Wind turbine tower failure analysis and wind-induced vibration control

Hui Gao, Xing Li *
School of Civil Engineering, Erdos Institute of Technology, Ordos, Inner Mongolia, China
*Corresponding author: 20090040@oit.edu.cn

Abstract. Wind energy has great potential for development in clean energy. The economic loss caused by the destruction of the wind turbine tower in a wind turbine failure is very huge. Therefore, this paper analyzes the gray correlation between the tower damage type and the cause of the damage. The results show that storms, pitch system failure, and wind speed exceeding the design wind speed have a good correlation with the tower damage type. In a storm environment, the dynamic response of the tower top of the wind turbine tower is relatively large, even leading to the overall collapse of the tower. The tuned mass damper (TMD) has an obvious damping effect on the wind vibration response of the tower.

1. Introduction
With the impact of human activities on the climate, the climate crisis has become more and more serious. A series of natural disasters tell us that the top priority is to reduce greenhouse gas emissions. Countries continue to take actions to deal with climate change and clarify the target time for carbon peak and carbon neutrality. In recent years, my country has vigorously developed clean energy. The installed capacity, power generation, consumption and investment scale of clean energy have increased year by year. Among them, wind power installed capacity and power generation rank second in clean energy, as shown in Figure 1. And from the perspective of development potential and development speed, wind energy ranks second among the six major renewable energy sources, second only to hydropower [1].

![Fig 1. Power generation and installed capacity of various types of clean energy.](image-url)
2. Correlation analysis on the causes of wind turbine tower failure

The destruction of the wind turbine tower is a serious wind turbine failure. Either the overall collapse or partial fracture of the tower will cause huge economic losses. Based on the statistics of the failure causes of many wind farms, tower damage and overall overturning accounted for 25%, and blade failure accounted for 75% [2]. From 1997 to 2009, there were a total of 64 wind turbine tower collapse accidents around the world, of which 18 were of unclear reasons, and the remaining 44 were caused by storms and strong winds with more than 50% collapse [3], Figure 2. Jui-Sheng Chou et al. analyzed 44 global wind turbine tower collapse accidents from 2007 to 2017, and divided the tower damage into three types: buckling damage, bolt failure, and foundation damage [4]. Based on this data, this paper uses the gray correlation method to analyze the correlation between the tower damage type and the cause of the damage. In the analysis process, the average value method is used to process the data without dimension.

Grey Relational Analysis (GRA) [5] is a multi-factor statistical analysis method, which is based on the sample data of various factors and uses the degree of gray relevance to describe the strength, size and order of the relationship between the factors. In grey relational analysis, first determine the reference series \( X^*_0 = (x^*_0(1), x^*_0(2), \ldots, x^*_0(m)) \), m is the number of indicators. Secondly, determine the comparison sequence \( X_i = (x_i(1), x_i(2), \ldots, x_i(k)) \); \( i = 1, 2, \ldots, n, k = 1, 2, \ldots, m \). Calculate the correlation coefficient:

\[
\zeta_i(k) = \frac{\min \min |x_0(k) - x_i(k)| + \rho \cdot \max \max |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \cdot \max \max |x_0(k) - x_i(k)|}
\]

(1)

Where, \(|x_0(k) - x_i(k)|\) is the difference sequence, \( i = 1, 2, \ldots, n, k = 1, 2, \ldots, m \). \( \rho \) is the resolution coefficient, 0.5 is usually taken. Calculate the degree of relevance:

\[
r_i = \frac{1}{m} \sum_{k=1}^{m} \zeta_i(k)
\]

(2)

The results show that the three causes of storm, pitch system failure, and wind speed exceeding the design wind speed have a good correlation with the three types of tower damage, as shown in Table 1.
Table 1. Correlation analysis of the causes of tower collapse (2007-2017).

| Cause of collapse | Stormy environment | Pitch system failure | Wind speed exceeding designed range | Tower blade collisions | Bolt problems | Structural problems | Total |
|-------------------|--------------------|----------------------|-------------------------------------|------------------------|--------------|---------------------|-------|
| Buckling failure  | 11                 | 11                   | 4                                   | 3                      | 0            | 0                   | 29    |
| Bolt failure      | 9                  | 7                    | 9                                   | 0                      | 2            | 2                   | 29    |
| Bolt failure      | 0                  | 1                    | 3                                   | 0                      | 0            | 1                   | 5     |
| Average value     | 6.667              | 6.333                | 5.333                               | 1                      | 0.667        | 1                   | 21    |
| Correlation       | 0.829              | 0.783                | 0.667                               | 0.492                  | 0.492        | 0.484               | 1     |

3. Tower wind-induced vibration control
The destruction of the wind turbine tower is caused by the vibration of the structure. Mainly consider the vibration of the tower structure caused by wind loads such as strong winds and hurricanes, and secondly consider the excitation of the tower by the vibration generated by the wind turbine during operation [6]. In the construction state of the high tower, the incoming flow on the tower is prone to a certain period of vortex shedding. If the vortex shedding frequency is the same as the natural frequency of the tower structure, vortex-induced vibration will occur. The destructive power of the vortex-induced vibration on the tower can not be ignored, but the damage to the tower foundation will cause greater economic losses. Therefore, structural measures are generally taken to prevent the vortex-induced vibration of the tower during construction. In a storm environment, the dynamic response of the top of the wind turbine tower is relatively large, even beyond the allowable range [7]. In severe cases, the tower may collapse due to buckling damage or foundation damage. By improving the strength and vibration control of the tower, it can prevent the tower from overturning. Improving the strength of the tower requires a balance between safety and cost. Passive control is to place the control device inside the structure. When the structure is excited to produce vibrations, the control device starts to work and dissipate the vibration energy generated by the structure, thereby reducing the dynamic response of the structure. The most commonly used energy absorbing and vibration damping device is a tuned mass damper (TMD), which has a significant damping effect on the wind vibration response of the tower. In recent years, various countries have devoted themselves to the development of offshore wind turbines. Due to the complex offshore wind environment and high typhoon wind speed, the wind resistance of the tower has become an important design link to improve the reliability of the wind turbine and reduce economic losses. TMD can effectively control the vibration of offshore wind turbines under the coupling action of multiple loads of earthquakes, wind and waves.

4. Conclusions
(1) The gray correlation analysis of the damage type and the cause of the wind turbine tower, it is concluded that the main factor leading to the damage of the wind turbine tower is the storm environment, followed by the failure of the pitch system.
(2) In a storm environment, the dynamic response of the tower top of the wind turbine tower is relatively large, even leading to the overall collapse of the tower. The tuned mass damper (TMD) has an obvious damping effect on the wind vibration response of the tower.

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