

**O. A. Basalkevych, D. V. Rudavskiy***Lviv Polytechnic National University, Lviv, Ukraine*

MODEL AND SOFTWARE MODULE FOR CALCULATING FATIGUE DAMAGE ACCUMULATION IN THE WIND TURBINE BLADE ROOT

Due to the rapid depletion of fossil fuel reserves and the intensification of problems associated with global warming, humanity is increasingly focusing on renewable energy sources. They have become not only an essential component of modern energy systems but also a foundation for the sustainable development of the future. Wind energy, as one of the most accessible sources of renewable energy, is attracting growing interest from both governments of developed countries and private investors. Modern wind turbines are becoming progressively larger, and their blades, which are key components for energy generation, are continually subjected to damage caused by the aggressive influence of the external environment and cyclic (i.e., time-varying) loads. Consequently, the issues of reliability and safety are paramount for ensuring the uninterrupted supply of electricity to both the population and businesses. To effectively monitor the condition of wind turbines, and particularly their blades, it is necessary to employ information technologies that enable precise and timely detection of potential failures and optimize maintenance processes [1].

The paper analyses and synthesizes a classification of general methods and tools for determining the remaining service life of components subjected to cyclic loads. The concept of a model for predicting the residual service life of the wind turbine blade root is described in detail. Test input data were generated using modern professional software packages for wind turbine dynamics modelling such as OpenFAST and TurbSim. The detailed description of the proposed solution architecture and a flowchart of the developed method algorithm for fatigue assessment of the cross-sectional sectors of the 5 MW wind turbine blade root are provided. The algorithm employs the rainflow counting method and the Palmgren – Miner hypothesis of linear damage accumulation. Based on these foundations software module was developed to implement the proposed model and the obtained results make it possible, at a first approximation, allow predicting the fatigue life of the root of a wind turbine blade after simulated dynamic loads.

Keywords: wind turbine, fatigue life, rainflow method, hypothesis of linear damage accumulation, parallel computing.

Introduction

Over the past decades, wind energy has become one of the most prominent directions in the field of renewable energy sources. Each year, the total capacity of wind power plants continues to grow steadily, reflecting the increasing interest in this type of energy from both developed countries and private investors.

Monitoring the condition and detecting damage to wind turbine blades is a leading and critically important area of research. Approximately 20 % of failures involve the blades [2], which are key components for converting the kinetic energy of air masses into electricity. They are often damaged due to complex operating conditions and high, irregular mechanical loads. The most hazardous are crack-like defects, particularly fatigue cracks, as they act as stress concentrators and can rapidly propagate during operation [3]. Longitudinal and transverse cracks in the root sections of wind turbine blades are primarily caused by high stresses resulting from geometric changes and fatigue loading in this area [4].

For effective monitoring of modern high-capacity wind turbines, particularly their blades, it is necessary to utilize information technologies that enable accurate and timely detection of potential faults and optimize maintenance processes.

The object of the study is the processes of blade root failure in wind turbines under the influence of irregular, cyclic, and time-varying loads.

The subject of the study is modern methods and tools for monitoring the condition of wind turbine blades, specifically the root area, and predicting their fatigue life using information technologies.

The aim of the study is to analyse methods and tools for assessing the fatigue life of wind turbine blade roots and, based on the identified shortcomings, propose an improved model.

To achieve the stated goal, the following *key research tasks* were defined:

- analysis of general methods and tools for determining the lifespan of load-bearing structural elements subjected to irregular cyclic operational loads;

- synthesis of the classification of modern methods and tools for assessing the lifespan of materials operating under conditions of irregular cyclic loads;
- development of the improved model for predicting the fatigue life of a wind turbine blade root;
- comparison of the developed model with a literature-known counterpart;
- development of a software module for implementing the proposed model.

Materials and methods. To achieve the set goal, a method of simulating wind speed fields was used based on statistical data. Additionally, for creating a model for predicting the fatigue longevity of the wind turbine blade root, a combination of the Rainflow Cycle Counting Techniques [5] and the Palmgren – Miner linear damage accumulation hypothesis [6] was employed.

Recent research and publications analysis. Determining the resource of materials subjected to irregular cyclically varying loads is one of the most important tasks in fracture mechanics and materials science. Modern methods and approaches to solving this issue can be divided into experimental, computational, and diagnostic categories.

Experimental methods are based on fatigue testing and fracture monitoring, allowing for the direct measurement of material resistance to cyclic loads through experimental tests and observations of crack development

Fatigue tests. Samples of materials are subjected to controlled cyclic loads until failure. The data collected is used to construct S-N curves, which depict the relationship between the number of cycles to failure and the load amplitude [7].

Computational methods use computer modelling to analyse the distribution of mechanical loads and predict fatigue longevity.

Finite element method. This technique allows for the modeling of the distribution of mechanical stress and strain fields within a material, thus predicting areas with a high likelihood of fatigue crack initiation [8].

Assessment of fatigue longevity. This is based on damage accumulation models in the material over its service life, such as the Palmgren – Miner linear damage accumulation model [6].

Diagnostic methods help to detect internal defects and cracks without the need to destroy the material, providing real-time quality control.

Non-destructive testing includes ultrasound and acoustic diagnostics, magnetic-particle inspection, radiography, etc. [1], to identify cracks and other defects.

Sensor monitoring involves the use of sensors for continuous real-time monitoring of mechanical stresses and deformations in the material of the research objects, allowing for the early detection of failure processes.

Also it is important to highlight modern approaches based on machine learning. Contemporary big data analysis and machine learning methods are used to predict resource longevity based on empirical data. They enable the identification of hidden patterns that are not always apparent when using traditional analysis methods [9].

Each of the aforementioned methods has its advantages and limitations. They are often combined for more accurate predictions of remaining resource and prevention of sudden failures. A comprehensive approach provides more reliable results, especially for complex engineering structures.

The model proposed by researchers M. Sirigu, E. Faraggiana, A. Ghigo, E. Petracca, G. Mattiazzo, and G. Bracco in their scientific paper “Development of a simplified blade root fatigue analysis for floating offshore wind turbines” employs a combination of experimental and computational methods to attempt to predict the fatigue longevity of the wind turbine blade root based on artificially generated wind speed fields. Its advantages include simplicity and speed of result attainment. However, the proposed approach exhibited very low accuracy, with the three presented models predicting fatigue longevity ranging from 581 to 1215 years (see Table 4 [10]) compared to an average value of 20–25 years [11].

The approaches outlined in the aforementioned paper serve as the foundation for developing an improved model.

Research results and their discussion

As auxiliary tools providing input data for the model, the software tools OpenFAST and TurbSim were used.

OpenFAST is a free software package for modelling the dynamics of wind turbines. It was developed by the U. S. National Renewable Energy Laboratory (NREL). Using this software, simulations were created that, based on an input file with wind characteristics, determine the force parameters of the operational load on the wind turbine blade root, which are necessary for further modelling.

TurbSim is a component of OpenFAST designed to generate random wind velocity fields used in modelling the behaviour of wind turbines. It takes into account a number of factors, including the main geometric parameters of the turbine, the average wind speed, its turbulence, and others, which allow for the creation of more realistic and accurate models of wind flows. With the help of this software, files containing time-dependent wind speed data are generated.

Fig. 1 shows the overall scheme of the proposed method for predicting the fatigue life of a wind turbine blade root.

Wind turbine farms are typically installed in coastal and mountainous areas due to the advantages these locations offer for energy production. In such regions, winds are characterized by more stable and stronger flows. Mountainous areas are also distinguished by low population density and large open spaces, which allow for the placement of a significant number of turbines.

The vector field of wind speed distribution for further calculations was generated based on statistical wind speed data for the Wellington region (New Zealand) since the area is known for strong winds, and the wind energy sector is well-developed there [12]. Wind speed fields were generated separately for each month of the year based on 30 years of historical wind speed data for this region (see Fig. 2).

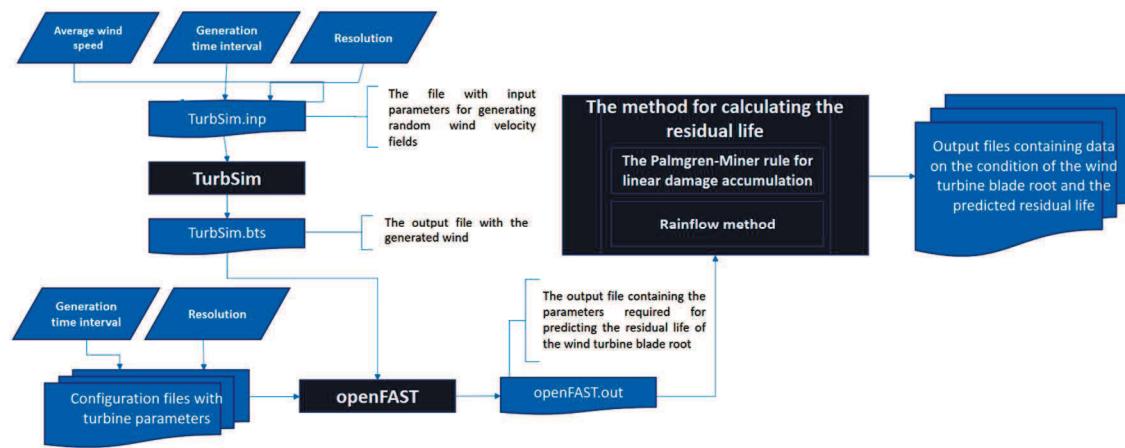


Fig. 1. The overall scheme of the proposed method for predicting the fatigue life of a wind turbine blade root

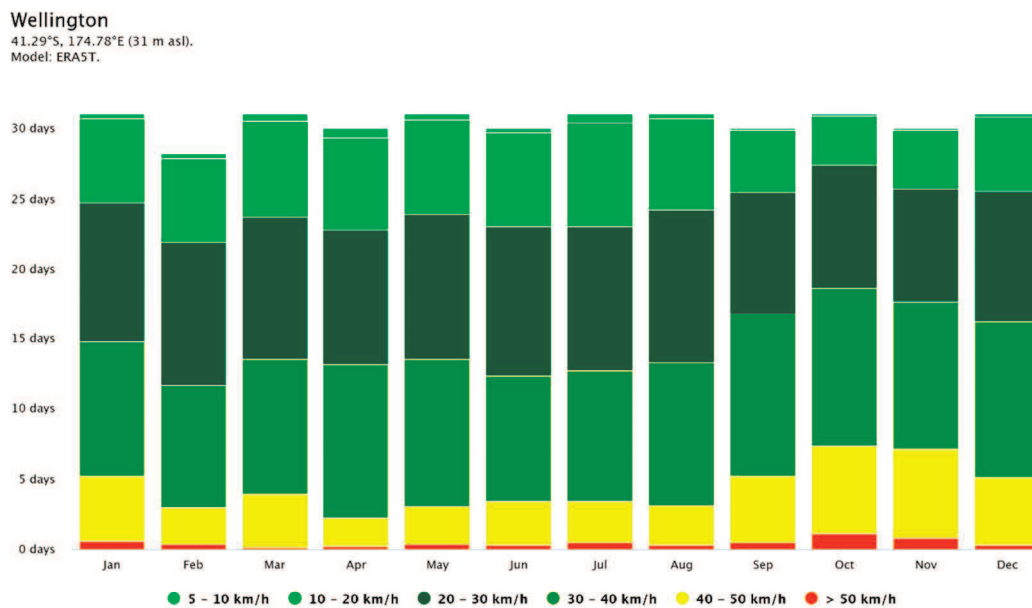


Fig. 2. Annual distribution of wind speed in Wellington area (New Zealand) for 30 years [13]

Table 1. The average monthly wind speed in Wellington

Month	Average wind speed, m/s	Month	Average wind speed, m/s	Month	Average wind speed, m/s
January	8.22	May	7.80	September	8.60
February	7.80	June	7.78	October	9.03
March	7.84	July	7.67	November	8.91
April	7.66	August	7.83	December	8.38

The average wind speed was calculated for each month (see Table 1). Based on this data, 12 files were generated using the TurbSim package, each containing 86,400 seconds (1 day) of wind speed data with a characteristic average value for the corresponding month of the year.

Using the OpenFAST package, 12 corresponding files were generated, each containing data on the blade load dynamics of a 5 MW wind turbine over 86,400 seconds (1 day) for each month of the year with a sampling frequency of 0.015 seconds. Each resulting file contains a table with 6 columns and 5,760,000 rows of data (see Table 2).

Table 2. Structure of output files generated by OpenFAST

Column name	Units of measurement,	Description
Time	s	Time of measurement
RootMxb1	kN · m	Blade 1 edgewise moment at the blade root
RootMyb1	kN · m	Blade 1 flapwise moment at the blade root
RootMzb1	kN · m	Blade 1 pitching moment at the blade root
RootFzb1	kN	Blade 1 axial force at the blade root
B1Pitch	°	Pitch angle of blade 1

The fatigue failure analysis of the blade root was performed for the case of uniaxial tension-compression within its volume, caused by bending moments on the blade due to aerodynamic and gravitational forces, as well as axial force induced by gravity and centrifugal effects. The influence of the shear force and torsional moment at the blade root was not considered. The mechanical tensile stress σ was calculated using formula (1) for each segment of the blade root cross-section with a discretization of 1 degree [10]:

$$\sigma = \frac{R}{J} (M_x \cos(\alpha + \beta) + M_y \sin(\alpha + \beta)) + \frac{N}{A}, \quad (1)$$

where M_x is the edgewise moment at the blade root; M_y is the flapwise moment at the blade root; R is the radius of the blade root cross-section; N is the axial force; α is the pitch angle; β is the angle defining the center of the current segment of the blade root cross-section; A is the area of the blade root cross-section; and J is the polar moment of inertia of the blade root cross-section.

The polar moment of inertia of the blade root cross-section J is calculated using formula [14]:

$$J = \frac{(D^4 - d^4) \cdot \pi}{32}, \quad (2)$$

where D is the outer diameter of a circle; d is the inner diameter of a circle.

The area of the blade root cross-section A can be calculated using formula:

$$A = \pi(R^2 - r^2), \quad (3)$$

where R is the radius of the outer circle; r is the radius of the inner circle.

The thickness of the blade root of a 5 MW turbine varies from 50 to 80 mm [15]. A value of 60 mm was used for the subsequent calculations. The outer radius provided in the standard configuration file of OpenFAST is 1.5 m (parameter HubRad, file NRELOffshrBsline5MW_Onshore_ElastoDyn.dat, turbine 5MW_Land_DLL_WTurb).

Arrays of mechanical tensile stresses σ , calculated for each of the 360 sectors of the blade root cross-section of the wind turbine, serve as input data for the rainflow counting method [5]. This method transforms the obtained cyclically varying irregular load into sets of cycles with equal amplitudes.

The final stage of the calculation involves the use of the Palmgren – Miner rule [6] for linear damage accumulation. Its main idea is that damage accumulation in a material is directly proportional to the number of load cycles. By summing up the damage caused by each load cycle, a measure of the total fatigue damage of the material is obtained, with its critical value assumed to be equal to one.

To apply the Palmgren – Miner rule, it is necessary to have an S-N curve [7], which describes the fatigue properties of the respective polymer material used to manufacture the root of the wind turbine blade. In our case, the calculation was performed for fiberglass with a tensile strength of $S_{ut} = 396$ MPa and a normalized fatigue curve slope of $m' = 0.1$ [10]. Its equation is as follows:

$$\lg N = \frac{S_{ut}^2 - \sigma_a \cdot S_{ut} - \sigma_m \cdot S_{ut}}{m(S_{ut} - \sigma_m)}, \quad (4)$$

where σ_a and σ_m are the amplitude and the mean value of the normal stresses in regular cycles obtained using the rainflow method from the irregular original loading; $m = m' \cdot S_{ut}$.

Research results discussion. Fig. 3 shows the flowchart of the algorithm for the developed method of calculating fatigue damage in the root sections of a wind turbine blade.

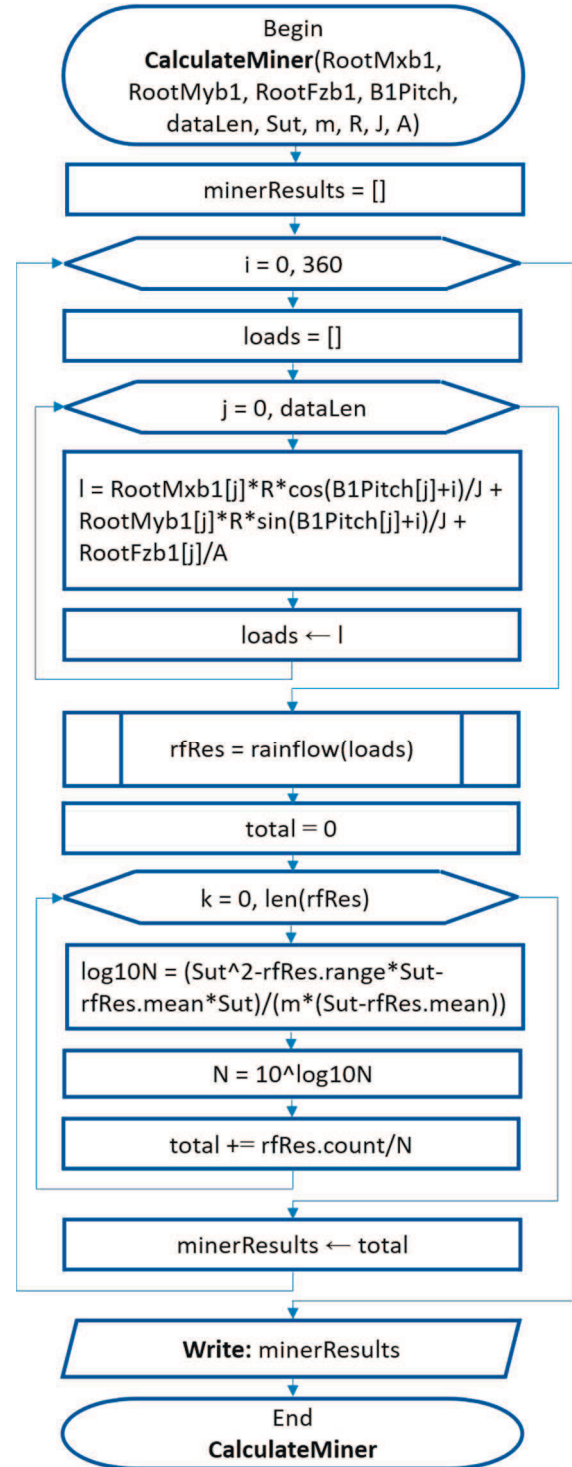


Fig. 3. Flowchart of the algorithm for the developed method of calculating the wind turbine blade root sectors fatigue

According to the Palmgren – Miner rule, it was assumed that the fatigue life of the blade root is exhausted when the value of the accumulated fatigue damage P reaches 1 in at least one of the sectors of the cross-section of the blade root. Therefore, by identifying the sector that experiences the

highest load during the entire operational period, the time at which the value of P will reach 1 in that sector is calculated using linear extrapolation.

A software module has been developed for the implementation of the proposed model (see Fig. 4).

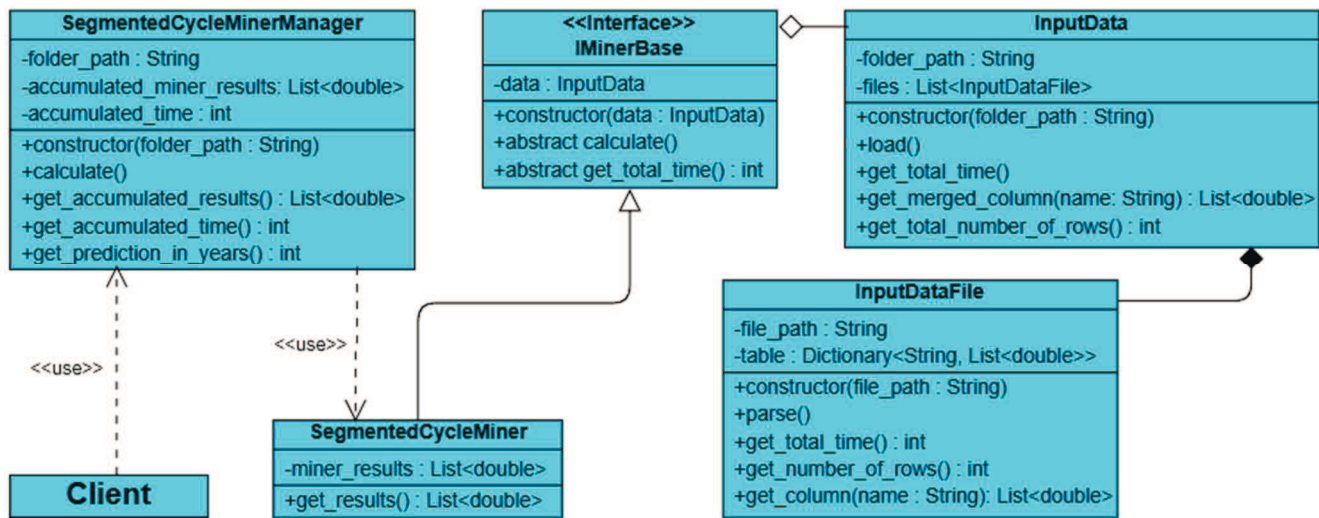


Fig. 4. UML class diagram for the developed model calculating the fatigue life of a wind turbine blade root

The *SegmentedCycleMiner* class, which implements the *IMinerBase* interface, performs calculations according to the algorithm shown in Fig. 3. Its *get_results* method returns a list of 360 elements of type *double*, each containing the value of the accumulated fatigue damage in a segment of the wind turbine blade root, determined by the corresponding angle. Tables generated by the OpenFAST package are read and stored in *InputDataFile* class objects after calling the *parse* method. Each such object contains the data of a single file. Using the *get_column* method, it is possible to retrieve the data of a column by its name, which is specified by the *name* parameter. The *InputData* class contains a collection of *InputDataFile* objects, representing all the collected input data for the experiment. This class provides an interface for determining the total experiment duration, the total number of data rows, as well as obtaining a combined column of data by the specified name.

As mentioned above, to ensure a high sampling rate of 0.015 s, each of the 12 input data files, representing one month of the year, contains a table with 6 columns and 5,760,000 rows. Sequential computations based on such a large amount of data are time-inefficient and require significant amounts of RAM. Therefore, each instance of the *SegmentedCycleMiner* class performs its calculations in separate threads. The number of the threads is specified in the program configuration. The *SegmentedCycleMiner Manager* class manages the operation of the *Segmented CycleMiner* objects. Their number can be configured based on the CPU performance and the amount of available RAM on a specific personal computer. Upon completion of the calculations, the next task for *SegmentedCycleMiner Manager* is to gather and consolidate the results obtained

from all *SegmentedCycleMiner* objects. The client code (*Client*) interacts only with the *SegmentedCycleMiner Manager* class, providing a simple and convenient interface. The constructor accepts the path to the directory containing all necessary input files. Calling the *calculate* method initiates the series of calculations described above. Once completed, the user can retrieve an array of accumulated fatigue damage values for each cross-sectional sector of the blade root using the *get_accumulated_results* method. The total experiment duration and the predicted turbine lifespan in years are available via the *get_accumulated_time* and *get_prediction_in_years* methods, respectively.

The proposed model has been implemented using Python programming language. For the 5MW turbine under consideration, the predicted lifespan was calculated to be 164.08 years. This result is more than 3.5 times better than the prediction obtained in [10]. This improvement is primarily due to the fact that this study addresses the problem of processing large datasets using a software solution with parallel computations rather than by simplifying the mathematical model of fatigue failure processes. However, the result still significantly deviates from the practical average lifespan values of 20–25 years commonly observed in real-world scenarios. Nevertheless, considering that this study employed a relatively simplified mechanical model, which, in particular, does not account for the effects of torque and shear forces in the blade root material, and the safety factor was also not taken into account, the calculated results obtained in this study can still be considered acceptable.

The following provides a portion of the source file with calculations for the root blade sectors (see Table 3).

Table 3. Fragment of the calculation of accumulated fatigue damage in the sectors of the blade root

Blade root sector number	Accumulated fatigue damage during experiment
1	5.782655053571344e-05
2	5.836736715987757e-05
3	5.897961127324312e-05
4	5.962046143909374e-05
5	6.04008068710324e-05
6	6.117528287662825e-05
7	6.203107468464909e-05
...	...
360	5.7434288020052686e-05

Fig. 5 presents a visualization of the predicted fatigue of the root blade sectors of the wind turbine operating in a simulated mode for 80 % of the calculated predicted service life.

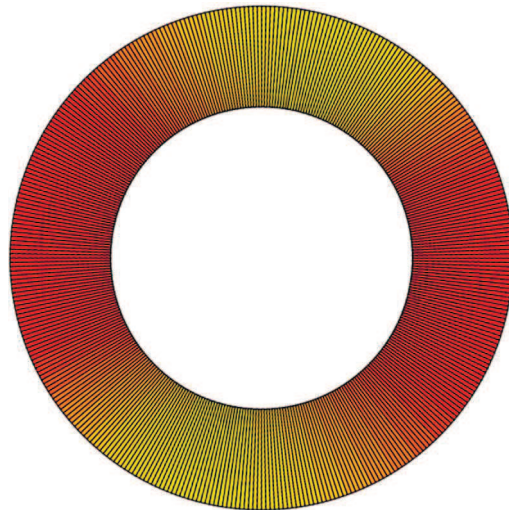


Fig. 5. Visualization of the predicted fatigue of the wind turbine blade root sectors during operation in a simulated mode for 80 % of the calculated predicted lifespan

Darker colours in Fig. 5 indicate sectors experiencing higher operational loads, while the fatigue of lighter-coloured sectors is lower.

The scientific novelty of the obtained research results lies in the improvement of the model that allows to predict the fatigue durability of the wind turbine blade root. As a result, the obtained outcome is more accurate compared to analogous calculations reported in the literature.

The practical significance of the research results lies in the development of a software tool for implementing a method to predict the fatigue durability of the wind turbine blade root with the capability to visualize the kinetics of fatigue damage accumulation. The proposed solution utilizes parallel computations and loads data into the computer's memory in parts, with the ability to configure the number of threads and the size of data blocks, enabling program optimization based on the processor speed and the available RAM size.

Conclusions

Predicting the service life of composite materials is an important task in the design of wind turbine blades, as there is a trend toward increasing their size, leading to higher operational loads. The development of effective methods and tools for assessing their safe operating periods can prevent unforeseen turbine failures with significant financial losses and, consequently, reduce the cost of generated energy.

Within this paper, an analysis has been conducted, and a classification of general methods and tools for determining the fatigue durability of structural elements subjected to cyclic loading has been synthesized.

The concept of a model for predicting the fatigue durability of a wind turbine blade is described in detail. Based on the proposed architecture, a software module was developed to implement the presented model, yielding results that are significantly better than those of similar calculations described in [10].

References

- [1] Basalkevych, O. A., Rudavskyy, D. V. (2023). The modern state of approaches to monitoring the technical condition of wind turbine blades using information technologies. *Ukrainian Journal of Information Technologies*, 2023, 5(2), 79–87 [in Ukrainian].
- [2] Wang, W., Xue, Y., He, C., Zhao, Y. (2022). Review of the Typical Damage and Damage-Detection Methods of Large Wind Turbine Blades. *Energies*, 2022, 15(15), 56–72. <https://doi.org/10.3390/en15155672>
- [3] Rudavskyy, D. V. (2011). Residual resource of metal structural elements in Hydrogen-containing environments. Kyiv: Naukova Dumka [in Ukrainian].
- [4] Ataya, S.; Ahmed, M.M. (2013). Damages of wind turbine blade trailing edge: Forms, location, and root causes. *Engineering Failure Analysis* 2013, 35, 480–488. <https://doi.org/10.1016/j.engfailanal.2013.05.011>
- [5] Lee, Y., Barkley, M., Kang H.-T. (2012). Metal Fatigue Analysis Handbook. Practical problem-solving techniques for computer-aided engineering: Chapter 3 – Rainflow Cycle Counting Techniques, pp. 89–114. <https://doi.org/10.1016/B978-0-12-385204-5.00003-3>
- [6] Lee, Y., Barkley, M., Kang H.-T. (2012). Metal Fatigue Analysis Handbook. Practical problem-solving techniques for computer-aided engineering: Chapter 9 – Vibration Fatigue Testing and Analysis, pp. 333–382. <https://doi.org/10.1016/B978-0-12-385204-5.00003-3>
- [7] Matsunaga, H. (2021). Essential Structure of S-N curve: Prediction of Fatigue Life and Fatigue Limit of Defective Materials and Nature of Scatter. *International Journal of Fatigue*, 2021, 146(5):106–138. <https://doi.org/10.1016/j.ijfatigue.2020.106138>
- [8] Zienkiewicz, O. C., Taylor, R. L., Zhu, J.Z. (2013). The Finite Element Method: Its Basis and Fundamentals. Seventh Edition, 2013. <https://doi.org/10.1016/C2009-0-24909-9>
- [9] Chandrasekhar, K., Stevanovic, N., Cross, E. J., Dervilis, N., Worden, K. (2021). Damage detection in operational wind turbine blades using a new approach based on machine learning. *Renewable energy*, 168, 1249–1264. <https://doi.org/10.1016/j.renene.2020.12.119>

- [10] Sirigu, M., Faraggiana, E., Ghigo, A., Petracca, E., Mattiazzo, G., Bracco G. (2022). Development of a simplified blade root fatigue analysis for floating offshore wind turbines. *Trends in Renewable Energies Offshore*, 2022, 935–941. <https://doi.org/10.1201/9781003360773-103>
- [11] Majewski, P., Florin, N., Jit, J., Stewart, R. A. (2022). End-of-life policy considerations for wind turbine blades. *Renewable and Sustainable Energy Reviews*, 2022, 164. <https://doi.org/10.1016/j.rser.2022.112538>
- [12] New Zealand Wind Energy Association. Wind Energy Association. Retrieved November 24, 2024, from <https://www.windenergy.org.nz/>
- [13] Meteoblue. Simulated historical climate & weather data for Wellington. Retrieved November 24, 2024, from https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/wellington_new-zealand_2179537
- [14] Structural Basics. Polar moment of inertia formulas. Retrieved November 24, 2024, from <https://www.structuralbasics.com/polar-moment-of-inertia-formulas>
- [15] Chrétien, A., Tahan, A., Pelletier, F. (2024). Wind Turbine Blade Damage Evaluation under Multiple Operating Conditions and Based on 10-Min SCADA Data. *Energies*, 2024, 17(5), 1202. <https://doi.org/10.3390/en17051202>

О. А. Басалкевич, Д. В. Рудавський

Національний університет "Львівська політехніка", м. Львів, Україна

МОДЕЛЬ ТА ПРОГРАМНИЙ МОДУЛЬ ДЛЯ ОБЧИСЛЕННЯ НАКОПИЧУВАННЯ ВТОМНОГО ПОШКОДЖЕННЯ У КОРЕНІ ЛОПАТІ ВІТРОВОЇ ТУРБІНИ

Унаслідок стрімкого вичерпання запасів викопних енергоресурсів, а також загострення проблем, пов'язаних із глобальним потеплінням, людство все більше звертає увагу на відновлювані джерела енергії. Вони не лише стають важливим елементом сучасної енергетики, але й формують основу для сталого розвитку майбутнього. Вітроенергетика, як одне з найдоступніших джерел відновлюваної енергії, викликає все більший інтерес з боку як урядів розвинених країн, так і приватних інвесторів. Сучасні вітрогенератори стають дедалі більшими, а їхні лопаті, що є ключовими елементами для генерації енергії, постійно зазнають пошкоджень через агресивний вплив зовнішнього середовища та циклічних, тобто змінних у часі, навантажень. Отже, проблема їх надійності та безпеки є однією з найважливіших для безперерйного забезпечення електроенергією населення та бізнесу. Для ефективного моніторингу стану сучасних вітрогенераторів та, зокрема, їхніх лопатей необхідно використовувати інформаційні технології, які дають змогу точно та своєчасно виявляти потенційні несправності й оптимізувати процеси технічного обслуговування [1].

У статті здійснено аналіз та синтезовано класифікацію загальних методів та засобів визначення ресурсу несучого елемента, що зазнає циклічних навантажень. Детально описано концепцію моделі для прогнозування втомної довговічності кореня лопаті вітрової турбіни, тестові входні дані для якої згенеровано за допомогою сучасних професійних програмних пакетів для моделювання динаміки вітрових турбін OpenFAST та TurbSim. Наведено детальний опис архітектури запропонованого рішення та блок-схему алгоритму розробленого методу визначення втоми секторів поперечного перерізу кореня лопаті вітрової турбіни потужністю 5 МВт, що використовує метод дощового потоку та гіпотезу лінійного накопичення пошкоджень Пальмгрена – Майнера. На їх основі розроблено програмний модуль для реалізації запропонованої моделі та отримано результати, які у першому наближенні дають змогу спрогнозувати втомну довговічність кореня лопаті вітрової турбіни після симульованих динамічних навантажень.

Ключові слова: вітрова турбіна, втомна довговічність, метод дощового потоку, гіпотеза лінійного підсумування пошкоджень, паралельні обчислення.

Інформація про авторів:

Басалкевич Олександр Андрійович, магістр, аспірант, кафедра автоматизованих систем управління. Email: oleksandr.a.basalkevych@lpnu.ua; <https://orcid.org/0009-0001-3049-9901>

Рудавський Денис Володимирович, д-р техн. наук, старший науковий співробітник, професор, кафедра автоматизованих систем управління. Email: denys.v.rudavskiy@lpnu.ua; <https://orcid.org/0000-0001-5541-3003>

Цитування за ДСТУ: Басалкевич О. А., Рудавський Д. В. Модель та програмний модуль для обчислення накопичування втомного пошкодження у корені лопаті вітрової турбіни. *Український журнал інформаційних технологій*. 2025, т. 7, № 1. С. 45–51.

Citation APA: Basalkevych, O. A., & Rudavskiy, D. V. (2025). Model and software module for calculating fatigue damage accumulation in the wind turbine blade root. *Ukrainian Journal of Information Technology*, 7(1), 45–51. <https://doi.org/10.23939/ujit2025.01.045>