Study on identification of structural damage to wind turbine blade based on modified fruit fly optimization algorithm

Gu Guimei*, Wang Zheng

School of Automation and Electrical Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China

Received 9 August 2014, www.cmnt.lv

Abstract

A damage diagnosis method was proposed based on modified fruit fly optimization algorithm for the identification of structural damage to wind turbine blade. By transforming the identification of structural damage into constrained optimization, this method identified the structural damage to wind turbine blade by fruit fly optimization with minimum inherent frequency and oscillation mode error as target function of constrained optimization. Given that the basic fruit fly optimization (FOA) has problems of partial optimization and low optimization accuracy, so chaos optimization algorithm was used to modify FOA. The numerical simulation of single- and multi-damage to wind turbine blade and various experiments of damage to small-scale wind turbine blade showed that modified fruit fly optimization (MFOA) can not only accurately identify the damage position, but also effectively identify the damage degree in detection of structural damage to wind turbine blade. Therefore, the identification accuracy of MFOA was obviously better than that of basic FOA and genetic algorithm (GA).

Keywords: Wind turbine blade; structural damage; fruit fly algorithm; constrained optimization

1 Introduction

In long-term service, damage accumulation, resistance attenuation, etc. may easily occur to wind turbine blade because of material aging, fatigue, corrosion and operation in adverse outdoor environment for a long time. Meanwhile, with the growth of generating capacity of monomer in wind turbine system, the scale of wind turbine blade may gradually increase, and the blade cost also increasingly raises [1]. Once upon the wind turbine blade is damaged, a huge economic loss and even persona injury may be caused. Therefore, the detection of structural damage to wind turbine blade has important meaning to safe operation of wind turbine [2-4].

Traditional detection of structural damage to wind turbine blade can be divided into partial damage detection and overall damage detection. Partial damage detection refers to directly conducting partial detection to the structure by modern structural non-destruction measurement to determine if there is any damage and the damage degree of detected part. At present, the common methods mainly include acoustic emission detection [5], ultrasonography [6], infrared thermography detection method, etc. The overall damage detection based on dynamic test is to determine if the structure has been damage and its damage degree by detecting the response change before and after overall structural damage. This method can be divided into damage identification based on static features and that based on dynamic features [8] according to different response features. Common methods of damage identification based on dynamic features include: identification method of structural damage based on inherent frequency [9], identification method of structural damage based on oscillation mode [10], identification method of structural damage based on residual force vector [11], etc. In recent years, with the development of intelligent technology, data processing technology, and signal processing technology, the identification of structural damage with powerful signal processing, non-linear mapping, and classification learning capacity of intelligent algorithm has become the research focus of damage identification. In 2010, B. Chao, et al. [12] transformed the identification of structural damage into constrained optimization. They diagnosed the crack failure of rotor blade under circumstance of multi-damage to effectively identify the structural damage to rotor blade. In 2012, Tian Yuan, et al. [13] applied FOA to the prediction of bearing damage in hydro-power generating unit to provide a new effective method for predicting the structural damage of bearing in hydro-power generating unit.

Enlightened by above ideas, this work applied FOA to the identification of structural damage to wind turbine blade. “Prematurity” may occur to basic FOA to make the convergence speed slow in late stage and reduce convergence accuracy, while chaos algorithm is featured with university, regularity, and randomness. Therefore, this work proposed a new chaos FOA by mixing chaos optimization into the evolutionism of FOA. Compared to basic FOA and GA, the algorithm in this work has

* Correspondihg authour’s E-mail: gugm@mail.lzjtu.cn

obviously improved the identification accuracy and effectiveness.

2 Theory of fruit fly optimization algorithm

2.1 BASIC FRUIT FLY OPTIMIZATION ALGORITHM

Fruit fly optimization algorithm is a new method for overall optimization proposed for the enlightenment of foraging behavior of fruit flies. When searching foods, fruit flies will determine the approximate position of food by smelling, and then the accurate position by vision. FOA is summarized as follows [14] according to the foraging behavior of fruit flies:

1) Random initialization was conducted for the location of fruit fly group X_axis and Y_axis.

2) Random direction and distance of food searching were given for every fruit fly by smelling:

$$\begin{cases} X_i = X\_axis + RandomValue \\ Y_i = Y\_axis + RandomValue \end{cases} \tag{1}$$

3) The food location cannot be determined, so the distance to initial point ($Dist_i$) was calculated firstly, and then the judgment value of concentration S_i at the location was calculated, which was also set as the reciprocal of distance:

$$Dist_i = \sqrt{X_i^{\,2} + Y_i^2} \tag{2}$$

$$S_i = 1/Dist_i \tag{3}$$

4) The judgment value of smell concentration S_i was substituted into smell concentration judgment function (or called the fitness function) to obtain the smell concentration at the position of individual fruit fly $Smell_i$:

$$Smell_i = \mathrm{Function}(S_i) \tag{4}$$

5) The fruit fly with the minimum smell concentration in group was found;

$$[bestSmell\ bestindex] = \min(Smell_i\ ) \tag{5}$$

6) The optimal smell concentration and coordinate X and Y were maintained. At this time, fruit fly group flied to the position by vision:

$$\begin{cases} Smellbest = bestSmell \\ X\_axis = X(bestindex) \\ Y\_axis = Y(bestindex) \end{cases} \tag{6}$$

7) Iterative refinement refers to repeating Step 2) ~ 5) to judge if the smell concentration is superior to that in last iteration. If yes, 6) will be taken.

2.2 MODIFIED FRUIT FLY OPTIMIZATION ALGORITHM

During the iterative refinement, the basic fruit fly optimization algorithm only learns from the optimal individual at present. When the optimal individual is found in the iteration, all the individuals will fly to the position. Therefore, the population diversity reduces to make the algorithm easily limited in a small region, and convergence speed slow and accuracy decreasing in late stage to cause the prematurity of convergence.

The modified fruit fly optimization algorithm proposed in this work conducted chaos optimization on basis of basic fruit fly algorithm. Chaos optimization refers to carefully searching the whole fruit fly group after obtaining the optimal individual in group with the features of university, regularity, and randomness of chaos optimization. Therefore, a new chaos fruit fly optimization is proposed by mixing fruit fly optimization algorithm with chaos optimization algorithm. This algorithm can give a play to advantages of both algorithms to greatly improve the optimization accuracy and efficiency. The major steps to modify the fruit fly algorithm are as follows:

1) Randomly initiate the position of fruit fly group;

2) Implement Step 2)-5) of basic fruit fly optimization algorithm;

3) Maintain the optimal smell concentration value and coordinate of X and Y. At this time, the fruit fly group should fly to this position by vision;

4) Conduct chaos optimization to the optimal individual of fruit fly group by equation (7), and judge if the smell concentration of new individual is superior to that of original individual. If yes, replace the original individual with new individual, otherwise, keep the original individual;

$$\begin{cases} X_L = X(bestIndex) + \alpha(t(k) - \frac{1}{2}) \\ Y_L = Y(bestIndex) + \alpha(t(k) - \frac{1}{2}) \end{cases} \tag{7}$$

where, $\alpha(t(k) - \frac{1}{2})$ is a chaotic variant with small traverse interval and α adjustment factor which can be less than 1.

5) Judge if above conditions are satisfied. If yes, implement Step 3), otherwise, turn to Step 2).

Chaos optimization algorithm is sensitive to the initial value [15-16], so chaos fruit fly algorithm can not only prevent partial optimization of fruit fly optimization algorithm, but also improve partial searching capability if parameters are rationally selected.

3 Application of FOA in identification of structural identification to wind turbine blade

Following target function for optimization was established by transforming the identification of structural damage to wind turbine blade into constraint optimization in detection :

$$f(x)=\sum_{i=1}^{s}((1-MAC(\phi_i^h,\phi_i^d))+ER(\omega_i^h,\omega_i^d)) \tag{8}$$

where, $ER(\omega_i^h,\omega_i^d)=\left|\frac{\omega_i^h-\omega_i^d}{\omega_i^h}\right|\times 100\%$

$$MAC(\omega_i^h,\omega_i^d)=\frac{\left|{\phi_i^h}^{T}\phi_i^d\right|^2}{\left|{\phi_i^h}^{T}\phi_i^d\right|\left|{\phi_i^h}^{T}\phi_i^d\right|},i=1,2,...,s$$

(ω_i^h,ϕ_i^h) and (ω_i^d,ϕ_i^d) are frequency and oscillation mode before and after structural damage to wind turbine blade, respectively; s is the model order of wind turbine blade; x the damage degree of unit stiffness, which is in scope of [0, 1] in theory, in which x =0 means no damage to unit stiffness, and x = 1 means that the damage degree of unit stiffness is 100%. However, when x = 1, paradox may occur to the solution of characteristic value. In the view of practice, the structure of wind turbine blade has been severely damaged or destroyed when the damage degree is 90%. Therefore, the scope of x should be set in [0, 0.9]. In this way, the identification of structural damage to wind turbine blade can be transformed into typical optimization of constraint solution:

$$\min f(x)=\sum_{i=1}^{s}((1-MAC(\phi_i^h,\phi_i^d))+ER(\omega_i^h,\omega_i^d)) \tag{9}$$

where, $0\le x\le 0.9;\ i=1,2,\cdots,s$.

Above constraint optimization was solved by AG, basic FOA, and MFOA as follows.

4 Numerical simulation

Figure 1 shows the model of wind turbine blade established in ANSYS software. The total length of blade was 35m, and the material parameters were defined as follows: E_x =42.6×10^9 Pa, E_y =16.5×10^9 Pa, G_{xy} =5.5×10^9 Pa, P_{rxy} =0.3 and ρ =1950 kg/m^3 [17]. The unit model adopted Shell99, and the grid division was conducted to blade as shown in Figure 2.

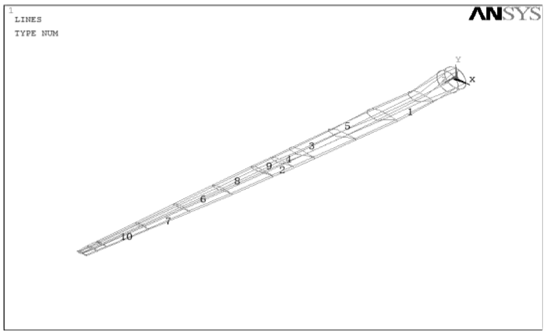

FIGURE 1 Structural model of wind turbine blade

Structural damage was stimulated by changing the unit stiffness with modal of the first 5 orders [18]. Taking Unit 3 and Unit 7 units as the possible damage units, there were 2 kinds of damage degree which are 30% and 50%, respectively. Condition 1 refers to single damage in 30% for Unit 3, while Condition 2 refers to multi-damage in 30% and 50% for Unit 3 and Unit 7, respectively as shown in Table 1. For above possible damage units, 3 algorithms were adopted: GA, basic FOA, and MFOA to conduct damage diagnosis. Figure 3 and Figure 4 show the judgment results. Figure 5 and Figure 6 show the convergence performance curve in corresponding conditions of single damage.

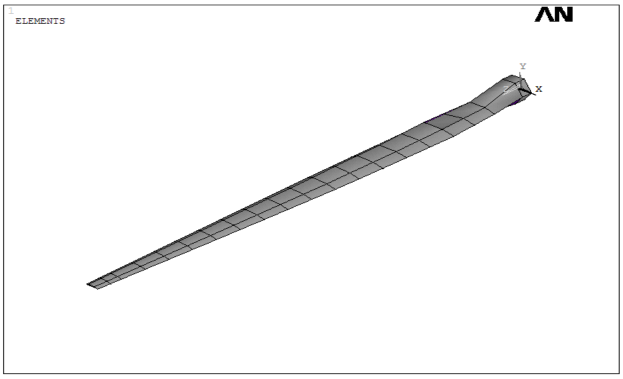

FIGURE 2 Finite element model of wind turbine blade

TABLE 1 Damage condition

Condition No.	Damage unit	Damage degree/%
1	3	30
2	3,7	30,50

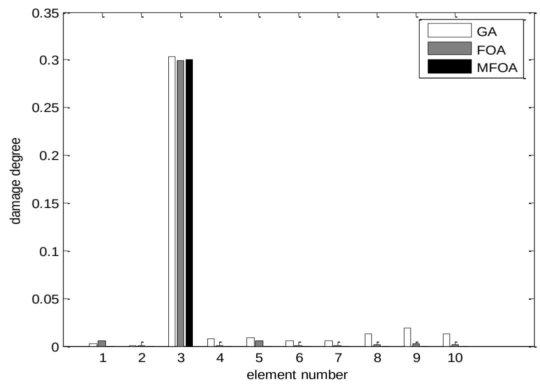

FIGURE 3 Comparison of identification results of single damage condition

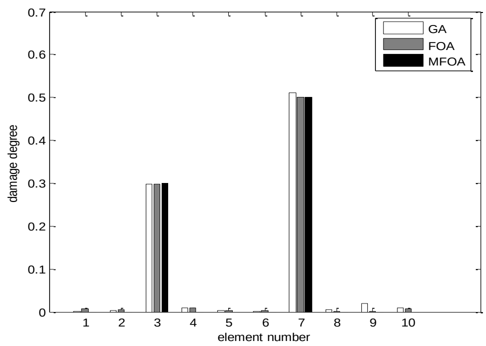

FIGURE 4 Comparison of identification results of multi-damage

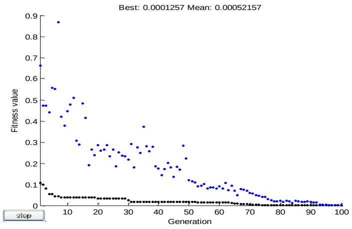

FIGURE 5 Convergence curve for identification of single damage by GA

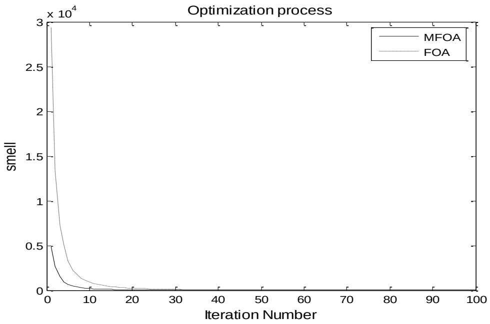

FIGURE 6. Convergence curve for identification of single damage by FOA and MFOA

According to Figure 3, the identification results are 0.3033 by GA, 0.2989 by FOA, and 0.3 by MFOA under single damage condition. According to Figure 4, the identification results are 0.2987 and 0.5109 by GA, 0.2973 and 0.5007 by FOA, and 0.3 and 0.5 by MFOA. It can be seen that the diagnosis results are all close to the real value of damage by these three algorithm, while the result by MFOA is better than that by FOA and GA.

Figure 5 and Figure 6 show the comparison of convergence performance by above 3 algorithms in single damage condition. According to these figures, the optimal value is reached at the 93 times by GA, the 32 times by FOA, and 16 times by MFOA. It can be seen the convergence curve of FOA is less than the maximum iteration steps when the *Y*-axis reaches the minimum by GA. In other words, the convergence speed is much faster when FOA reaches the minimum, while the convergence speed of MFOA is better than that of FOA. Therefore, MFOA is obviously better than FOA and GA according to convergence curves in Figure 5 and Figure 6.

5 Experimental verification

Experimental subject was small-scale wind turbine blade made of glass reinforced plastic in length of 1.5m. The blade tail was fixed, and 4 piezoelectricity acceleration sensors were distributed on blade surface in equal distance one by one to measure the vibration response in waving and swinging direction. Figure 7 is the distribution diagram of modal measure points in both waving and swinging directions numbered with 1 and 2, respectively. Figure 8 shows the test bed equipment.

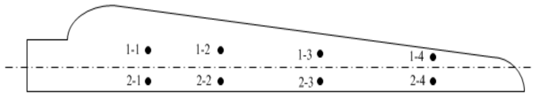

FIGURE 7 Distribution of modal measure points in waving and swinging directions

Without damage to blade, the response signal of blade in free oscillation was measured under transient excitation, and the vibration signal was analyzed by density method of self-cross spectrum [19] as shown in Figure 9 and Figure 10. In two figures, Figure 9 is the overlay chart of auto-power spectrum for each sensor, and Figure 10 is the overlay chart of self-cross spectrum between Channel 4 and Channel 1~3. According to the overlay chart of auto-power spectrum for each sensor in Figure 9, it can be roughly obtained that peak frequencies of sensors are 3.906 Hz, 23.44 Hz, 62.5 Hz, and 119.1Hz, respectively.

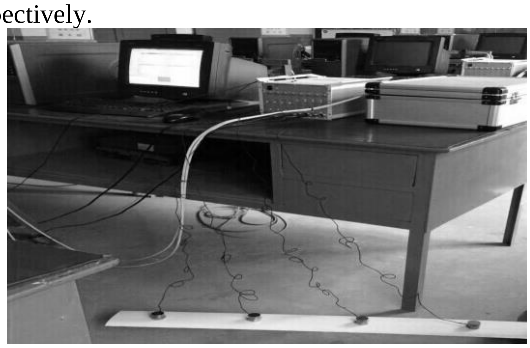

FIGURE 8 Test model of wind turbine blade structure

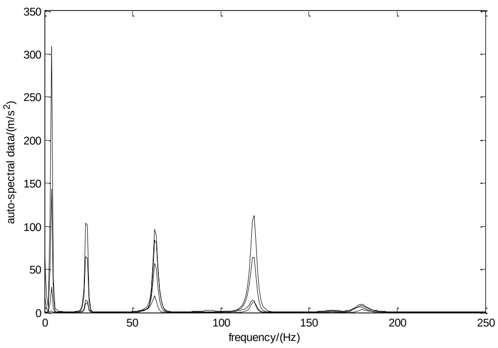

FIGURE 9. Curve for self-power spectrum of each channel

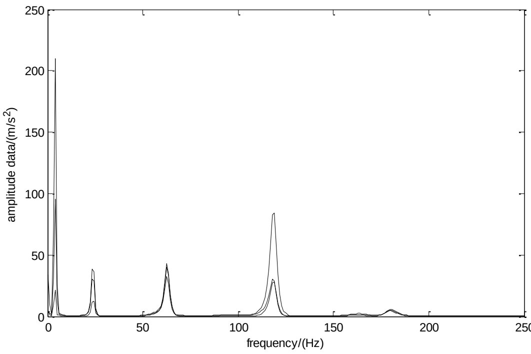

FIGURE 10 Curve for cross-power spectrum between channel 4 and channel 1~3

Then, the phase diagrams and relevant functional diagrams between Channel 4 and Channel 1~3 were checked, respectively to further judge the accuracy of these peak frequencies and determine the inherent frequency of wind turbine blade as shown in Table 2 and Table 3.

TABLE 2 Measurement results of frequency of wind turbine blade in waving direction

	Order 1	Order 2	Order 3	Order 4
Inherent frequency/Hz	3.906	23.44	62.5	119.1

TABLE 3 Measurement results of frequency of wind turbine blade in swinging direction

	Order 1	Order 2	Order 3
Inherent frequency/Hz	18.1	62.2	86.3

Finally, the amplitude of oscillation mode of modal in each order can be obtained by reading the corresponding value of inherent frequency in transmission rate curve. Then, mode amplitudes of sensors were normalized. curve-fitting for oscillation curve for overall blade structure can be obtained by fitting the oscillation curve. Figure 11 is the curve-fitting of the first order oscillation mode in blade waving direction.

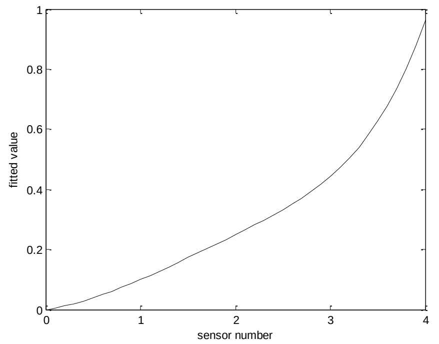

FIGURE 11 Curve-fitting of oscillation mode in waving direction of the first order

The major damage to wind turbine blade in practical operation is crack which is mainly transverse crack. Therefore, in this experiment, the damage was stimulated by crack in a unit of blade [20], and different damage degrees were simulated with different crack depth. In the experiment, the simulated crack depth (h/D, where D is diameter and h is damage depth, mm) is 31.4% and 50.8%, respectively. Then, operational modal analysis was conducted to damaged wind turbine blade by the same way as above to obtain dynamic features in different damage degrees as shown in Table 4 and Table 5. It is assumed that cracks will not affect the quality distribution of structure, and cracks may reduce the overall stiffness of blade structure.

TABLE 4 Measurement results of frequency of wind turbine blade in waving direction after damage

Damage degree/%	Order 1	Order 2	Order 3	Order 4
31.4	2.93	20.51	59.57	116.2
50.8	2.306	20.04	57.52	114.3

Taking the minimum inherent frequency and oscillation mode error as target function for designed optimization by equation (9), above 3 algorithms were adopted, respectively, to conduct detection study on this structure with measurements as shown in Table 6. According to Table 6, the damage identifications in all conditions by above 3 algorithms all reached satisfied effects, while the identification results for damage diagnosis by MFOA was much closer to the real value of structural damage. It can be seen that MFOA can effectively identify structural damage, and its identification accuracy is superior to that of basic FOA and GA.

TABLE 5 Measurement results of frequency of wind turbine blade in swinging direction after damage

Damage degree/%	Order 1	Order 2	Order 3
31.4	16.9	59.6	84.5
50.8	15.1	57.7	81.7

TABLE 6 Identification of damage to wind turbine blade

Damage degree/%	GA/%	FOA/%	MFOA/%
31.4	33.6	34.1	32.2
50.8	52.1	51.7	51.2

6 Conclusions

This work proposed a diagnosis method for structural damage of wind turbine blade based on modified fruit fly algorithm. Following conclusions were drawn by numerical simulation and experimental verification:

1) Fruit fly algorithm is featured with overall optimization, so good results were obtained by identifying with structural damage position and degree of wind turbine blade in this work. In addition, fruit fly algorithm can also play a role in identification of other large-scale complex structures.

2) Fruit fly algorithm is featured with fast convergence, simple realization, few parameters, etc., and the convergence performance of modified algorithm is obviously superior to basic FOA and GA, so MFOA can better apply to parameter identification. Therefore, it can play an important role in diagnosis for structural damage of wind turbine blade.

3) MFOA proposed in this work cannot only apply to the diagnosis of structural damage, but also the constraint optimization with multiple design variants.

This work mainly verified the effectiveness of MFOA in identification for damage of wind turbine blade, but it does not involve the slight damage to blade structure. Therefore, the accurate judgment of slight structural damage is the subsequent problem to be solved.

Acknowledgement

This paper was funded by Science and Technology Support Fund of Lanzhou Jiaotong University (ZC2012008).

References

[1] Y. P. Hu, J. C. Dai, D. S. Liu 2013 Research status and development trend on large scale wind turbine blades *Journal of Mechanical Engineering* **49**(20),140-51

[2] Y. Guo, Z. K. Wang 2011 A comparison between european and chinese offshore wind power industries *Sino-Global Energy* **16**(3),26-30

[3] J. Tao, X. Zhang, Y. L. Liu, M. H. Xu 2013 Discussion on the present situation and prospects of wind power generation in china *Modern Machinery* (3),26-28

[4] C. X. Luo 2012 Wind power generation today in the world and prospect forecast *Sino-Global Energy* **17**(3),24-30

[5] Y. Qu, C. Z. Chen, H. Wu, B. Zhou 2012 Research on crack recognition of blade based on acoustic emission and neural network *Machinery Design & Manufacture* (3),152-54

[6] X. F Chen, J. M. Li, H. Cheng, B. Li,Z. J. He 2011 Research and application of condition monitoring and fault diagnosis technology in wind turbines *Journal of Mechanical Engineering* **47**(9), 45-52

[7] J. S. Xiao, T. P. Yan 2006 Numerical analysis of NDT of wind turbine blades using infrared imaging *Journal of Beijing University of Technology* **1**(32),48-52

[8] Zhu H P 2008 *Intelligent Method for Structural Damage Detection* China Communication Press:Beijing

[9] A. Morassi, N. Rovere 1997 Localizing a notch in a steel frame from frequency measurements *Journal of Engineering Mechanics-Asce* **123**(5),422-32

[10] J. M. Ndambi, J. Vantomme, K. Harri 2002 Damage assessment in reinforced concrete beams using eigenfrequencies and mode shape derivatives *Engineering Structures* **24**(4),501-15

[11] A. Rao, J. Srinivas, B. S. N. Murthy 2004 Damage detection in vibrating bodies using genetic algorithms *Computers & Structures* **82**(11/12),963-68

[12]Y. Q. Yu,C. Bi 2010 Diagnosis of crack of rotor blades with genetic method *IEEE Computer Society* ,362-367

[13] Y. Tian, B. D. Zhang, D. W. Liu,F. Wang,H. F. Wu,X. Chen,P. Shi 2012 Status tend prediction of GRNN hydroelectric generating set based on fruit fly optimization *Water Resources and Power* **30**(12),127-29

[14] Pan W C 2011 *Fruit Fly Optimization Algorithm* Canghai Publishing House :Taipei

[15] Z. Xiang, T. Y. Zhang, J. C. Sun 2006 Prediction algorithm for fast fading channels based on the chaotic attractor *Journal of Xidian University* **33**(1),145-49

[16] X. M. Lv, K. L. Huang, G. Y. Lian 2010 Optimizing strategy of system level fault diagnosis based on chaos particle swarm optimization *Systems Engineering and Electronics* **32**(1),217-20

[17] S. Z. Chen, L. P. Li, F. H. Jing 2010 Three-dimensional modeling of wind machine blade and finite element calculation of dynamic features *Renewable Energy Resources* **28**(3),30-34

[18] Yu F H, Liu R Y 2010 *Computer Intelligent Technology and Its Engineering Application* Science Press:Beijing

[19] D. Z. Jiang, M. Hong 2010 Application of operational modal analysis in vibration of ship structures *Chinese Journal of Ship Research* **6**(5),22-26

[20] L. P. Li, M. M. Li, F. H. Jin, H. B. Li 2013 Application of oscillation detection technology in crack failure monitoring of wind turbine blade *Thermal Energy Engineering* **28**(2),23-27

Authors

Guimei Gu, 1970.02, Xingcheng City, Liaoning Province, P.R. China

Current position, grades: the Associate Professor of School of Automation and Electrical Engineering, Lanzhou Jiaotong University, China.
University studies: received her B.En. and M.En. from Lanzhou Jiaotong University in China.
Scientific interest: Her research interest fields include failure diagnosis of blades in wind turbine generator, Intelligent information processing
Publications: more than 10 papers published in various journals.
Experience: She has teaching experience of 20 years, has completed three scientific research projects.

Zheng Wang , 1988.09, Baoding City, Hebei Province, P.R. China

Current position, grades: the Graduate student of School of Automation and Electrical Engineering, Lanzhou Jiaotong University, China.
University studies: received her B.Eng. and M.Eng. from North China Institute of Science and Technology and Lanzhou Jiaotong University in China respectively.
Scientific interest: Her research interest field is failure diagnosis of blades in wind turbine generator.
Publications: 2 papers published in Fiber Reinforced Plastics/Composites.
Experience: She has researched the failure diagnosis theory more than 2 years and now is participating in a project about failure diagnosis of wind turbine blade.