Structural Analysis of a Small Wind Turbine Blade Subjected to Gyroscopic Load

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Abstract. A study was conducted to investigate the structural response of a composite constructed small wind turbine blade subjected to gyroscopic load using finite element analysis. An Aerogenesis 5 kW small wind turbine blade was used as a case study. As part of this study, a high-fidelity finite element model of the 2.5 m long composite blade was built, and the accuracy of its predictions validated against experimental data. The blade model was loaded using a comprehensive method for applying gyroscopic load to finite element models of small-scale blades. The predicted results show gyroscopic loading causes the blade to deflect in both the flap-wise and lead-lag directions and induce reasonably high strains in the composite blade structure. The direction of the gyroscopic loading is a function of the direction of turbine yaw as well as the blade position as it rotates, therefore gyroscopic loading can both exacerbate and reduce the effects of aerodynamic loading acting on the blade.

1. Introduction

Small wind turbines are generally equipped with passive yaw systems that utilise a tailfin or similar device to aid the turbine’s alignment to the wind direction [1]. As small wind turbines are free to rotate around their yaw axis, their yaw rate will be determined by the rate of change in the wind direction and the yaw inertia of the turbine. Small wind turbines are often sited at locations where the wind resource is not ideal, with high levels of turbulence and where high rates of change in wind direction can occur. The Coriolis acceleration of rotating and yawing blades can lead to large gyroscopic loads on the blades and other components of small wind turbines during operation. These cyclical loads can lead to additional fatigue cycles acting on the blade, which may lead to blade lifespan issues.

Small wind turbines are defined by the IEC 61400-2 Wind turbines: design requirements for small wind turbines [2] as having a swept area less than 200 m² and power output less than 50 kW. For small wind turbines, the gyroscopic load is usually the dominant load acting on the blades [3, 4] and it is the largest contributor to the stress on the main shaft of the turbine [2, 3]. The IEC standard [2] provides an equation to quantify the gyroscopic moment acting on the blade root, Equation (1), and for design purposes, Equation (1) is used in combination with the equation for maximum yaw rate of a small wind turbine, Equation (2), also provided by the IEC standard [2].

\[
M_{gyroscopic} = 2I_{blade} \omega_{rotor} \omega_{yaw} \cos \phi \quad (1)
\]

\[
\omega_{yaw, maximum} = 3 - 0.01 (\pi R^2 - 2) \quad (2)
\]

In Equations (1) and (2), \( M_{gyroscopic} \) is the gyroscopic moment acting on the blade root, \( I_{blade} \) is the blade inertia, \( \omega_{rotor} \) is the angular velocity of the turbine’s rotor, and \( \omega_{yaw} \) is the turbine’s yaw rate (for the
purposes of blade design the $\omega_{yaw}$ is calculated using Equation (2)), $\varphi$ is the azimuth angle of the blade (for design purposes and maximum gyroscopic moment, $\varphi = 0$) and $R$ is the blade radius. Equation (1) quantifies the total gyroscopic moment acting on the blade root due to the gyroscopic force, however it offers no information on the distribution of the gyroscopic force on the blade surface and how the blade responds structurally to the gyroscopic load.

To improve the design of small wind turbine blades, a study was conducted to investigate the structural response of a small wind turbine blade subjected to gyroscopic load using finite element analysis. The gyroscopic load was applied to the blade finite element model using a comprehensive and detailed methodology proposed in [5].

An Aerogenesis 5 kW two-bladed wind turbine was used as the case study for determining the effects of gyroscopic loading on the blade structure. This small wind turbine is extensively instrumented and available to the authors to conduct experimental measurement campaigns. The blades of the Aerogenesis turbine are 2.5 m long, weight approximately 6.3 Kg and are constructed with an outer shell of fiberglass reinforced polymer laminate material and H80 structural foam in its core. The blade finite element model was validated against experimental measurements undertaken on an instrumented Aerogenesis blade to ensure the model accurately captured blade flex and straining under load.

There are many papers documenting the results of finite element modelling of small wind turbine blades, such as [6 - 9], to the best of the authors’ knowledge, this is the first study to investigate the structural response of a small wind turbine blade model subjected to gyroscopic loading using finite element analysis.

This paper will present the high-fidelity finite element model of the Aerogenesis blade, its validation against experimental measurements, explain the methodology to load the blade model with gyroscopic load and discuss the structural analysis results, which include blade displacements and fiber strains within the composite constructed outer shell of the blade.

2. Methodology

2.1. Experimental measurements and blade finite element model validation

The finite element model used in this study was created and solved using Strand7 finite element software [10] version R3. The model consisted of low-order 4-node shell plate elements to model the composite constructed outer shell of the blade and low-order 8-node 3D brick elements to model its foam core. In total, 21681 plate elements and 10643 brick elements were used to build the blade model. The anisotropic laminate material properties of the outer composite shell were built and assigned within Strand7 from the properties of the constitute fiberglass layers that formed the shell, and the material properties of the foam core were assumed to be isotropic and obtained from the relevant data sheets. As the amount and lay of the fiberglass used in the blade shell varied both span wise and length wise within the blade, the properties of the shell elements in the finite element model also varied to accurately reflect the blade structure. Figure 1 shows a picture of the finite element model of the Aerogenesis blade with the various colored elements on the surface representing shell elements of different structural properties. At the top of Figure 1, the blade model pressure surface and on the bottom the blade model suction surface.

![Figure 1](attachment) - Aerogenesis 5 kW wind turbine blade model, at the top blade suction surface and at the bottom the pressure surface of the blade. Different colours indicate the different material properties.
The blade is bolted to the turbine’s rotor via four bolts through its attachment block – see Figure 1. This attachment was simulated in the blade model by fully constraining all nodes on the outside surface of the attachment block.

One of the Aerogenesis blades has been instrumented with 7 unidirectional strain gauge modules located radially along the pressure surface of the blade with the gauges aligned in the radial direction. The instrumented blade was subjected to stationary bench experiments that consists of holding the blade in a fixed rig by its attachment block and applying point loads of three magnitudes (3.3, 6 and 8.3 Kg) near the tip of the blade perpendicular to its operating plane of rotation – see Figure 2. The magnitude of the point loads applied during the bench experiment were determined by the weights available. Strains from the gauges and the deflections at the radial location of the gauges along the trailing edge of the blade were recorded during the experiment and subsequently used for blade model validation.

For a valid comparison between experimental measurements and computational predictions, the blade model was equipped with ‘virtual’ strain gauges. A ‘virtual’ strain gauge was a 2-node truss element (beam elements that offer stiffness to axial loading only) with a low stiffness (1 MPa) and small cross section (1 mm) in order to not interfere with the structural response of the blade model. The ‘virtual’ strain gauges were placed on the blade model pressure surface at the same location as the actual strain gauges are on the physical blade. Figure 2 illustrates the location of the strain gauge modules (numbered 1 to 7) and the how the point loads were applied to the blade during the bench experiment.

The data collected during the bench experiments was used to validate the predicted strains and deflections from the blade finite element model. Figures 3 to 5 present graphically the comparison between experimental measurements and computational predictions. Overall predictions were found to be in excellent agreement with experimental measurements, except for deflections measured at gauges 1, 2 and 3 (close to the attachment block) where magnitudes were very small. All remaining predicted deflections were less than 12.5% error of the measurements and all predicted strain values were within 5.5% of the measurements. The bench experiment with static loads was used to validate the blade model computational predictions as the loads used are known and the static nature of the experiment allows for the blade deflections to be measured.

The mass of the blade model as determined by Strand7 was 5.94 kg, approximately 0.4 kg lighter than the physical blade (6.33 kg) and the center of mass of the blade model was located 0.77 m from the blade root along the radial direction, approximately 0.02 m closer to the blade root than the measured center of mass (0.79 m). This small difference between experimental measurements and computational determined mass and center of mass was expected and it is mostly attributed to the presence of the strain gauges connecting cables that run through the blade’s core. The strain gauges are glued to the blade and their connecting cables are soldered to the gauges, making it impossible to remove the cables to weight the blade once they have been installed.
Figure 3 – Validation results, 3.3 kg load. (a) blade deflections (b) strain gauges

Figure 4 – Validation results, 6 kg load. (a) blade deflections (b) strain gauges signals

Figure 5 – Validation results, 8.3 kg load. (a) blade deflections (b) strain gauges signals
2.2. Gyroscopic load applied to small wind turbine blade finite element model

For the structural analysis of the Aerogenesis wind turbine blade, its finite element model was loaded with gyroscopic loading following the comprehensive methodology proposed in [5]. The direction of the gyroscopic force acting on the blade surface is a function of the direction of the yaw motion of the turbine as well as the position of the rotating blade. In this study, the investigation of the blade’s structural response to gyroscopic loading was limited to the case in which the blade is in its upright position, considering variations on the direction of the yaw motion only (clockwise and counterclockwise), as illustrated in Figure 6. Further investigation of the blade’s structural response to the gyroscopic load considering variations on the blade’s position as it rotates, is proposed in the future work section of this paper.

The gyroscopic load calculation method used here, was developed specifically for finite element analysis, as it depends on the discretisation of the blade model into finite elements to calculate the value and distribution of the gyroscopic force acting on the blade.

To quantify the gyroscopic force distribution on a small-scale blade using the method proposed by [5], it is necessary to start by calculating the linear acceleration of the centroid of each discrete element present on the blade model. The linear acceleration of each element depends on the turbine’s rotor angular velocity, turbine yaw rate and the location of the element in relation to center of rotation of the gyroscopic load ($G$), see Figure 7.

Equation (3) can be used to calculate the linear acceleration (due to the rotating and yawing motions) of any point on the blade. For brevity, the complete derivation of (3) is not presented here; the interested reader is referred to [5] for details.

$$\ddot{a} = (\dot{\omega} \times \ddot{r}) + (\dot{\omega} \times (\ddot{\omega} \times \ddot{r}))$$  \hspace{1cm} (3)

In (3), $\ddot{a}$ is the linear acceleration vector of a given point on the blade, $\ddot{r}$ is the distance vector from the point in which the acceleration is being calculated to the centre of rotation of the motion ($G$), $\dot{\omega}$ and $\ddot{\omega}$ are the total angular acceleration and total angular velocity vectors, respectively, of the point. All vectors in (3) have components in x, y and z orthogonal directions. Note that the total angular velocity vector ($\omega_{blade}$) refers to the cross product of the components of the angular velocity of the rotating ($\omega_{blade}$)
and yawing ($\omega_{\text{yaw}}$) blade. Figure 7 shows the coordinates system for the gyroscopic load calculations and it illustrates the concept for a given point $P$ on the blade. Note that the centre of rotation of the gyroscopic load is located at point $G$.

Once the linear acceleration of the centroid of each discrete element present in the blade model has been determined using (3), the force acting on the element can be calculate using (4).

$$F_{\text{gyroscopic}} = \bar{a} m$$  \hspace{1cm} (4)

In (4), $F_{\text{gyroscopic}}$ is the gyroscopic force vector acting on the discrete element, $\bar{a}$ is the linear acceleration vector previously calculated and $m$ is the element’s mass. $F_{\text{gyroscopic}}$ is also a vector with components in x, y and z orthogonal directions.

At this point an important observation must be made regarding the components of the gyroscopic load and how to correctly apply this load to the blade model. One of the components of the gyroscopic load is the angular velocity of the blade ($\omega_{\text{blade}}$). The blade angular velocity results in the centrifugal load that also acts on the blade, another critical operational load of small wind turbine blades [2, 3]. The centrifugal load causes centrifugal stiffening effects that aid the blade to resist the bending moments induced by other loads (manly the aerodynamic load) during operation of the turbine. As the centrifugal load is effectively a component of the gyroscopic load its stiffening effects must be account for during the finite element analysis. Calculating stiffening effects on the finite elements on the blade model would be a laborious and complex task as it requires the integration of the centrifugal force over the volume of the discrete elements [11]. It is recommended in [5] that finite element software capabilities are used to apply the centrifugal load to the blade model and calculate its resulting stiffening effects. To take advantage of the software’s capabilities, it is necessary to subtract the centrifugal force ($F_{\text{centrifugal}}$), Equation 5, from the gyroscopic force ($F_{\text{gyroscopic}}$), and simultaneously apply the centrifugal and gyroscopic loads to the blade model.

![Figure 7 – Gyroscopic load illustration and coordinate system](image-url)
\[ \vec{F}_{\text{centrifugal}} = m l \omega_{\text{blade}}^2 \]  

In Equation 5, \( m \) is the finite element mass, \( l \) is the element’s radial location along the blade and \( \omega_{\text{blade}} \) is the blade angular velocity. The centrifugal force (\( \vec{F}_{\text{centrifugal}} \)) is also a vector, however it has only one component in the \( y \)-direction – see Figure 7. The centrifugal force can now be subtracted from the gyroscopic force, according to Equation 6, to determine the magnitude of the force that will be applied to the blade model (\( \vec{F}_{\text{total}} \)).

\[ \vec{F}_{\text{total}} = \vec{F}_{\text{gyroscopic}} - \vec{F}_{\text{centrifugal}} \]  

To correctly apply the gyroscopic load to a small blade finite element model using the methodology proposed in [5] and described above, it is necessary to:

- simultaneously load the blade model with centrifugal load and \( \vec{F}_{\text{total}} \) (gyroscopic load),
- all finite elements in the blade model (plates and bricks) must be loaded, therefore a value of \( \vec{F}_{\text{total}} \) must be calculated for each discrete element in the model and
- the resulting force \( \vec{F}_{\text{total}} \) must be applied to the centroid of the finite elements, according to its magnitude and direction.

For the structural analysis of the Aerogenesis 5 kW blade, the gyroscopic load was calculated for clockwise and counter-clockwise directions of the yaw motion and the blade finite element model was loaded following the methodology explained above. For the calculation of the gyroscopic load (including the calculations of the centrifugal force) used in the structural analysis of the model, the rated operating rotational speed of the Aerogenesis turbine, 320 revolutions per minute, and maximum yaw rate for small wind turbines from (2) were used. The blade model was constructed, loaded with the gyroscopic load and the Strand7 non-linear solver was used to perform the simulation. The non-linear solver was chosen as its solution is resolved in increments, in every increment a percentage of the load is added to the model and model’s stiffness matrix is updated. Updating the stiffness matrix effectively updates the displacement vector and accounts for residual forces in the model, this process improves the accuracy of the simulation’s results [11].

3. Finite element analysis results

The results from the finite element analysis of the Aerogenesis blade model show a maximum tip displacement of 0.15 m in the blade flap-wise direction (out of plane), see Figure 8, and in the blade lead-lag direction (in-plane direction), a maximum tip displacement of approximately 0.03 m, see Figures 9 and 11.

The displacement results in the flap-wise direction show that the Aerogenesis blade would not contact the turbine tower (0.65 m gap between blade tip and tower), even if subjected to the maximum gyroscopic load.

The magnitude of the displacement in the lead-lag direction was the most surprising finding from the structural analysis, as to best of the authors’ knowledge, it has not yet been observed or quantified. This displacement corresponds to approximately 20% of the maximum blade deflection in the flap-wise direction. In Figures 8 to 10, the blade’s undeformed geometry in green for visualisation of the deflections.

Note that the results presented in Figures 8, 9, 12 and 13 are from simulations performed with the ‘worst’ case of the gyroscopic load, when it is acting on the blade in the same direction as the aerodynamic load and results presented in Figures 10, 11, 14 and 15 are from simulations in which the gyroscopic load is acting on the opposite direction of the aerodynamic load.
Figure 8 – Blade displacement in the flap-wise direction (clockwise direction of the yaw motion)

Figure 9 – Blade displacement in the lead-lag direction (clockwise direction of the yaw motion)

Figure 10 – Blade displacement in the flap-wise direction (counter-clockwise direction of the yaw motion)

Figure 11 – Blade displacement in the lead-lag direction (counter-clockwise direction of the yaw motion)
Figures 12 to 15 show the strains on the outer-most structural ply of laminate composite material of the blade shell in the radial and circumferential directions. The resulting strains were recorded at the centroid of the elements on the blade model as the accuracy of finite element analysis of composite material decreases towards the edges of the elements [11]. These results show the strains do not exceed the $10^6$ fatigue cycle strain limit of the composite material of the Aerogenesis (approximately 2200 micro ($\mu$) strain) on most of the blade surface, with small areas experiencing concentrations of strain due to geometrical singularities of the finite element model. As such, the predicted strain results suggest that the gyroscopic load does not adversely affect the blade fatigue life.

![Figure 12](image1.png)  
**Figure 12** – Fibre strain in the radial direction in the most outer structural layer of the blades composite shell. Blade pressure surface at the top and suction surface at the bottom (clockwise direction of the yaw motion)

![Figure 13](image2.png)  
**Figure 13** – Fibre strain in the circumferential direction in the most outer structural layer of the blades composite shell. Blade pressure surface at the top and suction surface at the bottom (clockwise direction of the yaw motion)

![Figure 14](image3.png)  
**Figure 14** – Fibre strain in the circumferential direction in the most outer structural layer of the blades composite shell. Blade pressure surface at the top and suction surface at the bottom (counter-clockwise direction of the yaw motion)
4. Discussion
The work presented in this paper details the results of structural analysis of a small wind turbine blade subjected to gyroscopic load. The results of this work clearly show that gyroscopic loading acting on a small wind turbine blade operating at design rotational speed and the maximum yaw rate from [2] causes the blade to deflect in both the flap-wise (out of plane) and lead-lag (in plane) directions and causes the blade structure to experience a reasonably high level of strain. The blade’s lead-lag deflection was some 20% of the blade’s maximum flap-wise deflection, which is reasonable given the second moment of area of the blade in the lead-lag direction is an order of magnitude higher than that in the flap-wise direction. The predicted maximum strain due to gyroscopic loading is reasonably high and this strain may add to the strain induced by aerodynamic loading, depending on the direction of turbine yaw.

The blade loading method briefly described in the paper and developed in [5], allows the effects of gyroscopic loading acting on a small-scale blades to be quantified and accurately captured in a high-resolution finite element model. The predicted strains from the finite element model of the blade give an accurate picture of the strain distribution through the blade structure and will allow potential areas of structural weakness to be reinforced with additional glass fiber.

5. Summary and future work
This paper presented the results of a structural analysis undertaken on a high-resolution finite element model of an Aerogenesis 5 kW small wind turbine blade subjected to gyroscopic load. The accuracy of the finite element model predictions was validated against blade deflection measurements and strain gauge signals acquired during a stationary bench experiment that held the blade by its attachment block and subjected to flap-wise tip loading. During the validation process, the predicted flap-wise deflection and blade strains were within 12.5% and 5.5% of measured values, respectively. A comprehensive method for calculating and assigning the loading due to gyroscopic forces to all elements in a high-resolution finite element model of the blade was presented, with the complete methodology detailed in [5]. The predicted results showed that an Aerogenesis blade operating at design rotational speed of 320 RPM and yawing at the maximum rate given by equation (2), experience a maximum flap-wise deflection of approximately 0.15 m and a lead-lag deflection of approximately 0.03 m with a maximum strain in the blade of 2250 μstrain.
In addition to the gyroscopic loading (including the centrifugal load), the aerodynamic loading must be applied to the blade model to give a comprehensive picture of the total load experienced by an operating small wind turbine blade. Further structural analysis of the blade model subjected to the gyroscopic and aerodynamic load simultaneously will be undertaken, as well as structural analysis of the blade subjected to gyroscopic load as a function of the blade’s position in its plane of rotation.

The work documented in this paper will be extended to include the effects of aerodynamic load and thereby give a more comprehensive view of the operational loads experienced by an operating small wind turbine blade. The results of this work coupled with results from experimental work examining the frequency and magnitude of yaw events, will allow a comprehensive fatigue analysis to be undertaken on the blade structure to ensure it is sufficiently strong yet lightweight to have at least a 20 year lifespan. Furthermore, the authors intend to use the results of finite element analysis of the blade subjected to gyroscopic load for structural optimisation of small-scale blades; reducing blade mass while maintaining structural integrity.

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