9–34.
[2] Schütz, W. (1996), “A history of fatigue”, Engineering Fracture Mechanics. 54 (2): 263–300.
[3] He, L.; Akebono, H., Sugeta, A. (2018). “Effect of high-amplitude loading on accumulated fatigue damage under variable-amplitude loading in 316 stainless steel”, International Journal of Fatigue, 116 (), 388–395.
[4] Gan, J.; Zhao, K., Wang, Z.; Wang, X. L., Wu, W. G. (2019). “ Fatigue damage of designed T-type specimen under different proportion repeating Two-Step variable amplitude loads”, Engineering Fracture Mechanics, 221(), 106684.
[5] Chaboche, J. L., and Lesne, P., M. (1985), "A NON-LINEAR CONTINUOUS FATIGUE DAMAGE MODEL", Fatigue & Fracture of Engineering Materials & Structures, 11 (1), 1-17.