Natural frequency measurement of a 13-meter wind turbine blade using different techniques

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ABSTRACT: Nowadays the wind energy markets continue to grow to accommodate the current demands of renewable energy. As the wind turbine blades are susceptible to suffer damage from complex and irregular loading caused by catastrophes, development of quick and reliable ways for wind turbine health monitoring is becoming crucial. Modal testing is one of the most commonly used non-destructive health monitoring methods, as any damages could lead to changes in the structural vibration characteristics. In this paper, a series of modal tests were carried out to measure the natural frequencies of a 13 m wind turbine blade. Various data acquisition devices, namely the accelerometer, the laser vibrometer and the mobile phone sensor, were employed and the accuracy of the recorded accelerations and the corresponding Fast Fourier Transform (FFT) diagrams, were compared. The advantages and disadvantage of the employed techniques were discussed. It was found that all the three devices could capture the blade natural frequencies accurately, while the mobile phone sensor is recommended for a quick outdoor natural frequency testing under limited testing conditions.

KEY WORDS: Renewable Energy; Wind Energy; Sustainable Development; Wind Turbine Blade; Natural Frequency Test; Non-Destructive Test.

1 INTRODUCTION

The wind energy is gaining increased attention as an unlimited, free and renewable resource. For the efficiency improvement of extracting wind energy, wind turbines are becoming larger and are expanding to offshore locations. With the rapid improvement of technologies, the global offshore wind market grew nearly 30% per year between 2010 and 2018 [1].

During operation, the wind turbine blades are suffering from complex wind conditions which make the blades susceptible to damages. As the essential components of wind turbines, the failure of blades are very costly as the failure can potentially damage other components of the turbine (e.g. the tower, the nacelle, etc.) and the adjacent turbines [2]. Hence, besides the necessary quality control in the manufacturing stage, the wind turbines should be inspected periodically to prevent the damages and accidents of the components during operation. There are many challenges in the inspection of blades, such as the high-thickness of the composite laminates, the complex-geometry of the blade components and the on-site environmental conditions [3]. For the purpose of compromising the original state of the wind turbine blade and not affecting the blade quality, non-destructive testing (NDT) techniques are widely used in blade inspection. In the past, there are many NDT techniques, such as vibration analysis [2], shearography techniques [4], thermography techniques [5], ultrasonic techniques [6] and X-ray CT techniques [7], proposed for the damage detection and the condition monitoring of structures. As one of the most widely used techniques for condition monitoring, the vibration analysis will be of focus in this research. Regarding the wind turbine blade, strain gauges are usually integrated and are capable of providing the data for vibration analysis. But these instruments are not robust for long-term use [2]. Hence, periodical blade inspection with external devices is necessary and a quick, simple but accurate NDT technique will gain benefits of the wind turbine blade inspection.

There are two main objectives of this research - to obtain the natural frequencies of a 13 m wind turbine blade and to explore the suitable testing devices for a purpose of simple but accurate on-site natural frequency testing. A reference natural frequency test, using the modal testing method, is carried out in flapwise, edgewise and torsion-wise direction of the blade. With the test results used as the reference data, the feasibility of three devices, namely the mobile phone sensor, the laser vibrometer and the accelerometer, in the outdoor natural frequency testing are explored. The advantages and disadvantages of using the three devices are discussed and compared based on the testing data.

2 REFERENCE NATURAL FREQUENCY TESTING

The test described in this section aims to acquire the blade natural frequencies with the most commonly used testing method, which employs single-axis accelerometers installed on the blade. The obtained natural frequency values will be used as the reference values to be compared to in the next section. The natural frequencies will also provide useful data to the future static and fatigue tests of the wind turbine blade.

2.1 *Overview*

The test specimen is a 13 m long wind turbine blade made with glass-fibre reinforced powder epoxy. As shown in Figure 1, the blade is mounted on a steel support frame, with the trailing edge in the upward direction. It will be tested under static loading to verify its strength in ultimate weather conditions, and under fatigue loading to validate its durability in long-term operations. The natural frequency testing performed in this study aims to detect the dynamic characteristics of the wind turbine blade, which can provide useful information when designing the test setup and defining the test loading for the later static and fatigue tests.

Figure 1. The 13 m wind turbine blade

The modal testing, a widely used testing methodology for characterising vibration properties of an object, is carried out in this study. As a kind of vibration testing, modal testing is capable of measuring natural frequencies, damping ratios and modal shapes of an object. The modal testing consists of two phases, which are the testing phase and analysing phase. In the testing phase, the blade is vibrated and its acceleration responses are recorded. In the analysing phase, the fast Fourier transform (FFT) algorithm is employed for analysing the blade responses under different frequencies. The blade natural frequencies, damping ratios and modal shapes can be addressed from the FFT spectrum. In the following subsections, three tests, for addressing the blade natural frequencies in flapwise, torsion-wise and edgewise directions, are detailed and the corresponding results are discussed.

2.2 *Flapwise testing*

For testing the flapwise natural frequencies, four single-axis accelerometers were installed on the blade suction side. As shown in Figure 2, the accelerometers were placed along the blade at distances of 5 m, 7 m, 9 m and 12 m from the root, respectively. The accelerometer locations were adopted based on the blade modal shapes, given by a preliminary numerical natural frequency analysis. To vibrate the blade in flapwise direction, a hammer was utilised to give a transient impact to the blade tip.

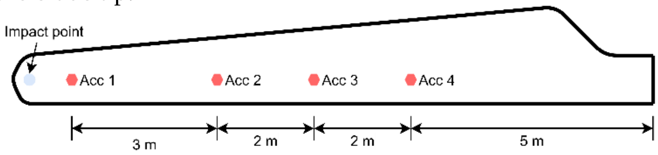


Figure 2. Accelerometer layout for the flapwise natural frequency testing

The recorded accelerations (sampling rate: 1000Hz) were analysed using the FFT algorithm. The obtained four FFT spectra were averaged to minimise the data deviation at different locations. The average plot is shown in Figure 3. As the first 5 blade modes are of concern, only the responses in the frequency range of 0 ~ 50 Hz are displayed. Significant low-frequency noises (< 5 Hz) can be found in the FFT plot. These noises could be introduced by the data acquisition accessories and instruments (e.g. the cable, the ports and the accelerometers). From the FFT analysis, the first two flapwise natural frequencies of the wind turbine blade can be addressed as 2.56 Hz and 7.77 Hz. It should be noted that the blade vibration in torsion-wise direction can also cause the flapwise responses of the accelerometers. Therefore, conducting the torsion-wise natural frequency testing is necessary, which are detailed in section 2.4.

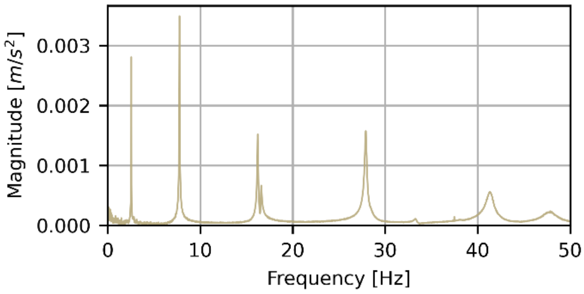


Figure 3. Average FFT spectrum of the flapwise natural frequency testing

2.3 *Edgewise Testing*

Figure 4 shows the accelerometer locations in the edgewise natural frequency testing. The four accelerometers, pointing to the blade trailing edge, were installed along the leading edge of the blade. Similarly, the blade was triggered to vibrate in flapwise direction with a transient impact at the tip location. The average response spectrum calculated by the FFT algorithm is shown in Figure 5. It could be observed that the first two edgewise natural frequencies of the blade are 4.25 Hz and 16.22 Hz, respectively. It should be highlighted that the second edgewise frequency is the same as the third flapwise frequency of the blade, as can be figured out in Figure 3. It means that under a frequency of 16.22 Hz, the blade has a combined flapwise and edgewise vibration. As the blade has a relative thin thickness compared to its chord length, the blade torsion-wise vibration can be considered to have a negligible influence on its edgewise vibration.

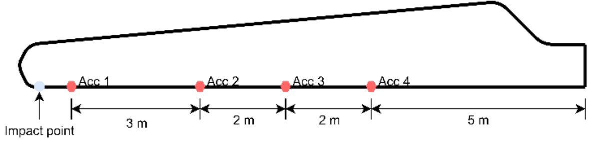


Figure 4. Accelerometer layout for the edgewise natural frequency testing

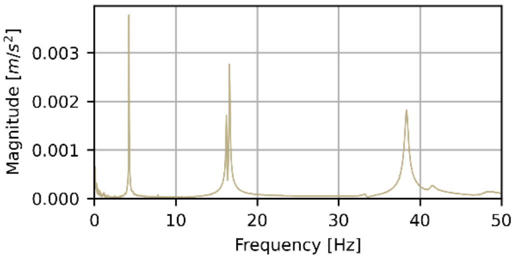


Figure 5. Average FFT spectrum of the edgewise natural frequency testing

2.4 *Torsion-wise Testing*

It should be noted that the torsion-wise vibration will cause the accelerations in the flapwise direction. Thus, the torsion-wise testing was carried out to distinguish the torsion-wise modes from the obtained flapwise modes. To capture the blade torsional vibration, the accelerometers were placed on the blade as a 2×2 array. Any torsion-wise movements of the blade will cause opposite responses of the accelerometers located on the upper row and lower row. Similar to the flapwise testing, a transient impacted was imposed to the blade tip. Figure 7 shows the average FFT plot of torsion-wise testing. The response spectrum has a similar frequency distribution as that of the flapwise testing since the blade was vibrated in the same direction. But by comparing the amplitude-phase of the FFT results, it could be figured out the under the frequency of 33.7 Hz, the blade has a torsion-wise movement.

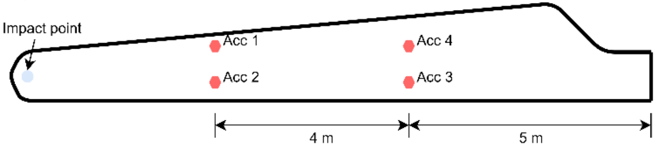


Figure 6. Accelerometer layout for the torsion-wise natural frequency testing

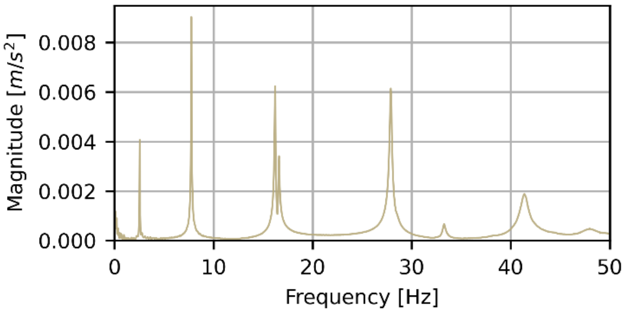


Figure 7. Average FFT spectrum of the torsion-wise natural frequency testing

The aforementioned tests were repeated 3 times each to ensure the accuracy of the results. The natural frequencies of the 13 m wind turbine blade were addressed and summarised in Table 1. These frequencies will be used as the referenced values to validate the accuracy of the testing results obtained from various data acquisition techniques, which are detailed in the following sections.

Table 1. Natural frequencies of the blade

Mode #	Frequency [Hz]	Period [s]
1st Flapwise	2.56	0.39
1st Edgewise	4.25	0.24
2nd Flapwise	7.77	0.13
2nd Edgewise	16.22	0.06
1st Torsion-wise	33.27	0.03

3 TESTING WITH VARIOUS TECHNIQUES

The second objective of this research is to propose an easy but accurate natural frequency testing methodology, which can be suitable for outdoor inspections. As utilised in the reference tests, using the accelerometer could be one option of measuring the blade response in the modal testing. Alternatively, laser vibrometer is also a reliable and precise tool for measuring the blade vibrations. Based on the Doppler effect, the laser vibrometer can make non-contact vibration measurements of a surface. This could simplify the test setup progress and reduce the test preparation time. With the rapid development of the hardware, it is quite common for engineers to integrate sensors into smartphones. Nowadays, most smartphones have built-in motion sensors (e.g. accelerometer, gyroscope, compass, etc.) which make them more than a communication tool. Thus, the internal accelerometer of a smartphone has the potential to capture the blade vibration. In the following sections, the accelerometer, the laser vibrometer and the mobile phone sensor are used to carry out the modal testing of the blade. The performances of each device, in terms of accuracy, compatibility, and ease-of-use, are compared and discussed.

3.1 *Test Setup*

Different from the reference test, only the acceleration of a single point on the blade surface was measured. The measurement point was addressed at a location of 7 m away from the blade root as this location was found to be sensitive to the first 5 models of the blade in the reference test. Figure 8 shows the test setup. To capture the blade vibration, the mobile needs to be attached to the blade surface so that both objects share the same vibration. To simulate the outdoor condition, the mobile phone is constrained to the blade by the tapes instead of any specially designed fixtures. The mobile internal gyroscope was utilised to ensure the mobile phone was parallelly attached to the blade. The mobile acceleration data was recorded by its internal system, and thus no connection wire was required. This can simplify the test set up progress and shortens the preparation time, which makes the mobile phone suitable for quick outdoor testing. As the mobile phone sensor is not specifically designed for precise data acquisition, it only has a maximum sample rate of 100 Hz. It means that the mobile phone cannot capture any response with a frequency higher than 50 Hz.

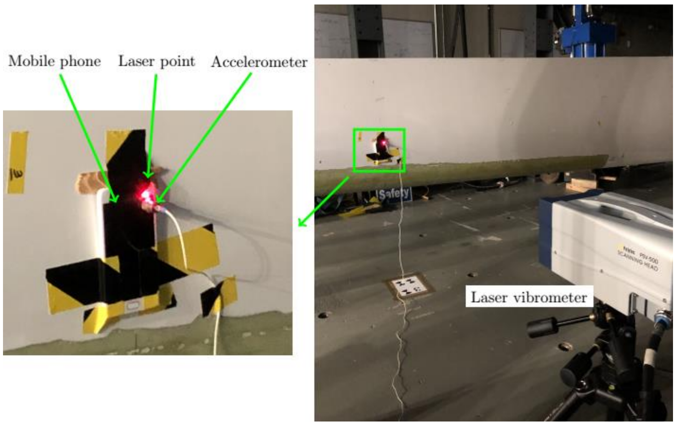


Figure 8. Detailed test setup of the three devices

The laser vibrometer was also set up for recording the acceleration. It consists of three components, namely the scanning head, the controller and the laptop. The scanning head shoots the laser beam to the target surface to capture the raw vibration data. The raw data is transferred to the controller to be further converted to acceleration data and then is recorded by the controlling software in the laptop. One of the benefits of using laser vibrometer is that it has highly integrated hardware and software, which enables real-time data processing. With data automatically analysed during the data capturing, time of post-processing is saved. As this device employs laser for vibration measurement, there is no direct contact between the scanning head and the blade, which is another benefit of using the laser vibrometer. But on the other hand, the three components of the vibrometer will induce issues of mobility. In this test, the laser beam was targeting the mobile phone instead of the blade surface to measure the vibration of the mobile phone. In such way, the vibration of the mobile phone is recorded by the vibrometer, which makes it easy to compare the accuracies of the two devices. Additionally, one accelerometer was also attached to the mobile phone to provide reference data for accuracy validation.

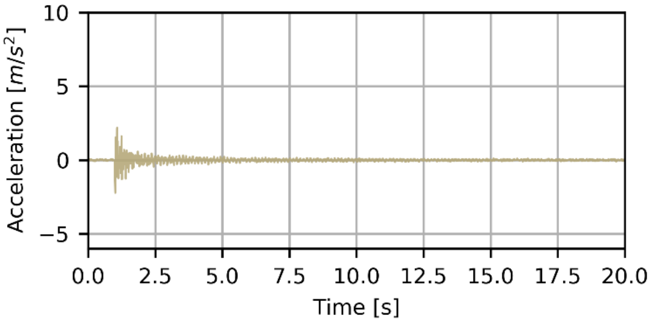
In this study, two ways of vibrating the blade were considered. The first method is to impose a transient impact to the blade tip, which was used in the reference test. Under the transient impact, the blade vibrated under tint magnitudes in a short interval. The second method is to deflect the blade tip manually with a distance of a 400 mm and release the force to vibrate the blade. The blade vibrated under relatively large magnitudes in a long interval. As the test focuses on the accuracy of different devices, only the flapwise natural frequency testing was conducted.

3.2 Test Results and Discussions

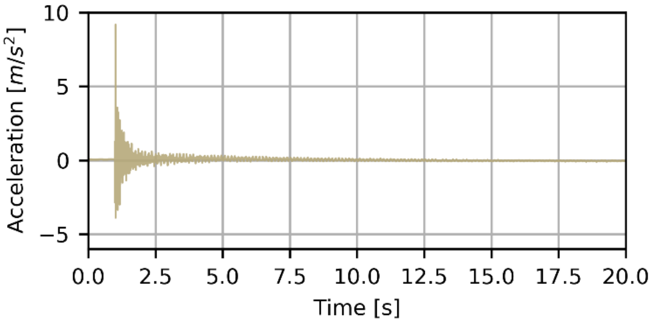
3.2.1 Hammer Impact Test

Similar to the reference test, a transient impact was introduced to the tip to vibrate the blade in flapwise direction. Figure 9 shows the acceleration data captured by the three devices. It can be observed that the peak acceleration recorded by the mobile phone sensor is 2.22 m/s^2 while that recorded by the vibrometer and accelerometer are 8.49 m/s^2 and 9.19 m/s^2, respectively. The mobile phone sensor failed to capture the peak acceleration introduced by the transient impact, due to its low sample rate, which is 100 Hz. Moreover, significant noises can be observed in the data recorded by the mobile phone sensor, which is another disadvantage of using the mobile phone sensor for the acceleration recording.

(a) Acceleration recorded by the mobile phone sensor



(b) Acceleration recorded by the accelerometer



(c) Acceleration recorded by the laser vibrometer

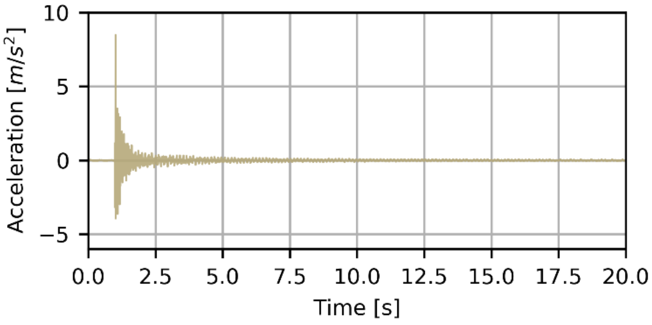
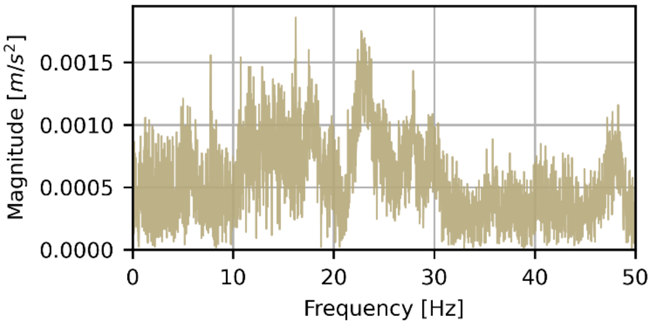


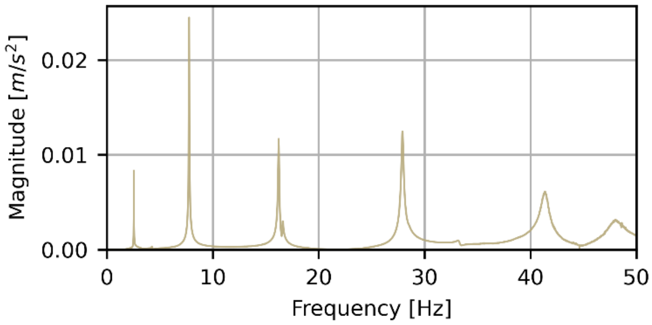
Figure 9. Acceleration time-history plots of the three devices

Figure 10 shows the FFT results calculated from the recorded acceleration data of the three devices. Due to the influence of noises, there is no significant spike found in Figure 10 (a), indicating the mobile phone sensor is not suitable for the natural frequency testing under the transient impact. It can be observed that the FFT spectrum analysed from the laser vibrometer data matches well with that from the accelerometer data, which proves the high accuracy of the laser vibrometer. Similar to the reference test, the data recorded by the accelerometer had low-frequency noises, as shown in Figure 10 (b). But in the FFT plot of vibrometer, the spectrum is clear in the low frequency range (< 5 Hz). The natural frequency values obtained under transient impact can be found in Table 2. Both the 1st and 2nd flapwise natural frequencies agree well with the reference values in Table 1, proving that the laser vibrometer is of high accuracy. As the accelerometer and the laser vibrometer were both targeting the mobile phone, which was attached to the blade surface. It could be concluded that the simple fixture with tape can be a sufficient way of constraining the mobile phone in the outdoor testing.

(a) FFT result obtained from the mobile phone sensor



(b) FFT result obtained from the accelerometer



(c) FFT plot result from the laser vibrometer

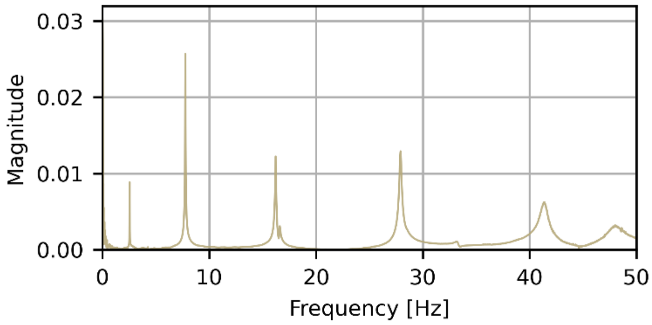


Figure 10. FFT results of the three devices (hammer impact)

Table 2. Natural frequency testing results comparison (transient impact)

Mode #	Frequency [Hz] Mobile	 Accelerometer	 Vibrometer
1st Flapwise	-	2.56	2.56
2nd Flapwise	-	7.77	7.77

3.2.2 Pull-Release Test

As the mobile phone sensor failed in the natural frequency testing under the transient impact, an alternative way of vibrating the blade, called the pull-release, was employed. Initially, the blade tip was manually pulled to have a flapwise deflection of around 400 mm. Then the applied force was released to trigger the blade flapwise vibration. Compared to the vibration caused by the transient impact, the blade vibrates under larger amplitudes in a longer interval. It should be noted that the laser vibrometer is not suitable for measuring object under large movements. As there is no direct contact between the scanning head and the blade, the large deflection will cause the shift of the targeting point, which is shown in Figure 11. Errors will be introduced to the recorded data, and hence, the laser vibrometer will not be considered in this pull-release test.

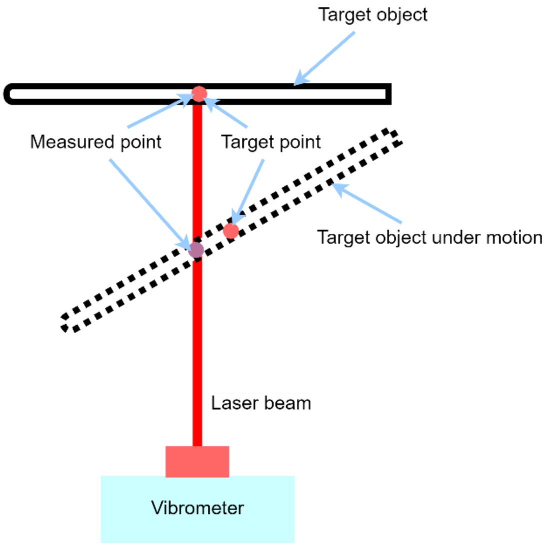
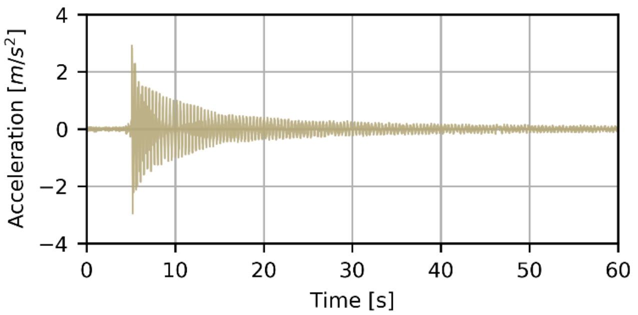


Figure 11. The shift of target point under large vibration

The accelerations recorded by the mobile phone sensor and the accelerometer are plotted in Figure 12. The peak accelerations from the two devices are 2.95 m/s^2 and 2.59 m/s^2, respectively. Compared to the test under the transient impact, fewer differences between the peak data from the mobile phone sensor and the accelerometer was observed, indicating that the mobile phone sensor is possible to capture the blade vibration under the pull-release vibration.

(a) Acceleration recorded by the mobile phone sensor



(b) Acceleration recorded by the accelerometer

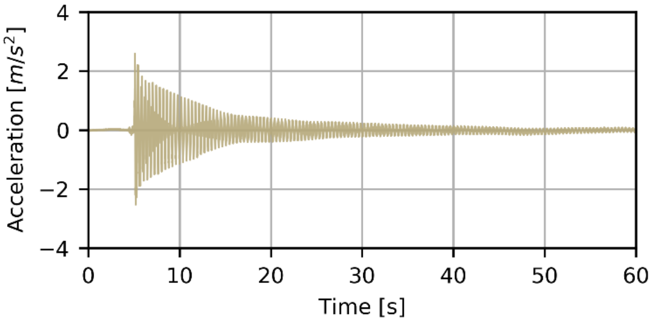
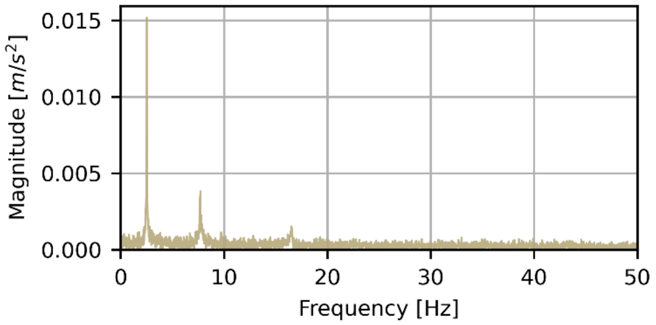


Figure 12. Acceleration time-history plots of the two devices

The FFT responses obtained from the two devices are shown in Figure 13. Regarding the mobile phone sensor, despite the noises found in the spectrum, the first two blade flapwise natural frequencies are clear. This proves that under large vibration magnitudes and long vibration intervals, the mobile phone sensor can capture adequate data to reduce the influence of noises in post-processing. Compared with Figure 10 (b), the FFT spectrum obtained from the accelerometer only captured the first two flapwise blade natural frequencies. It can be concluded that less information can be seized in the pull-release triggered vibration than that of the transient impact triggered vibration. But considering that the first 2 flapwise natural frequencies are of main concern to the engineers, this vibration method could be utilised in the outdoor testing, especially when test conditions are limited. Table 3 summarises the natural frequency values obtained in this test. Excellent agreement between the test results and the reference values can be found.

(a) FFT result obtained from the mobile phone sensor



(b) FFT result obtained from the accelerometer

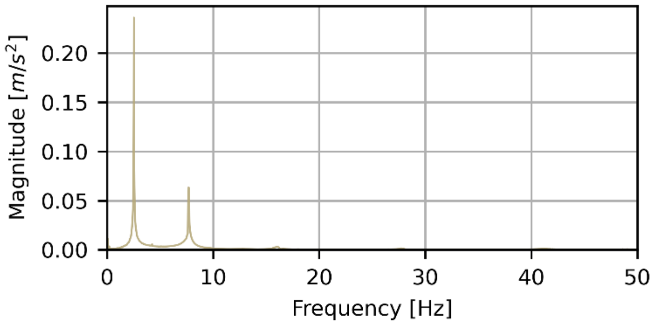


Figure 13. FFT results of the two devices (pull-release)

Table 3. Natural frequency testing results comparison

Mode #	Frequency [Hz]		
	Mobile	Accelerometer	Vibrometer
1st Flapwise	2.54	2.54	-
2nd Flapwise	7.69	7.69	-

4 CONCLUSIONS

In this study, the natural frequencies of a 13 m wind turbine blade were tested with various acceleration acquisition devices. A reference test, which employed a widely used modal testing method, was carried out to obtain the blade natural frequencies. Aiming to adopt a suitable method for a quick and accurate outdoor testing, three data acquisition devices - the mobile phone sensor, the laser vibrometer and the accelerometer - were utilised in the natural frequency testing. Their accuracy, mobility and compatibilities were discussed and compared based on the test results.

The main advantage of using the mobile phone sensor is mobility. All the data acquisition could be completed on the mobile phone. No additional board and wires are required. These features make it suitable for testing the blade natural frequency under limited condition. But compared to the other two devices, it has a lower sample rate and more noise is observed. Hence, it is only suitable when the blade is under large vibration amplitudes and long vibration time. The laser vibrometer employs non-contact testing techniques by using laser beams. It has the least noise among the three devices. No wires are required for connecting the blade to the scanning head. All the data is processed automatically. But to conduct the test, scanning head, controller and laptop are required, which reduces its mobility. Due to the feature of the laser beam, the vibrometer is only suitable for testing of objects under small vibration. The accelerometer is suitable for tests under both large and small vibrations. It has less mobility compared to the mobile phone sensor but has higher accuracy. The main disadvantage of using the accelerometer is that it requires a wired connection, which may introduce difficulties under restricted conditions.

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