Technical Disclosure[1]

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BLCS Sensors Faults Based on Thrust Correlation

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Technical Disclosure

5. Abstract

Disclosed is a method and associated analytical framework for monitoring blade load control system (BLCS) sensor health using correlation between thrust and measured wavelength. The disclosure is based on the observation that, at substantially constant pitch angle conditions, wavelength exhibits a predictable and substantially linear relationship with estimated thrust. A thrust-based reference wavelength may therefore be calculated and compared with actual sensor wavelength output to identify deviations indicative of fault conditions. In representative implementations, the relationship may be expressed as wavelength = gain × thrust + offset, with gain and offset values derived for individual sensor positions including sensors located either at the blade flap, edge or both. Differences between actual wavelength and the thrust-based reference may be evaluated statistically, including by probability-of-exceedance analysis, to identify high error conditions, drift, offset changes, step changes, degradation, debonding, and other sensors or blade-related anomalies. The disclosed approach enables individual sensor health monitoring without requiring blade-to-blade comparison and may be incorporated into turbine operability or monitoring dashboards for online or offline analysis.

6. Technical field

The present disclosure relates generally to wind turbine monitoring, blade load control systems, structural sensing, and condition-based diagnostics. More particularly, the disclosure relates to methods for identifying BLCS sensor faults and degradation using estimated thrust as a reference variable for expected wavelength behavior.

7. Background

Wind turbine blade load control systems may rely on sensors positioned at different blade regions to infer blade loading, strain-related behavior, or other operating conditions. Over time, such sensors or their associated mounting and bonding interfaces may experience degradation, drift, offset changes, debonding, or abrupt fault events. Conventional approaches may depend on blade-to-

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blade comparison or broad anomaly screening, which can be limited when turbine-specific operating variability or sensor-to-sensor differences are present.

A need therefore exists for a monitoring approach that can assess sensor health independently and with reduced dependence on cross-blade comparison. A further need exists for a method capable of distinguishing different fault signatures, such as gradual drift, abrupt steps, or persistent high-error conditions, while remaining compatible with operational turbine data and existing analytics environments.

8. Summary of the disclosure

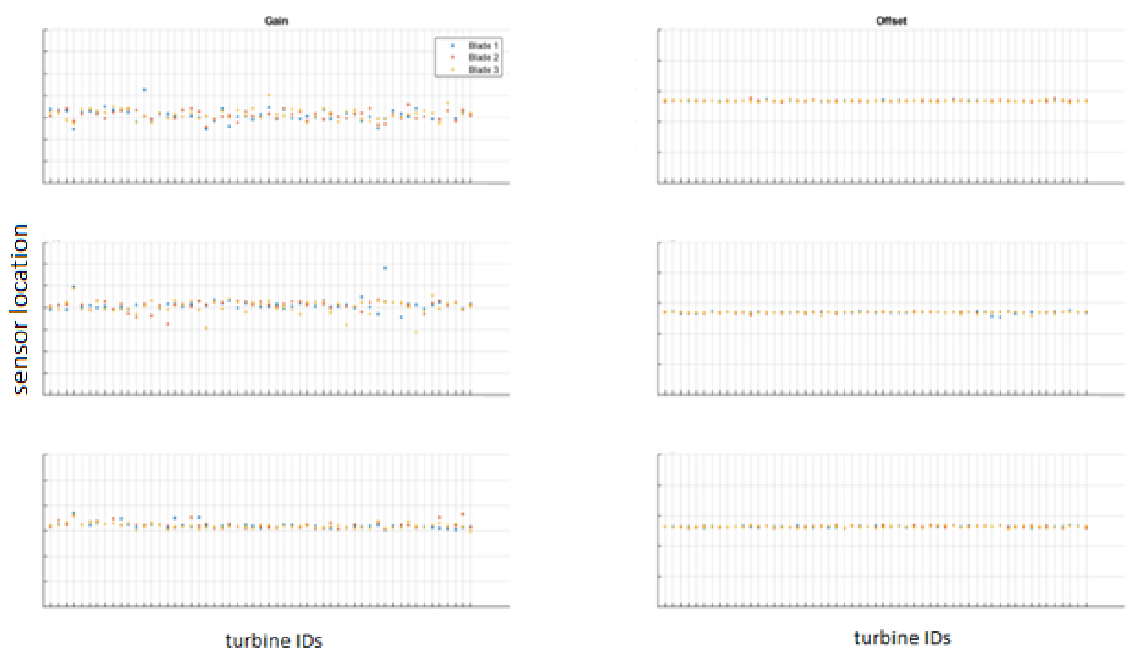
In one aspect, the disclosure provides a method for estimating a reference wavelength from thrust and comparing that reference against actual measured wavelength from BLCS sensors. The disclosure recognizes that thrust and wavelength may exhibit a substantially linear relationship under selected operating conditions, such as substantially constant pitch angle conditions. For example, the relationship may be represented as: wavelength = gain × thrust + offset.

Gain and offset parameters may be determined for each relevant sensor channel or sensor location. Error between the estimated wavelength and actual wavelength may then be assessed. If the error exceeds a threshold, such as approximately ±0.1%, the condition may indicate sensor issues.

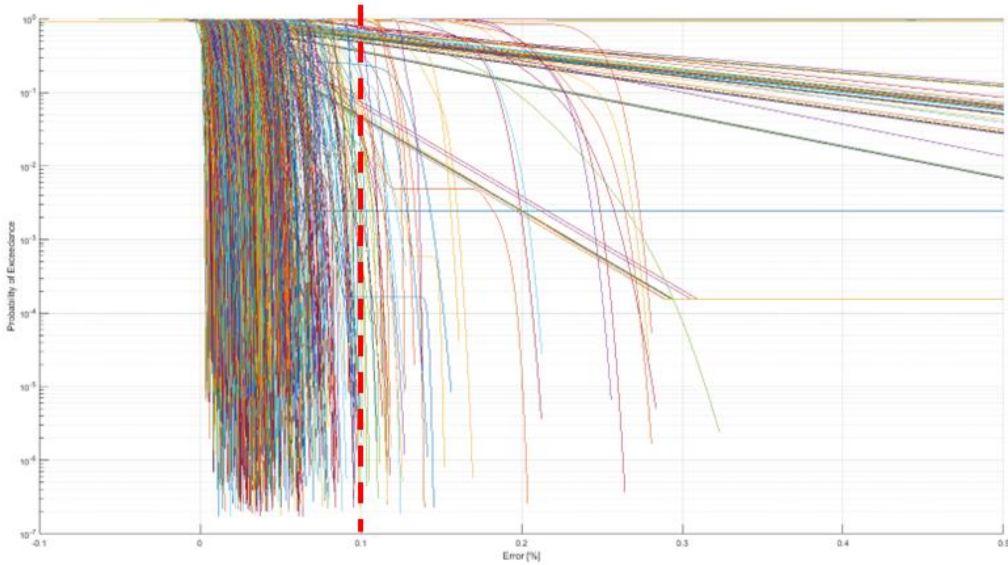
The resulting error patterns may further be interpreted diagnostically. For example, drift may indicate sensor or blade degradation, including possible debonding. Step-like changes may indicate larger or more abrupt sensor faults. Persistent high error may indicate sensor issues requiring inspection, recalibration, or replacement. The method supports independent sensor health monitoring and may be extended to online gain and offset tracking, dashboard integration, calibration workflows, and compensation approaches for higher pitch angles.

9. Brief description of drawings

[FIG. 1] Example plots showing gain values and offset values for multiple BLCS sensor positions



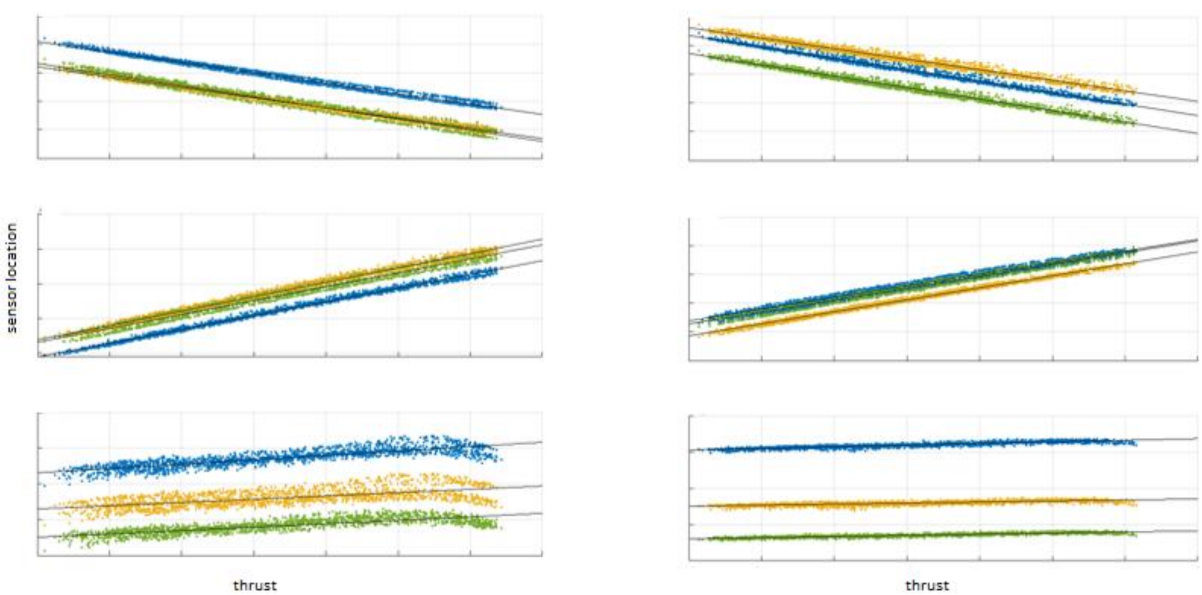
[FIG. 2] Example probability-of-exceedance plot showing error between estimated wavelength and actual wavelength relative to a threshold criterion, such as approximately 0.1% error.



[FIG. 3] Example tabular summary of representative gain and offset values for sensors at different locations.

Sensor	Gain	Offset
location 1	-2×10^{-3}	1.5535×10^{6}
location 2	2×10^{-3}	1.5535×10^{6}
location 3	1×10^{-4}	1.5535×10^{6}

[FIG. 4] Example plots of wavelength versus estimated thrust illustrating linear fitting behavior for different sensor locations and blades.



10. Detail description

The disclosure is directed at identifying BLCS sensor faults using a thrust-based analytical reference. In representative implementation, operational turbine data are processed to obtain estimated thrust values and corresponding wavelength measurements from BLCS sensors. The method may be applied to one or more sensor locations on a blade, including sensors located either at the blade flap, edge or both.

A foundational observation of the disclosed approach is that wavelength has a substantially linear correlation with thrust over selected operating conditions. In one implementation, the operating window may be chosen such that pitch angle remains constant or substantially constant, thereby reducing confounding effects and enabling stable fitting between thrust and wavelength. A line or other suitable fit may be calculated for each sensor channel, yielding a gain term and an offset term. In representative form, the estimated wavelength is given by:

estimated wavelength = gain × thrust + offset.

The fitting may be carried out using historical data, filtered operational data, high-frequency data, or combinations thereof. For example, similar gain and offset values were observed between turbines and blades, supporting the use of a thrust-based reference approach.

Once the thrust-based reference wavelength is determined, the measured wavelength may be compared against the estimated wavelength. The resulting residual or error signal may be analyzed directly or statistically. In one implementation, a probability-of-exceedance analysis is applied to the error between estimated wavelength and actual wavelength. Such analysis may provide an interpretable threshold-based criterion for sensor health assessment. For example, error with respect to reference greater than approximately ±0.1% may indicate potential sensor issues.

Different error patterns may correspond to different fault modes. A gradual drift from the thrust-based reference may indicate sensor degradation, blade degradation, or debonding. A step change may indicate major damage or a larger sensor fault event. Persistent large residuals may indicate sensor malfunction, calibration change, installation shift, or other abnormalities. Because the comparison is performed against a thrust-derived reference rather than another blade, the approach can assess sensor health on an individual basis.

In some embodiments, separate gain and offset values are tracked over time. Trending of gain and offset may itself serve as a health indicator. For example, slowly changing offsets may indicate long-term drift, while abrupt offset changes may indicate a fault occurrence. Gain deterioration or divergence from expected fitted values may indicate altered sensor sensitivity, installation condition changes, or structural coupling changes.

A representative tabular summary indicates approximate example values of sensors located either at the blade flap, edge or both.

The disclosed method may be implemented offline for engineering review or online within a monitoring environment. Example next-step implementations include addition of the analysis to operability dashboards, identification of recurrent fault patterns, online gain and offset monitoring, compensation for higher pitch angles, and in-house calibration workflows.

11. Advantages

The disclosed approach provides several technical and operational advantages. First, it enables estimation of a reference wavelength from thrust without requiring blade-to-blade comparison. Second, it supports independent sensor health monitoring for individual BLCS sensors. Third, it provides a framework for identifying different error signatures, including drift, steps, and high-error conditions, thereby improving interpretability of sensor anomalies. Fourth, it expands monitoring capability beyond debonding detection alone and opens the possibility of identifying other sensor faults. Fifth, it is compatible with incorporation into operability dashboards and online analytics tools. Sixth, it may support preventive maintenance, calibration refinement, and earlier fault identification.

12. Example Embodiments

In one embodiment, a wind turbine monitoring system receives estimated thrust and measured wavelength data for sensors located either at the blade flap, edge or both. The system fits a linear relationship between thrust and wavelength for each sensor and generates a reference wavelength for each incoming thrust value. Residual error between reference and actual wavelength is then monitored to detect fault conditions.

In another embodiment, a probability-of-exceedance model is applied to the residual error distribution. If the probability of exceedance indicates that the error crosses a threshold, such as approximately ±0.1%, an alert is generated for likely sensor abnormality.

In a further embodiment, temporal evolution of gain and offset is tracked. Gradual variation in offset is classified as drift-related degradation, while abrupt changes are classified as step-like faults or damage events.

In another embodiment, the method is applied using high-frequency operational data to generate a thrust-based reference for selected datasets, such as representative high-frequency turbine operating intervals.

In still another embodiment, compensation factors are applied for higher pitch angles so that the thrust-based reference remains accurate across a broader operating envelope.

13. Industrial Applicability

The disclosure is industrially applicable to utility-scale wind turbines and associated blade monitoring systems. It may be used by wind turbine manufacturers, operators, service teams, and monitoring platform developers to assess BLCS sensor health, diagnose sensor faults, identify degradation trends, and support maintenance planning. The approach may be deployed within fleet monitoring platforms, turbine operability dashboards, engineering analytics workflows, commissioning processes, and service diagnostic tools.

14. Variations and Alternatives

Although the disclosure emphasizes a substantially linear thrust-to-wavelength relationship, other fitting models may be used where appropriate, including segmented linear models, higher-order functions, machine-learning models, or look-up-based references. The threshold for identifying abnormal error may vary by turbine platform, sensor type, operating regime, or confidence requirement. Additional operating filters may be used beyond pitch-angle filtering, such as rotor speed ranges, turbulence screening, temperature filtering, or power-state selection.

The method may be applied to fewer or additional sensor positions beyond sensors located either at the blade flap, edge or both. Reference values may be calculated per blade, per turbine, per fleet, or per operating class. Error analytics may use raw residuals, normalized residuals, exceedance probabilities, trend slopes, change-point detection, or combinations thereof. The method may also be integrated with calibration routines, digital twin models, or automated maintenance workflows.

15. Conclusion

This disclosure describes a thrust-correlation-based method for identifying BLCS sensor faults and degradation. By estimating a reference wavelength from thrust and comparing that reference to actual sensor output, the method enables detection of sensor issues, drift, debonding-related behavior, and step changes. The disclosed approach supports independent sensor health monitoring, reduces reliance on blade-to-blade comparison, and is suitable for incorporation into wind turbine monitoring and operability systems.

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