



Kent Academic Repository

Liao, Yi-Hsiang, Wang, Lijuan and Yan, Yong (2026) *Flap-wise vibration frequency measurement of wind turbine blades through Moiré Pattern analysis*. Measurement: Energy, 10 .

Downloaded from

<https://kar.kent.ac.uk/115528/> The University of Kent's Academic Repository KAR

The version of record is available from

<https://doi.org/10.1016/j.meane.2026.100107>

This document version

Publisher pdf

DOI for this version

Licence for this version

CC BY (Attribution)

Additional information

Versions of research works

Versions of Record

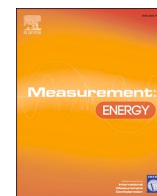
If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

Author Accepted Manuscripts

If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in **Title of Journal** , Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries

If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our [Take Down policy](https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies) (available from <https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies>).



Regular Paper

Flap-wise vibration frequency measurement of wind turbine blades through moiré pattern analysis

Yi-Hsiang Liao^a, Lijuan Wang^{a,*}, Yong Yan^b

^a School of Engineering, Mathematics and Physics, University of Kent, Canterbury, CT2 7NT, United Kingdom

^b Hangzhou International Innovation Institute, Beihang University, Hangzhou, 311115, China



ARTICLE INFO

Keywords:

Wind turbine blades
Flap-wise vibration measurement
Moiré pattern analysis
Image processing

ABSTRACT

Accurate vibration measurement of blades is essential for monitoring wind turbines to reduce downtime and ensure operational safety in wind farms. Although imaging-based methods such as digital image correlation and photogrammetry have been applied to achieve non-contact vibration measurement of wind turbine blades, these methods require two or more cameras, complex synchronisation and calibration. This paper proposes a single camera-based approach to measure the vibration frequency in flap-wise direction (i.e. the direction perpendicular to the rotor disk plane) by analysing the moiré pattern generated by a marker on a blade. Experiments were conducted on a laboratory test rig to assess the proposed measurement method for different camera distances, spatial periods of marker pattern, camera pitch and yaw angles, and vibration frequencies. The results show that the moiré pattern analysis method is able to accurately determine the vibration frequency up to 30 Hz with a camera frame rate of 60 fps, compared with the reference vibration frequency obtained from a commercial accelerometer. The developed method provides a feasible and robust way for measuring flap-wise vibration frequency of wind turbine blades under laboratory conditions.

1. Introduction

As wind turbines have grown in size in both height and blade lengths to generate more energy, the operation and maintenance work becomes more challenging. The rotor system (including the hub and the blades), the brake system and the pitch system are the top three reasons for failure in a wind turbine [1]. This signifies the importance of online and accurate monitoring of the vibration of wind turbine blades.

The mechanism of vibration measurement is based on the frequencies, velocities, accelerations, and magnitudes of the vibrations of an object [2]. As an important diagnostic parameter for detecting faults in machinery, vibration frequency can be determined by analysing vibration signals in the frequency domain. A variety of sensors based on different sensing techniques have been applied to measure vibration signals. The vibration acceleration of wind turbine blades is typically measured using wireless inertial sensors [3], [4], [5]. However, the inertial sensors are embedded inside the blade, making it nearly impossible to repair. Another common way is to use strain gauges to measure

the vibration displacement using the cantilever beam theory [6], [7]. With multiple strain gauges placed at specific locations on the blade, this method could even get the blade's mode shape. However, the accuracy of the strain gauge is affected by the adhesive and the environment temperature. Strain can also be measured using Fibre Bragg Grating (FBG), which reflects certain wavelengths that shift when the optical fibre is under stress. FBG can also be applied to wind turbine blades by glueing them to the surface or binding them into the composite material during manufacture [8]. In comparison with strain gauges, optical fibres are not affected by temperature or electromagnetic forces, making them suitable for operating in the harsh environments of wind farms. Nonetheless, it is still a contact measurement method and hard to replace or repair optical fibres. Laser Doppler Vibrometer (LDV) is an instrument for non-contact measurement of vibration displacement and velocity. The returning wavelength shifts when the object moves toward or away from the LDV, which can be converted into vibration displacement [9]. More recent studies have shown the capability of LDVs to identify mode shapes [10] and detect crack signatures [11]. However, LDVs are usually

This article is part of a special issue entitled: MEAENE_ICME2025 published in Measurement: Energy.

Given his/her/their role as Editor-in-Chief, Prof. Yong Yan had no involvement in the peer review of this article and had no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to another journal editor.

* Corresponding author.

E-mail address: l.wang@kent.ac.uk (L. Wang).

<https://doi.org/10.1016/j.meane.2026.100107>

Received 4 September 2025; Received in revised form 6 April 2026; Accepted 24 April 2026

Available online 3 June 2026

2950-3450/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

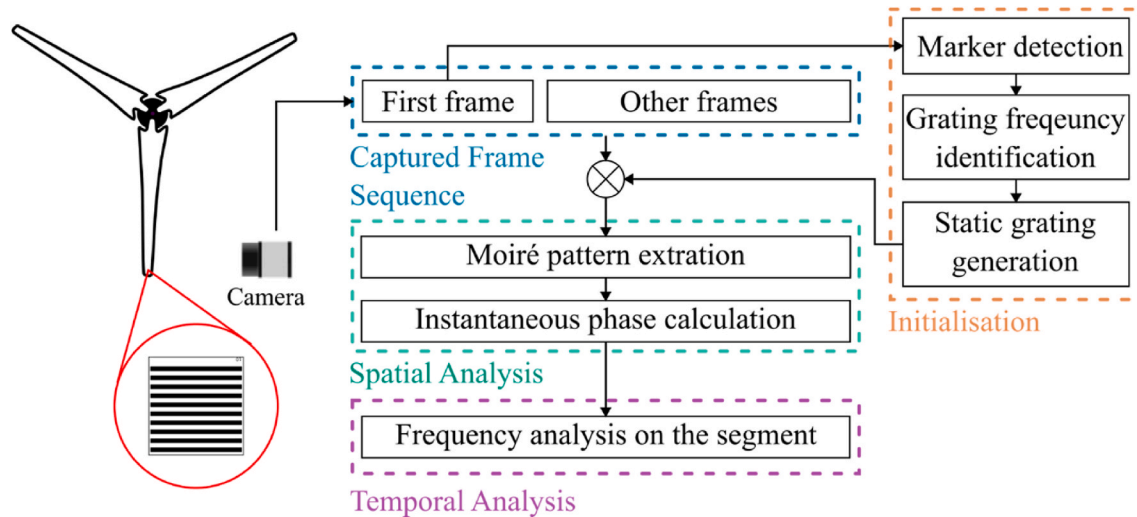


Fig. 1. Overview of the proposed method.

costly and require careful calibration, alignment and maintenance.

With advancements in image-processing algorithms and the maturity of related software libraries, imaging-based methods have become increasingly used for vibration measurement. Digital image correlation (DIC) is a common technique to measure the vibration displacement of objects. DIC measures displacement by calculating the correlation between two or more cameras in different perspectives. Speckle patterns are usually applied to the surface of the measuring target to increase features for the DIC algorithm to track. DIC has been used to measure the vibration displacement of wind turbine blades in operation [12]. The biggest advantage of DIC is its ability to measure the full-field vibrations at locations covered with the speckle patterns. However, the cost of DIC systems and software is also very high. Phase-based motion processing (PBM) [13], originally proposed to visualise tiny movements in videos, was found to be useful for vibration displacement measurement by analysing the phase at different orientations. The unique thing about PBM is the temporal filtering stage, which allows the algorithm to focus on specific motions to amplify. Using data-driven filters such as single value decomposition or empirical mode decomposition, PBM can overcome shaky camera movements [14] and measure non-stationary vibrations [15]. PBM was also used to estimate the mode shapes of wind turbine blades [16] and displacement of cantilever beams [17] as small as 0.2 mm. However, PBM is very computationally expensive with spatial and temporal analysis of videos happening at the same time. The sampling moiré method is another imaging-based method for structural health monitoring. It works by sampling or overlapping periodic patterns to create an inference pattern called moiré pattern. The moiré pattern amplifies the object's movement making it perfect for measuring small vibrations. Studies have shown that the sampling moiré method can be exploited to measure displacement and strain of materials using a laser scanning microscope [18] and large concrete structures using commercial cameras [19], [20]. A great benefit of the sampling moiré method is that it only needs a simple periodic marker (points, stripes, or grid lines), which does not interfere with the object's structure. These markers can also be used for tracking and thus suitable for measuring the vibration of moving objects such as wind turbine blades [21]. However, there has been no systematic evaluation of the moiré analysis method in the application of wind turbines.

The novelty of this paper lies in that a new method based on the moiré pattern analysis is proposed to measure the transverse vibration frequency of wind turbine blades in flap-wise direction (i.e. the direction perpendicular to the rotor disk plane). The performance evaluation of the proposed method is conducted through a series of experimental tests under laboratory conditions. This method can measure flap-wise

vibration frequency with a camera positioning in front of the wind turbine. It only uses a single camera without specific calibration steps, making it cost-effective for deployment on unmanned aerial vehicles to inspect wind farms autonomously. Furthermore, the proposed method reduces the information required for further process, making it computationally efficient. The main contributions of the work are summarised as follows:

- (1) To measure the flap-wise vibration frequency based on a single camera, the moiré pattern analysis method including the marker design, segmentation, spatial analysis and temporal analysis is proposed and presented with detailed descriptions in this paper.
- (2) To evaluate the robustness of the developed measurement system, experimental investigations are conducted on a laboratory test rig for different camera distances, spatial periods of marker pattern, camera pitch and yaw angles, and vibration frequencies.
- (3) The accuracy of the proposed method is evaluated in comparison with a commercial accelerometer under a range of experimental tests.

2. Measurement principle

2.1. Overall principle of measurement

The principle of the proposed measurement method is shown in Fig. 1. The camera is positioned in front of the wind turbine pointing to the marker on the blade. Each frame goes through spatial analysis to obtain the moiré signal. The moiré signals from all frames then go through temporal analysis to determine the wind turbine blade's vibration frequency. The first frame in the frame sequence is used for initialisation, which detects and analyses the marker's grating pattern and generates a static grating. By superimposing the static grating on each frame, moiré patterns will appear on the image. The moiré signals can be extracted using a bandpass filter. Finally, the instantaneous phases of the moiré signals are calculated by taking the angle of the Hilbert transform on each frame. Then the vibration frequency can be measured by applying frequency analysis on the phase differences between frames.

2.2. Theory of moiré analysis

The theory of moiré analysis is introduced firstly as it affects the initialisation and spatial analysis stages of the proposed method. Using the notation from Ref. [22], cosinusoidal gratings are described as

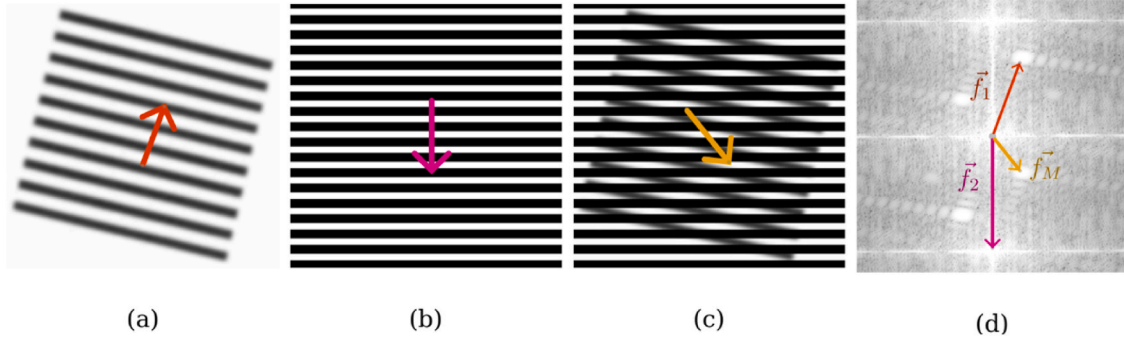


Fig. 2. Travel direction of pattern 1 (a), pattern 2 (b), and the moiré pattern (c). (d) is the spectrogram of (c) showing the travel direction and magnitude of all three patterns.

frequency vectors whose magnitude signifies the spatial frequency of the grating and the angle shows the direction of travel. Moiré patterns occur when two cosinusoidal gratings overlap. The relationship between two cosinusoidal grating patterns and the generated moiré pattern is defined as follows:

$$\vec{f}_M = \vec{f}_1 - \vec{f}_2 \quad (1)$$

where $\vec{f}_1$ and $\vec{f}_2$ are the frequency vectors for the two cosinusoidal gratings shown in Fig. 2(a) and (b), respectively, and $\vec{f}_M$ is the frequency vector of the moiré pattern shown in Fig. 2 (c). Fig. 2 (d) is the spectrogram of Fig. 2 (c), showing the travel direction and magnitude of all three patterns.

Equation (1) can be simplified into scalar notations when both gratings are travelling in the same direction (i.e. the angle between $\vec{f}_1$ and $\vec{f}_2$ is either 0° or 180°). Denoting the gratings as spatial periods, the reciprocal of spatial frequency, the spatial period between the moiré pattern (T_M) and the two cosinusoidal gratings are shown in (2).

$$\frac{1}{T_M} = \left| \frac{1}{T_1} - \frac{1}{T_2} \right| \quad (2)$$

where T_1, T_2 are the spatial periods of patterns 1 and 2, respectively.

Rewriting equation (2) as a fraction between the moiré spatial period

and one of the pattern spatial periods, the magnification factor (μ) is defined as:

$$\mu = \frac{T_M}{T_1} = \frac{1}{\left| 1 - \frac{T_1}{T_2} \right|} \quad (3)$$

It can be seen that the closer the grating periods T_1 and T_2 , the larger the magnification factor. With a fixed T_1 , the larger the moiré spatial period T_M , the larger the magnification. A larger moiré spatial period also means the same pixel movement will result in a larger phase shift, which is especially useful for measuring small vibrations.

The following process is needed to exploit the magnification properties of the moiré effect. First, the marker's spatial frequency is identified. Then, specify the target moiré spatial frequency and use equation (2) to obtain the static grating frequency. The same static grating is generated and composed onto each frame to achieve vibration motion magnification.

2.3. Marker design

A marker was designed to be used with the moiré analysis method to measure the vibration on wind turbine blades. Aside from the physical constraints of the wind turbine blade, a few factors contributed to the marker design. Firstly, the marker has to be visible to the camera from at

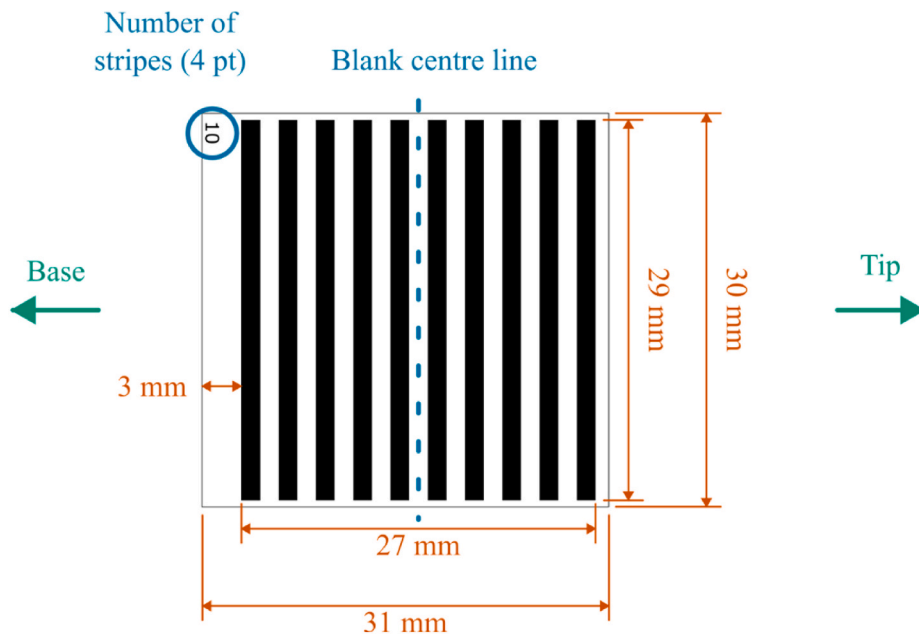


Fig. 3. Marker dimensions.

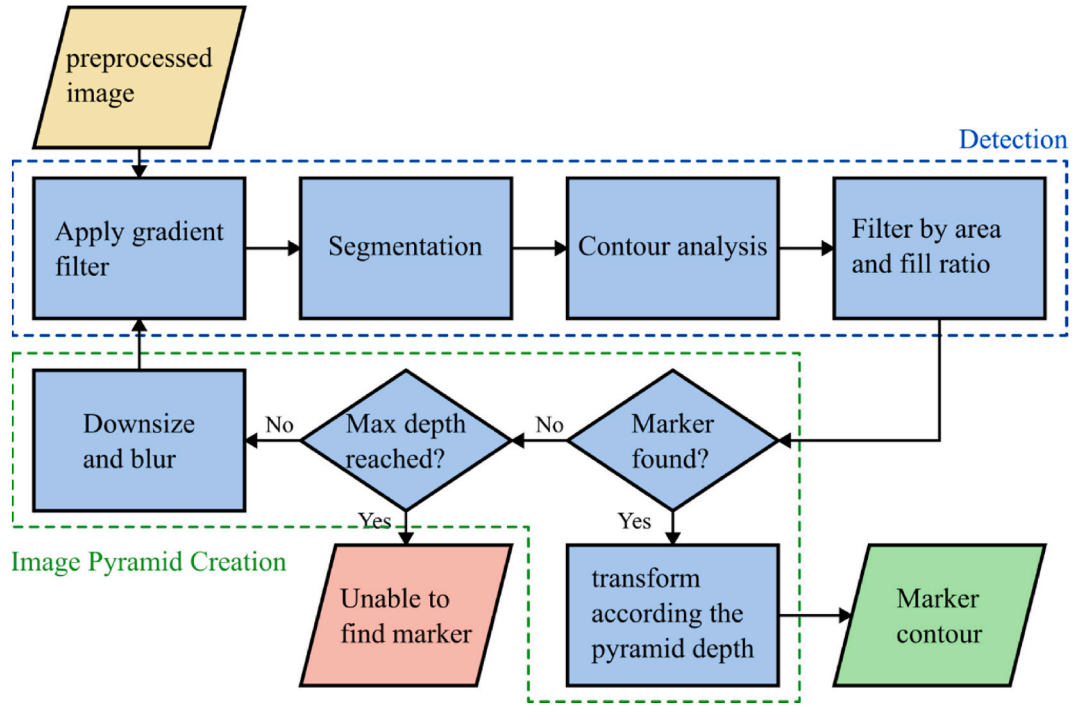


Fig. 4. Flow chart of the marker detection algorithm.

least 1 m away. Secondly, the orientation of the marker should be easily determined.

According to equation (3), the higher the marker's grating frequency ($\vec{f}_1$), the wider the magnification could be. However, higher grating frequency will result in lower visibility when the camera is further away. On the other hand, lowering the grating frequency will reduce the accuracy of marker stripe frequency determination. To make sure the marker is visible, the marker stripes should have a stripe width above 1 mm and no more than 3.86 mm.

Theoretically, moiré patterns can be generated not only on stripes but also on dot and grid patterns. The reason why stripe patterns are chosen in this study is their difference in pattern between the horizontal and vertical directions, which makes finding their orientation easier. This can be accentuated by making the stripes symmetrical to the centre of the marker with a white stripe running down the middle. Using a high camera exposure, the white stripe will blend into the white blade in the background, making marker detection and orientation determination easier.

The resulting marker is shown in Fig. 3. The marker has an outer dimension of 31mm × 30 mm with the 30 mm side matching the width of the wind turbine blade at its tip. The area of the pattern is 27mm × 29 mm. The reduced width allows a 3 mm space for a small text

indicating the number of stripes in this marker on the top left corner. The added text provides information about the marker in a human-readable format and has been inspired by the STag fiducial marker system [23]. The small print of 4 pt means that the text is unlikely to be captured by the camera at higher exposures, improving user experience without sacrificing detection accuracy. The marker height creates a gap between the stripes and the edge of the blade, which also increases the success rate of marker detection. To measure the vibration closest to the tip, the side with the small text is oriented towards the hub and the other side toward the tip. This also has the benefit of acquiring the blade orientation from the marker's orientation.

2.4. Initialisation

The initialisation stage starts with marker detection. A good marker segmentation is crucial to get the correct marker grating frequency, which will result in higher stability of the moiré pattern. The marker detector, illustrated in Fig. 4, is split into two main stages – detection and image pyramid creation. The former is the routine to identify the marker and the latter is a mechanism to improve the scale-invariance of the marker detector.

The detection stage starts with preprocessing by converting the first

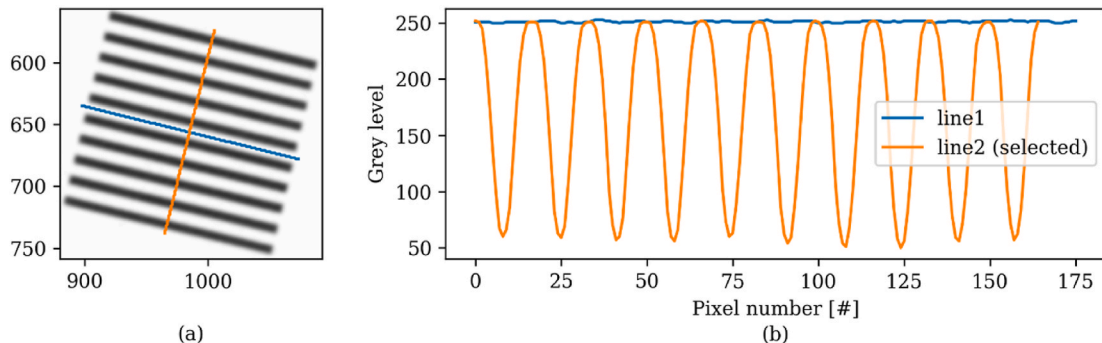


Fig. 5. Sampled line coordinates at crossing the marker's centre overlaid on the original image (a) and the sampled grayscale values (b).

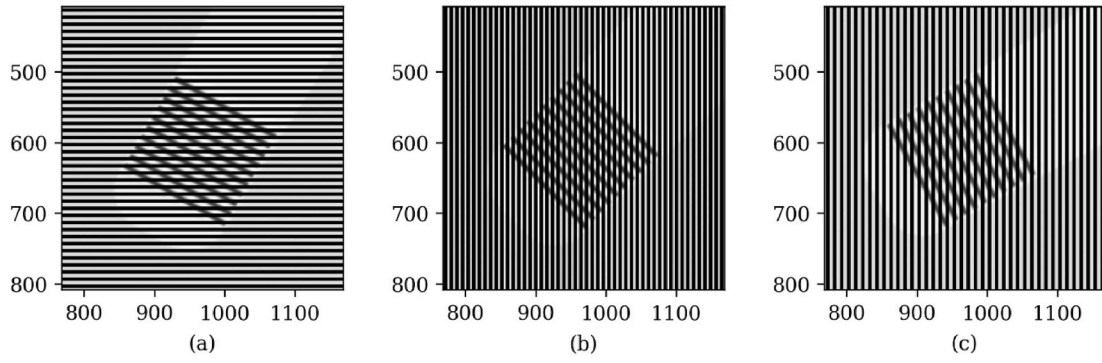


Fig. 6. Generated static grating with markers at 30° (a), 45° (b), and 60° (c).

frame into grayscale and smoothed using a 7-by-7 Gaussian filter followed by a gradient filter. The gradient filter forms a gradient map by calculating the difference between the maximum and the minimum grey levels in each patch selected by a kernel. By choosing the right kernel size, the gradient filter highlights the stripes on the marker. The gradient map is binarised using Otsu's method followed by a morphological close with a 7-by-7 circular kernel to fill in the holes, and a morphological open with a 5-by-5 circular kernel to reduce small blobs and clear up the edges. Finally, the stripe marker is located using contour analysis to identify all patches in the binary image followed by an area filter and a fill ratio filter defined in equation (4). The fill ratio of a contour is the ratio between the contour area and the fitting square with the largest area. Hence, the denominator of equation (4) is to find the larger side out of the width and height of the bounding rectangle to compute the fitted square with the largest area.

$$Q_A = \frac{A}{\max(w_{bbox}, h_{bbox})^2} \quad (4)$$

where Q_A is the fill ratio; A is the contour area; w_{bbox} , h_{bbox} are the width and the height of the bounding rectangle, respectively.

The image pyramid creation stage is only triggered when no marker is found on level 0 (the original scale) to reduce computational costs. If the current pyramid level has no marker found, the image is blurred and downsized to half the size of the previous level and then the detection stage is repeated until the max pyramid depth is reached.

After locating the marker, its orientation is determined by the marker's minimum bounding rectangle. Based on the orientation shown in Fig. 5 (a), two lines crossing the marker's centre are sampled. The marker is designed to have a white strip running across the centre, resulting in one of the grey levels having a greater variance than the other as shown in Fig. 5 (b). The standard deviation of the pixel grey levels determines the sampled lines' contrasts. By selecting the sampled line with a higher contrast and finding its dominant peak in the spectrogram, the marker's spatial period (T_1) is derived.

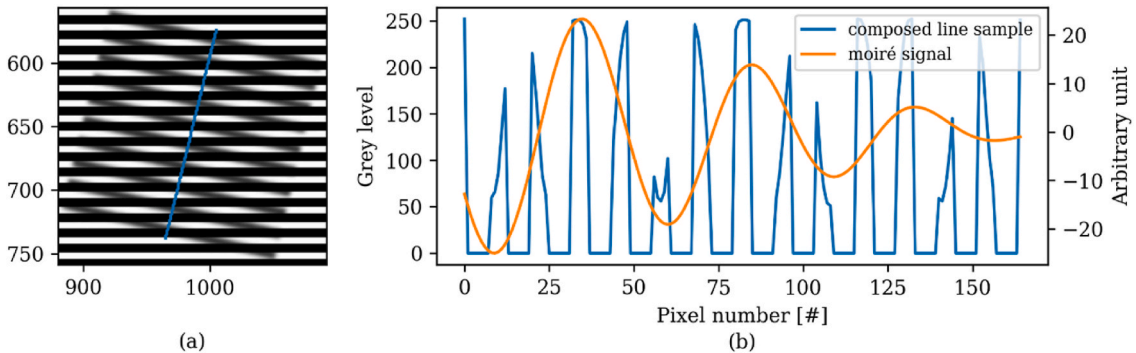


Fig. 7. Composed image with sampled line (a) and the extracted grey level and moiré signal (b).

To create the moiré pattern for analysis, a static grating is generated to be composed on top of the marker. The static grating provides the other spatial period (T_2), which is carefully designed to achieve the magnification needed for the measurement. Taken from Ref. [24], the cosinusoidal grating can be generated using equation (5) and thresholded to create a binary image.

$$I_{ij} = \frac{1}{2} \left(1 + \cos \left(\frac{2\pi W}{T_2} (x_i \cos \theta + y_j \sin \theta) \right) \right) \quad (5)$$

where I_{ij} is the grey level of the pixel (i, j) in an image with a width of W and height of H ; $x_i \in \left[-\frac{W}{2}, \frac{W}{2} \right]$; $y_j \in \left[-\frac{H}{2}, \frac{H}{2} \right]$; θ is the rotation about the x -axis.

It is important to note that for marker angles less than 45° from the y -axis, the generated grating is 90° (top-down) when, and for the marker angles more than 45° the generated grating is 0° (left-right). This is to compensate for the pixel sizes when T_1 was derived. When the sampling line is not exactly 0 or 90°, the sampled line interval is not precisely one pixel. Hence, by generating the static grating on the pixel grid, the drift in spatial frequency can be eliminated. An example of generated static grating at various blade angles can be found in Fig. 6.

2.5. Spatial analysis

The static grating is composed onto each frame and the moiré patterns will appear. Since the moiré spatial period is known, the moiré signal can be extracted along the sampling line using a simple second-order Butterworth bandpass filter, as shown in Fig. 7 (b). Through composing the static grating onto each of the recorded frames, moiré signals of each frame are stacked together, as shown in Fig. 8.

Hilbert transform, as formulated in equation (6), is used to quantify the phase shift of the moiré signals between frames. This is done by taking the angle of the Hilbert transform, which calculates the instantaneous phase of the moiré signal.

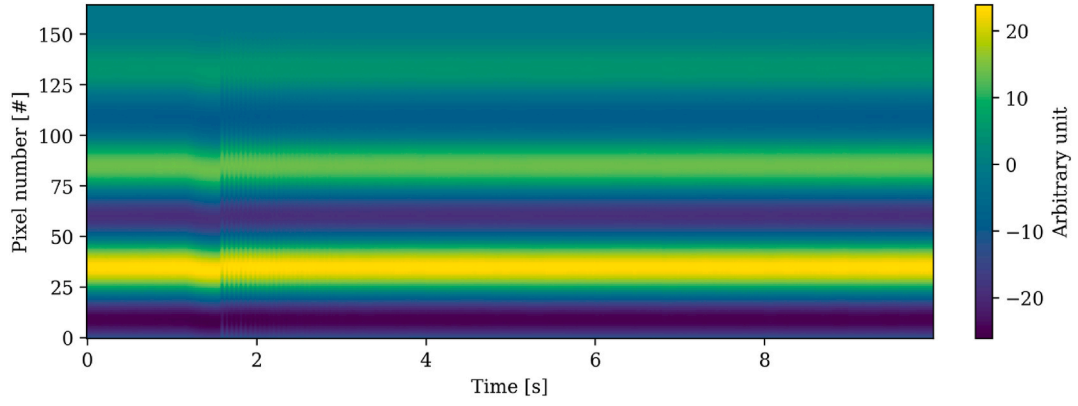


Fig. 8. Moiré signals of each frame stacked together.

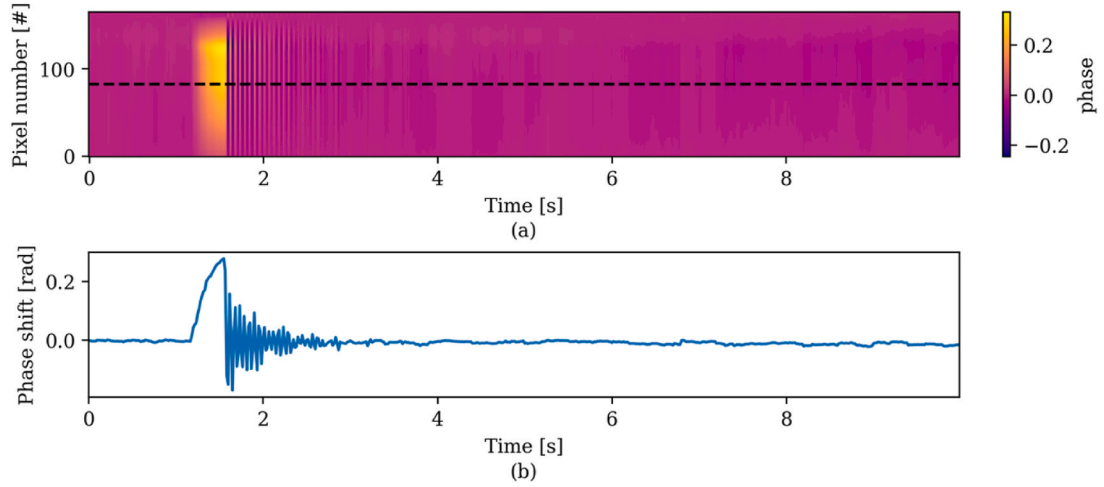


Fig. 9. Phase difference from the first frame (a) and the phase shift signal extracted from the centre of the marker (b).

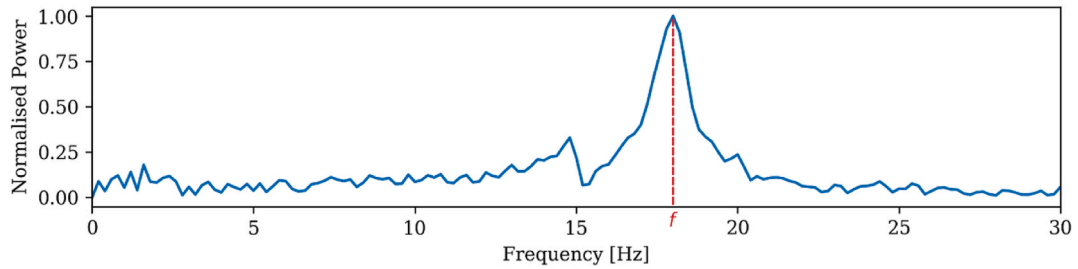


Fig. 10. Normalised power spectrum of the signal from Fig. 9 (b) with the vibration frequency annotated in red.

$$H(u)(x) = \frac{2}{\pi} \lim_{\epsilon \rightarrow 0} \int_{\epsilon}^{\infty} \frac{u(x-s) - u(x+s)}{2s} ds \quad (6)$$

where $u(x)$ is the sampled line and $H(u)(x)$ is the Hilbert transform of the moiré signals; x is the pixel number which is sampled from the sampling line.

Using the instantaneous phase of the first frame as a reference, the phase shift of each frame can be calculated. The phase shift of each frame with respect to the first frame is shown in Fig. 9 (a), which clearly shows the variation in phase over time. The phase shift signal with the maximum of 0.26 radians and the minimum of -0.16 radians, depicted in Fig. 9 (b), is acquired by sampling the centre of the phase shift where the black dashed line is located in Fig. 9 (a). This ensures that the sampled vibration is at the marker's centre, which happens to be where the instantaneous phase is the most stable.

2.6. Temporal analysis

In the temporal analysis, the Fast Fourier transform (FFT) is applied to the extracted phase shift signal. The obtained power spectrum from FFT is normalised to its maximum power, resulting the normalised power spectrum as shown in Fig. 10. The vibration frequency f is determined by finding the maximum of the normalised power spectrum. The normalised power spectrum of the signal from Fig. 9 (b) is shown in Fig. 10.

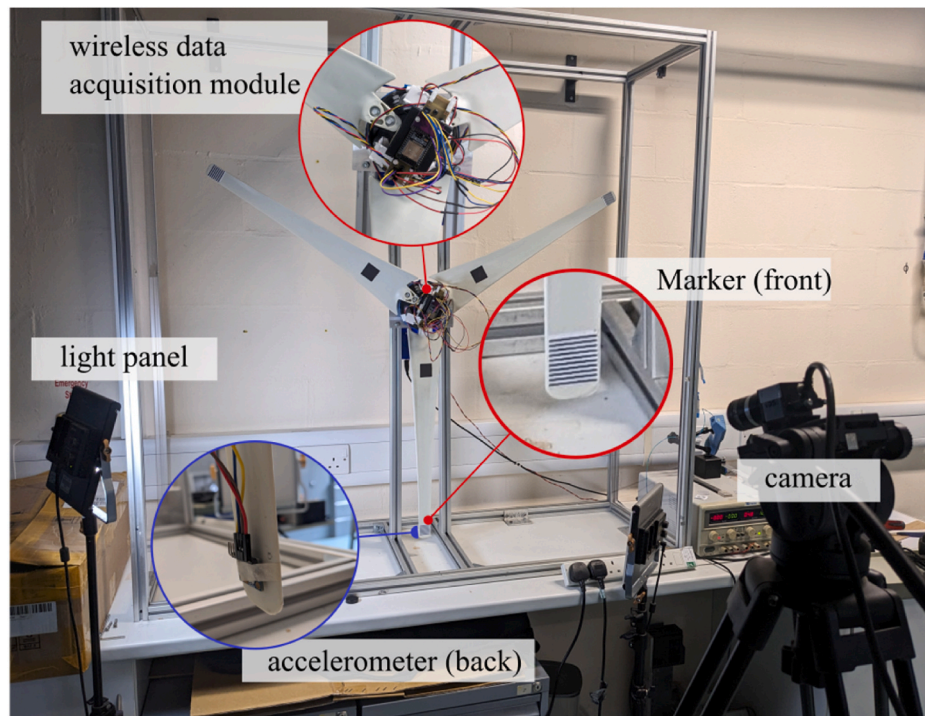


Fig. 11. Experimental setup.

Table 1

Test matrix.

No	Spatial Period (mm)	Camera Distance (m)	Camera Pitch (°)	Camera Yaw (°)	Flap-wise Vibration Frequency (Hz)
I	2.0, 2.84, 5.0	1.0, 1.2, 1.5, 1.8, 2.0	0	0	18.01
II	2.84	1.0, 1.2, 1.5, 1.8, 2.0	0	0	18.01
III	2.84	1.5	0, 5, 10, 15	0	18.01
IV	2.84	1.5	0	0, 5, 10, 20, 30	18.01
V	2.84	1.5	0	0	18.01, 16.61, 14.81

3. Experimental setup and test conditions

3.1. Experimental setup

The experimental setup is shown in Fig. 11. The apparatus consists of a hub and three blades 600 mm in length, all of which are from a commercial household wind turbine. The hub is attached to a stepper motor mounted on an aluminium frame covered with acrylic side panels. The stepper motor is powered so the electromagnets lock the wind turbine blades in place. The marker in Fig. 4 is placed at the blade's tip. A small accelerometer circuit board is installed on the back side of the blade to provide reference. This ensures the LED light and wires on the accelerometer circuit board won't affect the video capture of the marker. The wireless data acquisition unit at the hub's centre gathers the measured acceleration at a data rate of 58.82 Hz and streams the data to a laptop via Bluetooth. The wireless data acquisition module is mobile and can be placed on the blade to change the natural frequency of the wind turbine blade.

The camera used in this study is an industrial camera (UEYE U3-3060CP-C-HQ Rev.2), which has a sensor size of 1/1.2" and is set to record at 60 fps at a resolution of 1936×1216 with an exposure of

13.34 ms and a gain of 70%. The camera is paired with a 50 mm lens with an aperture of $f/2.8$ to get a zoomed-in view of the marker. The marker is located on the blade 3 mm away from the tip and the direction of the lines on the marker is vertical to the length of the blade. During the experimental tests, the flap-wise vibration was generated by displacing the blade tip by 5–10 mm and releasing it to create a free oscillation.

3.2. Test conditions

The proposed method was tested under the conditions listed in Table 1. Experiment I is to investigate how the spatial period of the marker pattern affects the robustness of the proposed method. Experiment II evaluates the effect of camera distance on the accuracy of the measurement. The camera is located at the same height of the marker centre and points to the marker centre. The further the marker is to the camera, the smaller the spatial resolution, which may affect the moiré pattern's ability to magnify the vibration. However, the closer the camera, the stripes on the marker appear further apart, which results in a lower grating frequency, leading to a smaller magnification range. Experiments III and IV are designed to test the effects of camera position. Since the marker is only symmetrical in one direction, both pitch and yaw have to be tested. Pitch angle is the angle when the camera points upward or downward. Positive pitch means camera points upward, while negative pitch means camera points downward. Yaw angle is the angle when the camera rotates to the right or left. Positive yaw means camera rotates to the right, while negative yaw means camera rotates to the left. Experiment V tests different vibration frequencies by changing the natural frequency of the blade. During the experiments, the flap-wise vibration was generated by plunking the blade tip and each test were repeated five times. Except tests III and IV, the camera is always aligned to the marker centre and perpendicular to the rotational plane.

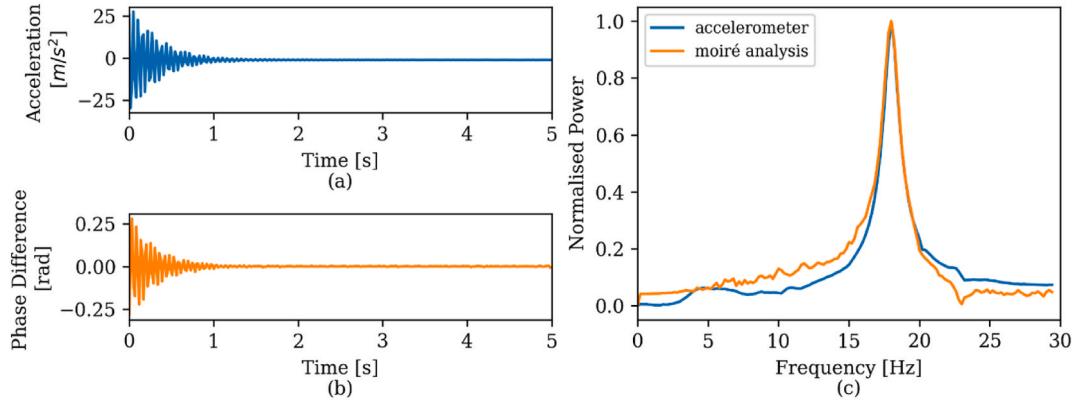


Fig. 12. Typical measurement results: reference acceleration signal (a), phased shift signal from the moiré analysis method (b), and their normalised power spectrum (c).

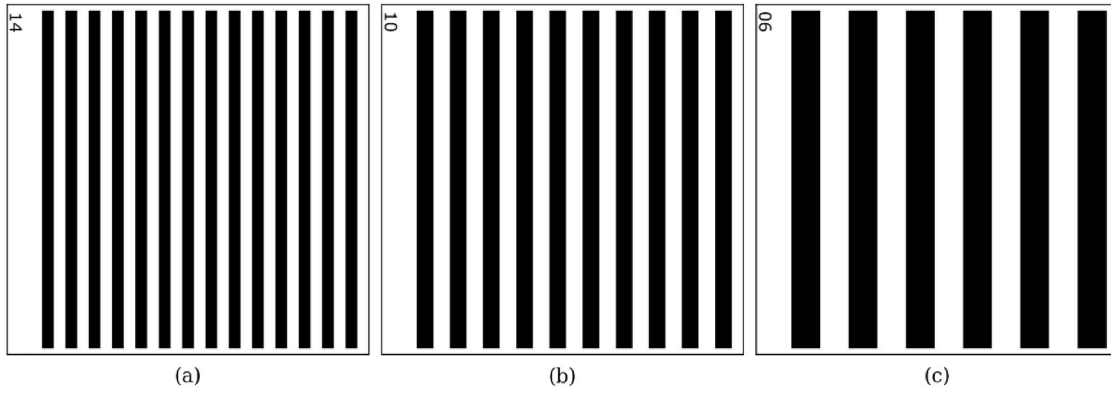


Fig. 13. Marker with spatial periods 2.0 mm (a), 2.84 mm (b), and 5.0 mm (c).

4. Results and discussion

4.1. Typical measurement results

A data logger was developed to capture the reference acceleration and the video simultaneously. To synchronise the data rates of the accelerometer and the camera, the phase difference from the moiré analysis method is resampled to 58.82 Hz matching the sampling rate of the accelerometer. Fig. 12 shows the typical acceleration data from the z-axis (i.e. the flap-wise direction) of the accelerometer, the phase shift signal using the moiré analysis method, and their respective normalised spectrum. The acceleration attenuates and stabilises back to zero. The same trend, shown in Fig. 12 (b), is found in the measured phase difference using moiré analysis. As the experiments were conducted under free oscillation conditions, the dominant frequency in the accelerometer's FFT spectrum provide the reference for the vibration frequency to

be measured. Fig. 12 (c) shows the normalised power spectrum of acceleration and moiré phase difference with the DC term removed, which shows great similarity between the two power spectra.

4.2. Different spatial periods of marker pattern

A larger spatial period of the marker pattern means higher visibility when the camera is further away. However, fewer stripes can be fitted inside the same marker dimensions. This experiment is designed to find the optimal stripe width balancing between visibility and spatial resolution. Spatial periods of 2.0 mm, 2.84 mm, and 5.0 mm, shown in Fig. 13, are chosen because the number of strips fit exactly 14, 10, and 6 in the marker with white spacing at the centre. Each spatial period is tested with camera distances of 1.0 m, 1.2 m, 1.5 m, 1.8 m, and 2.0 m to evaluate the robustness of the marker segmentation.

The normalised power spectrum of acceleration and the result from

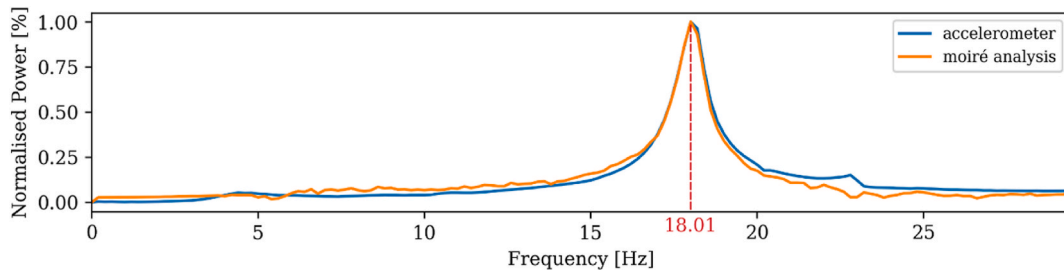


Fig. 14. Normalised power spectrum of the acceleration and moiré analysis method with a marker (2.84 mm spatial period) and a camera 1.0 m away from the marker.

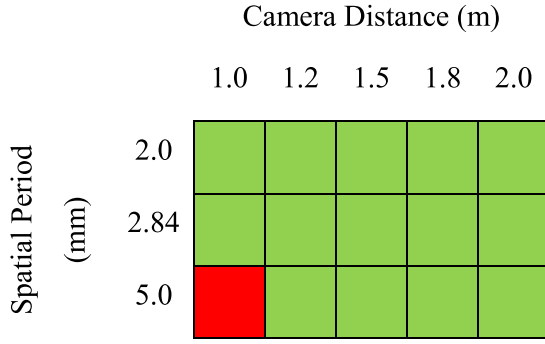


Fig. 15. Marker detection success rate for different marker spatial period at different camera distances (red indicating 0% and green indicating 100%).

the moiré analysis method with a 2.84 mm spatial period at a camera distance of 1.0 m are shown in Fig. 14. The results from spatial period 2.0 mm and 2.84 mm were successful and achieved 0% relative error for camera distances set during experiments. The marker detection success rate for each spatial period at different distances are shown in Fig. 15.

The marker with a 5.0 mm spatial period, however, was unable to obtain results at a camera distance of 1.0 m due to the unsuccessful segmentation of the marker. This is because when the camera is closer to the marker, the gap between the stripes is wider. This leads to the binarised image being separated into individual stripes Fig. 16 (a), resulting in a failed marker detection. Therefore, the image pyramid introduced in Section 2.3 was applied to improve the success rate of the marker segmentation. The image pyramid applies a Gaussian blur to smooth out the image and downsize it to the half of its original size. The binary image containing the same marker using the image pyramid is shown in Fig. 16 (b), which shows that the stripes are grouped into one patch. Once the marker is successfully segmented, vibration frequency is also correctly determined from the obtained normalised power spectrum.



Fig. 16. Binary image containing a marker with a 5.0 mm spatial period at a camera distance of 1.0 m broken into stripe contours (a). Binary image under the same conditions using an image pyramid (b).

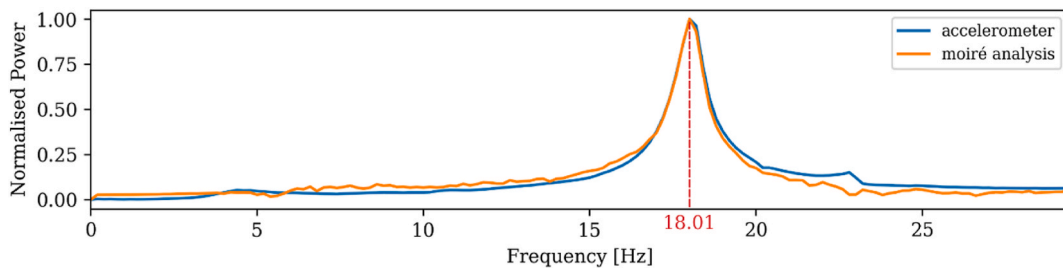


Fig. 17. Normalised power spectrum of the accelerometer and the results from moiré analysis with the camera 1.0 m away from the marker.

4.3. Different camera distances

The distance between the camera and the marker affects the spatial resolution of the pixels. On one hand, the further the camera, the harder it is for the camera to perceive the vibration due to the marker's decreased size in the captured video. On the other hand, although the closer the camera is to the marker, the higher the spatial resolution, the gaps between the stripes on the marker become wider and harder to get a clean segmentation. To evaluate how the camera distance will affect the measurement accuracy, the moiré analysis method is tested at the blade's natural frequency with a varying distance of 1.0 m, 1.2 m, 1.5 m, 1.8 m, and 2.0 m, respectively. The minimum distance of 1.0 m is chosen based on the flap-wise vibration magnitude of a large wind turbine. It is shown in Ref. [25] that flap-wise vibrations on a 96-m-long wind turbine blade can have magnitudes close to 0.5 m, which makes 1.0 m a minimum safety distance to measure using a small drone. The normalised power spectrum of the accelerometer and the moiré analysis method are shown in Fig. 17. It can be seen that the peak is at the same location of 18.01 Hz. The same result is obtained for all camera distances being tested. This demonstrates the robustness of the moiré analysis method against camera distance varying from 1m to 2 m.

4.4. Different camera pitch angles

Camera position changes parallel to the grating's travelling direction may create perspective changes, affecting the marker's aspect ratio, and making the segmentation stage challenging. Furthermore, it will cause the stripe frequency to shift and alter the magnification range of the moiré pattern. Thus, testing different pitch angles can give us a sense of how much tolerance is acceptable for future applications using such systems. In this experiment, the blade is pointing downwards, so the marker's grating travel direction is top-down, which corresponds to changing the pitch of the camera. Camera pitch angles of 0°, 5°, 10°, and 15° were tested on the test rig, respectively. The markers captured at different camera pitch angles are shown Fig. 18.

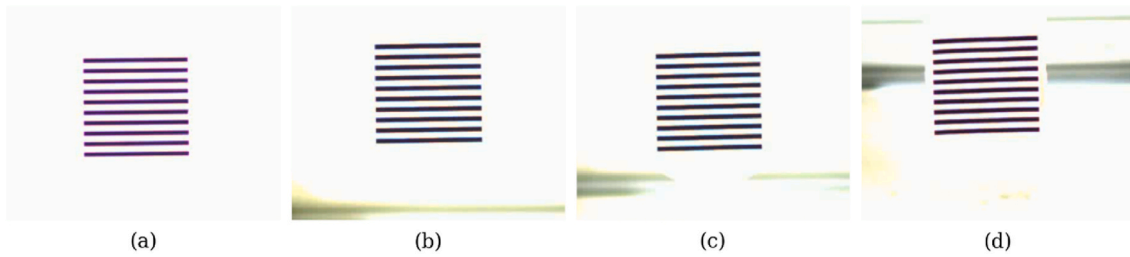


Fig. 18. Stripe markers viewed at camera pitch angles 0° (a), 5° (b), 10° (c), and 15° (d).

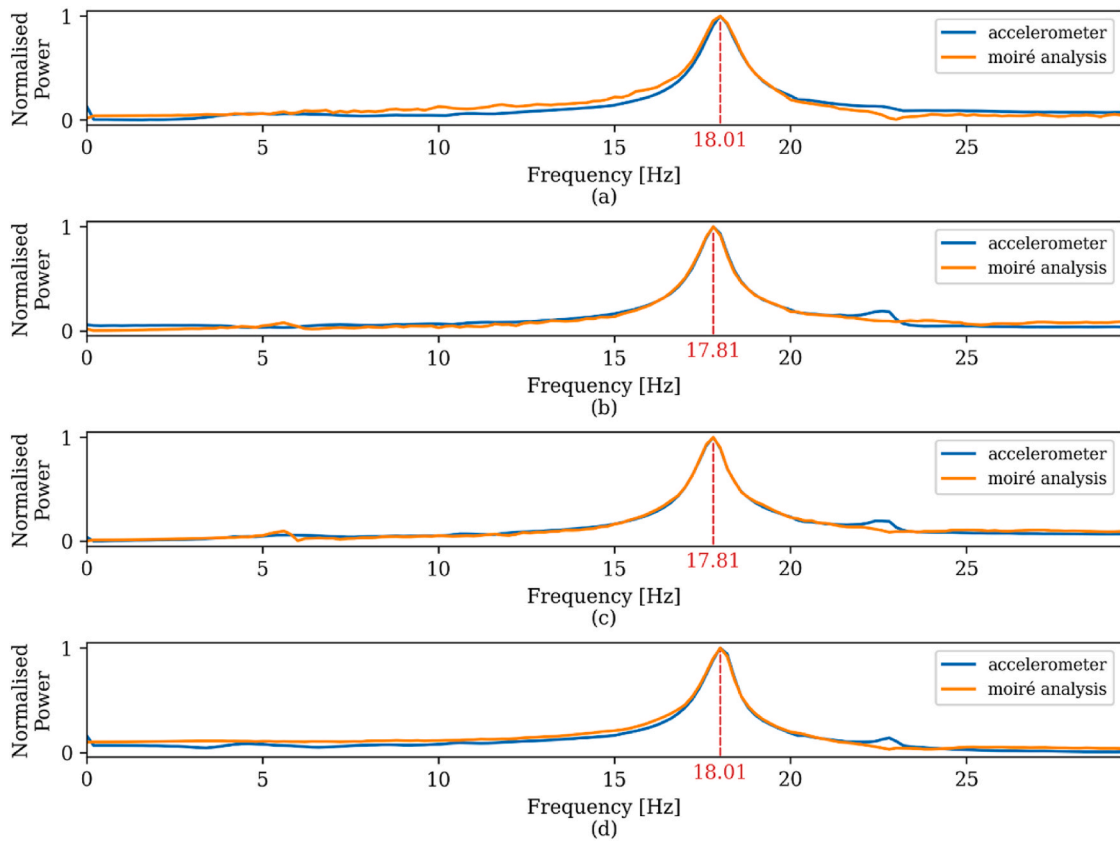


Fig. 19. Power spectrum at camera distance 1.5 m with camera pitches 0° (a), 5° (b), 10° (c), and 15° (d).

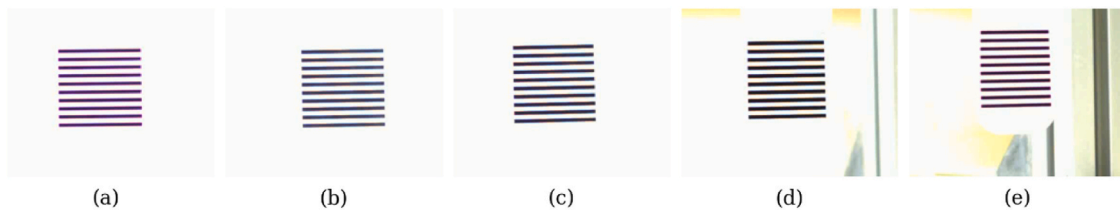


Fig. 20. Stripe markers viewed at camera yaw angles 0° (a), 5° (b), 10° (c), 20° (d), and 30° (e).

The normalised power spectrum measured at camera pitch angles of 0°, 5°, 10°, and 15° is shown in Fig. 19. It shows that the moiré analysis method can successfully capture the most significant vibration frequency.

4.5. Different camera yaw angles

Another type of perspective change is when the camera position changes perpendicular to the grating travel direction. Although it still

affects the marker geometry, the stripes should have less change in width and thus be less of a problem in general. A broader angle range of 0°, 5°, 10°, 20° and 30° is chosen to test more extreme distortions of the marker. The marker captured at different camera yaw angle is shown in Fig. 20.

The normalised power spectrum of all tested angles is shown in Fig. 21. The most significant vibration frequency is also successfully identified in all cases.

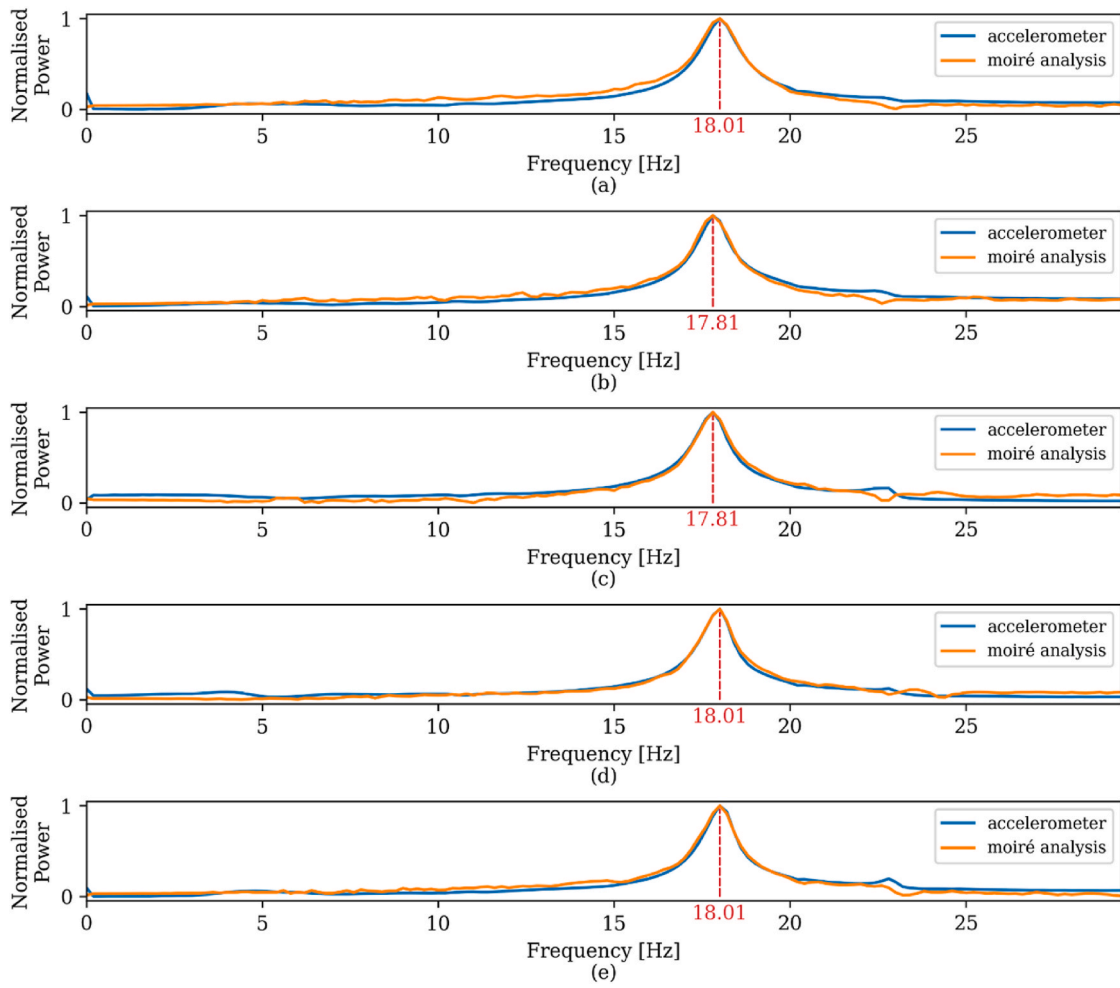


Fig. 21. Normalised power spectrum with camera yaw angles 0° (a), 5° (b), 10° (c), 20° (d), and 30° (e).

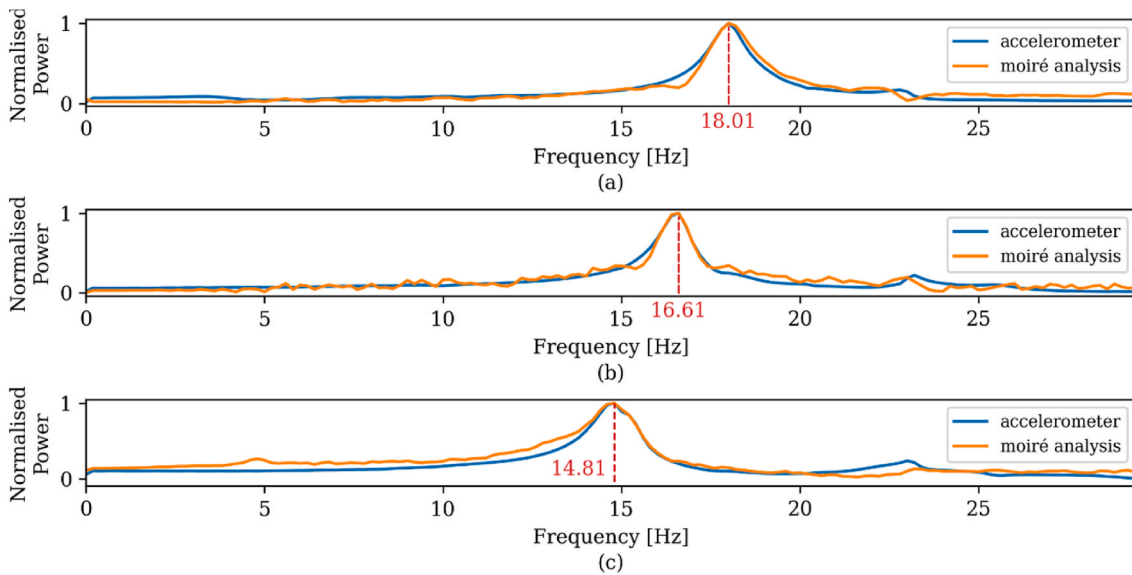


Fig. 22. Normalised power spectrum of acceleration and the moiré phase shift with the wireless data acquisition module positioned at 0 cm (a), 25 cm (b), and 30 cm (c).

4.6. Different vibration frequencies

The vibration frequency is changed by positioning the wireless data

acquisition module at different locations on the blade. The default position of the wireless data acquisition module is 0 cm, which is mounted at the centre of the hub. In this case, the vibration frequency of the blade

is 18.01 Hz from the accelerometer. Then, the wireless data acquisition module is moved to 25 cm and 30 cm on the blade to change the vibration frequency to 16.61 Hz and 14.81 Hz, respectively. As shown in Fig. 22, the measured frequency from the moiré analysis method is 18.01 Hz when the module is at 0 cm to 16.61 Hz when the module is located at 25 cm and 14.81 Hz when the module is at 30 cm on the blade.

5. Conclusion

This paper has presented a new method based on moiré pattern analysis to measure the flap-wise vibration frequency of wind turbine blades. The proposed method was tested extensively on the wind turbine test rig to quantify its performance under the laboratory conditions of different spatial periods of marker pattern, camera distances, camera pitch angles, camera yaw angles and vibration frequencies. Experimental results have shown that the moiré pattern generated by the markers with a spatial period from 2.0 mm to 5.0 mm and a camera distance from 1.2 m to 2 m can be correctly detected and converted to vibration frequency. The exceptional case of the marker with a spatial period of 5.0 mm was not detected at a camera distance of 1.0 m due to the wider gap between the stripes, resulting in the binarised image being separated into individual stripes. In this case, an image pyramid is created to improve the success of marker segmentation and determination of vibration frequency. Variations in camera pitch angles from 0° to 15° and yaw angles from 0° to 30° do not affect the measurement of vibration frequency, demonstrating the robustness of the measurement system based on moiré pattern analysis. In comparison with the reference vibration frequency from the accelerometer, the moiré pattern analysis method is able to determine the flap-wise vibration frequency under all test conditions. These results have demonstrated the feasibility and robustness of the proposed method under laboratory conditions. As the conditions in real scenes are more complex, investigation on the effects of the environmental conditions such as light condition and wind condition, and the operating conditions such as rotational speed and multi-mode vibration will be continuously studied in the future.

CRediT authorship contribution statement

Yi-Hsiang Liao: Data curation, Formal analysis, Methodology, Software, Writing – original draft. **Lijuan Wang:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Yong Yan:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Corresponding author - Dr Lijuan Wang is currently an associate editor for the Measurement: Energy Journal. Co-author - Prof. Yong Yan is currently Editor-in-Chief for the Measurement: Energy Journal. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] S. Pfaffel, S. Faulstich, K. Rohrig, Performance and reliability of wind turbines: a review, *Energies* 10 (11) (Nov. 2017) 1904, <https://doi.org/10.3390/en10111904>.
- [2] J. Smith, 'Choosing the correct parameter for vibration analysis', IVC Technologies - Predictive Maintenance Leaders. Accessed: January. 14, 2025. [Online]. Available: <https://ivctechnologies.com/2022/05/02/choosing-the-correct-parameter-for-vibration-analysis/>.
- [3] F. Aswin, Z.S. Suzen, Analysis of free vibration measurement by mems accelerometer device on wind turbine blade, in: 2018 International Conference on Applied Science and Technology (Icast), Oct. 2018, pp. 425–431, <https://doi.org/10.1109/ICAST1.2018.8751570>.
- [4] R. Anslow, Choosing the best vibration sensor for wind turbine condition monitoring [Online]. Available: <https://www.analog.com/en/resources/analog-dialogue/articles/choosing-the-best-vibration-sensor-for-wind-turbine-condition-monitoring.html>. (Accessed 14 January 2025).
- [5] F. Berkemeyer, W. Lang, Wireless inertial measurements on wind turbine rotor blades, *IEEE Sens. J.* 21 (24) (Dec. 2021) 27938–27946, <https://doi.org/10.1109/JSEN.2021.3122952>.
- [6] A. Aihara, T. Kawaguchi, N. Miki, T. Azami, H. Sakamoto, M. Okuma, A vibration estimation method for wind turbine blades, *Exp. Mech.* 57 (8) (Oct. 2017) 1213–1224, <https://doi.org/10.1007/s11340-017-0295-x>.
- [7] K. Lee, A. Aihara, G. Puntsgdash, T. Kawaguchi, H. Sakamoto, M. Okuma, Feasibility study on a strain based deflection monitoring system for wind turbine blades, *Mech. Syst. Signal Process.* 82 (Jan. 2017) 117–129, <https://doi.org/10.1016/j.ymssp.2016.05.011>.
- [8] L. Glavind, I.S. Olesen, B.F. Skipper, M.V. Kristensen, Fiber-optical grating sensors for wind turbine blades: a review, *Opt. Eng.* 52 (3) (Mar. 2013) 030901, <https://doi.org/10.1117/1.OE.52.3.030901>.
- [9] Q.V. Davis, W.K. Kulczyk, Vibrations of turbine blades measured by means of a laser, *Nature* 222 (5192) (May 1969) 475–476, <https://doi.org/10.1038/222475a0>.
- [10] A.U. Dilek, A.D. Oguz, F. Satis, Y.D. Gokdel, M. Ozbek, Condition monitoring of wind turbine blades and tower via an automated laser scanning system, *Eng. Struct.* 189 (Jun. 2019) 25–34, <https://doi.org/10.1016/j.engstruct.2019.03.065>.
- [11] A. Zabih, F. Aghdasi, C. Ellouzi, N.K. Singh, R. Jha, C. Shen, Non-contact wind turbine blade crack detection using laser doppler vibrometers, *Energies* 17 (9) (Jan. 2024), <https://doi.org/10.3390/en17092165>, 9.
- [12] R. Wu, D. Zhang, Q. Yu, Y. Jiang, D. Arola, Health monitoring of wind turbine blades in operation using three-dimensional digital image correlation, *Mech. Syst. Signal Process.* 130 (Sep. 2019) 470–483, <https://doi.org/10.1016/j.ymssp.2019.05.031>.
- [13] N. Wadhwa, M. Rubinstein, F. Durand, W.T. Freeman, Phase-based video motion processing, *ACM Trans. Graph.* 32 (4) (Jul. 2013) 1–10, <https://doi.org/10.1145/2461912.2461966>.
- [14] Z. Zang, X. Yang, G. Zhang, J. Wang, J. Chen, Phase-based vibration frequency measurement from videos recorded by unstable cameras, *IEEE Trans. Instrum. Meas.* 71 (2022) 1–14, <https://doi.org/10.1109/TIM.2022.3197750>.
- [15] Z. Liu, Q. He, S. Chen, Z. Peng, W. Zhang, Time-varying motion filtering for vision-based nonstationary vibration measurement, *IEEE Trans. Instrum. Meas.* 69 (6) (Jun. 2020) 3907–3916, <https://doi.org/10.1109/TIM.2019.2937531>.
- [16] A. Sarrafi, P. Poozesh, C. Niezrecki, Z. Mao, Mode extraction on wind turbine blades via phase-based video motion estimation, in: *Smart Materials and Nondestructive Evaluation for Energy Systems 2017*, International Society for Optics and Photonics, Apr. 2017, p. 101710E, <https://doi.org/10.1117/12.2260406>.
- [17] J.Y. An, S.I. Lee, Phase-based motion magnification for structural vibration monitoring at a video streaming rate, *IEEE Access* 10 (2022) 123423–123435, <https://doi.org/10.1109/ACCESS.2022.3224601>.
- [18] Q. Wang, S. Ri, H. Tsuda, M. Koyama, K. Tsuzaki, Two-dimensional Moiré phase analysis for accurate strain distribution measurement and application in crack prediction, *Opt. Express* 25 (12) (Jun. 2017) 13465–13480, <https://doi.org/10.1364/OE.25.013465>.
- [19] S. Ri, H. Tsuda, K. Chang, S. Hsu, F. Lo, T. Lee, Dynamic deformation measurement by the sampling moiré method from video recording and its application to bridge engineering, *Exp. Tech.* 44 (3) (Jun. 2020) 313–327, <https://doi.org/10.1007/s40799-019-00358-4>.
- [20] V. Saveljev, J.-Y. Son, H. Lee, G. Heo, Non-contact measurement of vibrations using deferred moiré patterns, *Adv. Mech. Eng.* 15 (4) (Apr. 2023) 16878132221143885, <https://doi.org/10.1177/16878132221143885>.
- [21] Y.-H. Liao, L. Wang, Y. Yan, Vibration measurement of wind turbine blades through image analysis of moiré pattern, *Meas. Sens.* (Dec. 2024) 101718, <https://doi.org/10.1016/j.measen.2024.101718>.
- [22] I. Amidror, *The theory of the Moiré Phenomenon*, vol. 38, in: *Computational Imaging and Vision*, vol. 38, Springer, London, 2009, <https://doi.org/10.1007/978-1-84882-181-1>.
- [23] B. Benligiray, C. Topal, C. Akinlar, 'STag: a Stable Fiducial Marker System', *arXiv: 1707 (July 2019) 06292* <https://doi.org/10.48550/arXiv.1707.06292>.
- [24] S. Gruppetta, '2D fourier transform in python: create any image using only sine functions', *The Python Coding Book*. Accessed: January. 14, 2025. [Online]. Available: <https://thepythoncodingbook.com/2021/08/30/2d-fourier-transform-in-python-and-fourier-synthesis-of-images/>.
- [25] S.G. Horcas, N.N. Sørensen, F. Zahle, G.R. Pirrung, T. Barlas, Vibrations of wind turbine blades in standstill: mapping the influence of the inflow angles, *Phys. Fluids* 34 (5) (2022), <https://doi.org/10.1063/5.0088036>.