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Structural vibration monitoring and operational modal analysis of offshore wind turbine structure

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ABSTRACT

In order to reduce the structural failure and accident occurrence of the offshore wind turbine, the researches on structural operational safety of offshore wind turbine based on the measured data during the operation periods should be carried out and considered as the key way to solve these problems. However, the current researches are only focused on numerical simulation, model experiment and theoretical analysis and ignore the structural vibration characteristics analyzed from condition monitoring and prototype observation data from the actual wind turbine structure. To compensate for this study defect, the structural vibration displacement signals of one Chinese offshore wind power prototype under different conditions were obtained based on a long-term prototype observation in order to achieve the comprehensive and systematic research on vibration response characteristics and operational modal analysis of measured structure. Considering the complicated operational environment of offshore wind turbines, the structural response regular pattern and vibration safety are also discussed emphatically under different conditions such as standstill, normal operational, startup, shutdown and extreme typhoon status. Simultaneously, the integral operational modal identification method of offshore wind turbine in the range of full power is proposed based on traditional and modified stochastic subspace identification technologies, and further the modal identification results and the relationship between structural modal parameters and environmental/operational factors are also illustrated in this paper. The researches on the structural vibration characteristics and operational modal analysis of offshore wind turbine not only provide powerful data and technology support for the operation safety evaluation, but also provide the necessary theoretical and practical bases for the design and maintenance of wind turbine structures.

1. Introduction

The offshore wind power project has developed rapidly in recent years with the advantages of high wind speed, low turbulence, large output and long service life. With the quick development of wind power, the complexity of the structure greatly increases the operation safety risk of wind turbine because of larger capacity, higher towers, and bigger blades (Rodrigues et al., 2015). Especially in recent years, the global safety accidents of wind turbine structures occurred frequently with the number of nearly 1000 only in 2014 (Seyr and Muskulus, 2016), the issues on operational behavior and structural safety of offshore wind turbine under different working conditions have begun to attract universal attention.

As we all known, structural vibration monitoring and operational modal analysis are important means to master the operational behavior and structural safety of offshore wind turbine effectively. With the development of modern measurement technology, the researchers began to be interested in understanding the vibration characteristics of offshore wind turbine based on the measured data, and try to obtain the operational behaviors (Bassett et al, 2010), dynamic parameters (Ozbek et al., 2010, 2013)and structural safety (Benedetti et al., 2011a, 2011b)by the feedback analysis in recent years. Firstly, the monitoring systems applied to practical engineering were established, improved and optimized based on existing system according to the dynamic characteristics of the wind turbine structure, the environment and operational conditions with a view to more accurate and efficient collection, processing, analysis of prototype observation data (Yang, 2013; Schlechtingen et al., 2013; Schlechtingen and Santos, 2014). For example, Gokhan (Kilic and

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Unluturk, 2015)took the Supervised Event Server Health Monitoring System (SESHMS) as a relatively simple, economical wireless system for use within the arena of structural health assessment. Secondly, the intuitive, comprehensive and systematic researches on dynamic response characteristics, change law, the relationship between the operational parameters and vibration were carried on the basis of measured data (Kusiak and Zhang., 2010). Hu (Hu et al., 2015a, 2015b)focused on a resonance phenomenon, environmental and operational influences on structural dynamic properties under normal operational conditions of a wind turbine system in 5 MW wind turbine, on the basis of dynamic signals acquired continuously from the tubular tower under normal operational conditions during two years. Thirdly, it is also necessary to carry out the feedback identification on the operational parameters and dynamic indexes of the wind turbine structure. Further, the structural operational safety under different working conditions and long-term monitoring can be evaluated by using these analysis indexes and the real-time change rules (Andrew Swartz et al, 2010; Bang et al., 2012). A typical example is that Moritz W (Hackell and Rofles., 2013) took one 5 MW offshore wind turbine structure as the research object, the extraction of modal parameters and the estimation of condition parameters of wind turbine were implemented respectively by data driven stochastic subspace identification method and Vector Auto-Regressive (VAR) Models. Finally, the above-mentioned research results on dynamic characteristics and work performance indicators can be utilized to establish the early warning or control system of wind turbine structure in order to ensure the operational safety of offshore wind turbine structure in the complex conditions (Currie et al., 2015). Iliopoulos A (Iliopoulos et al., 2015)made use of a modal decomposition and expansion algorithm in order to predict the unknown position responses of offshore wind turbine structures with limited condition measured data. However, the present researches were also limited to the monitoring and analysis of single unit such as fan unit (Hackell and Rofles., 2013), tower (Kilic and Unluturk, 2015), foundation (Currie et al., 2015) lacking of the consideration on the coupling vibration measurement of multiple structural components. Simultaneously, the detailed interpretation on vibration characteristics and vibration mechanism of the whole offshore wind turbine structure should be completed.

Further, the most critical problem is how to deal with the interference of harmonic components in the modal analysis of offshore wind turbine structure. In the current study, Jacobsen (Jacobsen et al., 2007)and Peeters (Peeters et al., 2007) both tried to eliminate the harmonic components ahead of identifying modal frequencies so that the measured vibration signals are completely composed of the structural modal information. Nevertheless, choosing an unsuitable filter will result in the easy loss of useful component because the frequencies of operational modes and harmonic modal frequencies may be close to each other. Gade (Gade et al., 2009), Jacobsen (Jacobsen, 2006; Jacobsen et al.)and Modak (Modak et al., 2010; Modak, 2013)considered that there are differences in statistical properties, such as kurtosis and probability density function, between random signals and harmonic signals and distinguished the real structural modes among the identification results from the unknown harmonic modes respectively using the frequency domain decomposition method, singular value decomposition method and random decrement technique. But the unavoidable deficiency is that the actual modal parameters cannot be obtained properly when the structural information completely submerges in the harmonic components. In addition, the new theories of transmissibility function, Hilbert-Huang transform and optimized spectral kurtosis have been applied successively to differentiating the actual structural and harmonic modes by Devriendt (Devriendt et al., 2009; Weijtjens et al., 2014), Agneni (Agneni et al., 2012)and Dion (Dion et al., 2012). However, the ability of these methods to extract the natural modal information under the disturbances of strong harmonic energy has not been known. To solve this difficult problem originated from harmonic disturbance, P. Mohanty (Mohanty and Rixen, 2004a, 2004b, 2004c, 2006)had modified several classic modal identification methods, including LCSE, ITD, ERA and SSTD method, to obtain the actual modal information considering the influence of the harmonics on the characteristic matrix of structural system. However, it has a limitation in engineering application for the above modified methods because of the unstable identification resulted from the defect of the algorithm itself and their poor noise resistance. On the basis of P. Mohanty's ideas, Dong et al. (2014).introduced the strong harmonic interference information obtained from measurement data into the traditional stochastic subspace identification method (SSI) possessed stronger anti-noise and better recognition stability. Subsequently, a new modal identification method called harmonic modified stochastic subspace identification (HM-SSI) method was proposed to successfully complete the studies on operational modal identification and operational safety evaluation of offshore wind turbine structure, and the superiority of the method and engineering applicability were also verified. In this paper, the structural operational modal identification of tested offshore wind turbine affected by the strong harmonic excitations will be implemented based on the above method.

In summary, it can be seen that it is lack of the vibration safety monitoring of the whole wind turbine and the support structure, at the same time, the field observation data of the offshore wind power project is extremely scarce. The basic vibration characteristics of the offshore wind turbine structure and the operational modal analysis of the wind turbine under different conditions are lacking in comprehensive, in-depth and systematic research. Therefore, the structural vibration characteristics of offshore wind turbines under different conditions such as standstill, normal, startup, shutdown and extreme typhoon status were deeply analyzed to further illustrate the influence regularity resulted from operational factors, and subsequently, the vibration safety of the wind turbine structure under different operational conditions was fully discussed combined with a new modal analysis method called HM-SSI method (Dong et al., 2014). Firstly, the project overview of the measured offshore wind turbine is introduced in Section 2. Secondly, the operational conditions of offshore wind turbine are proposed in Section 3 to understand the characteristics and relationship between operational conditions and environmental factors. Additionally, a detailed and comprehensive study on the vibration response characteristics of the offshore wind turbine structure under typical operational conditions is achieved in Section 4. Lastly, the operational modal analysis of offshore wind turbine in the range of full power, structural operational safety assessment and influence on modal identification from environment and operational factors are demonstrated systematically in Section 5 based on the measured vibration responses. The framework of this paper was shown in Fig. 1.

2. Prototype observation of offshore wind turbine structure

The offshore wind turbine of this measurement is located in the Yellow Sea area adjacent to Nantong City in Jiangsu Province of China. A new foundation form of offshore wind turbine called the composite bucket foundation (Jijian et al., 2012; Lian et al., 2011)was applied as the first prototype in the wind turbine experiment globally with 30.0 m in diameter, 18.0 m in height, and 2500t in the total weight. A three-blade direct-drive wind turbine generator with rated power of 2.5 MW and the rotor rated speed of 18 rpm were selected simultaneously. The cut-in, rated and cut-out wind speed is 3.0 m/s, 12.0 m/s and 25.0 m/s respectively. The 80 m tall tower, which has working platforms between two adjacent parts of steel tower, was installed in three parts (Zhang et al., 2014). As described in Fig. 2, five observed points, located at 1.5 m from each platform, were instrumented inside the tower along the height direction. Three vibration displacement sensors with the frequency range of 0.1–200 Hz in each measured location were used to acquire low-frequency and multi-directional structural vibration response signals. The X (tangential direction of cylinder wall) and Z (vertical direction of cylinder wall) directions are horizontal and Y (vertical ground direction) direction is vertical. Besides, the total testing time was more than one month and sampling frequency was chosen as 200 Hz in this