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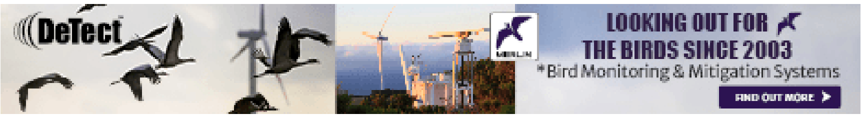

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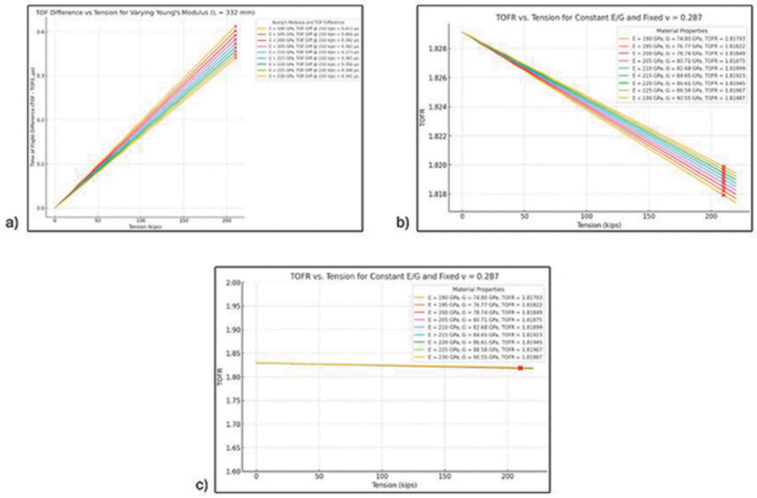
Improved Bolt Tension Measurement

Category: Articles
Published: 26 March 2025

Utilising Bi-Wave Ultrasonics and Machine Learning

Maintaining bolt preload is critical to ensure the structural integrity of a wind turbine. Current non-destructive testing approaches for estimating bolt tension, such as ultrasonic elongation measurements, are impractical on a large scale for new and in situ bolts. However, the limitations of elongation measurement techniques (untensioned baseline measurements, compounding errors from material and environmental variation, and complex calibrations) can be overcome by combining bi-wave ultrasonics technology and machine learning.



By Joshua Scott, Director of Research and Innovation, Predictant, USA

This new approach was applied to bolts and studs of different diameters and lengths in multiple geometric and environmental variations. The result was a DNV-verified error of less than 5% with 93.3% confidence.

The presented work is the method utilised by Predictant's Bolt iQ, a novel system for measuring the tension of new and in situ bolts. Differing from traditional approaches, the work leverages the advantages of bi-wave ultrasonics technology (UT) with the ability of machine learning (ML) to recognise complex patterns to make accurate bolt tension measurements.

Bi-Wave Ultrasonics Technology

Bi-wave UT operates by transmitting (orthogonally) two types of waves (longitudinal and shear) into the end of a bolt and measuring the time each wave takes to travel the length of the bolt and get reflected to its source. This time is referred to as the ‘time-of-flight’ (ToF). ToF values have a direct relationship with the tension that is applied to the bolt due to the acoustoelastic effect, whereby the velocity of the wave changes with tension. Using a single wave transmission mode, the elongation of a bolt can be ultrasonically estimated and converted to a tension estimate, but this requires the untensioned length and wave properties to be known. By taking the ratio of the longitudinal and shear waves, bi-wave UT bypasses the need for these baseline measurements, thereby enabling testing on in situ bolts and easier deployment overall.

Bolt Material Properties

While tension applied to a bolt will change the velocity of the wave within it, the velocity of a wave in any material is dictated by the material’s properties. For steel, these properties are Poisson’s ratio and the elastic modulus and shear modulus. If only a single wave is considered, a change in modulus can greatly impact the wave velocity and result in erroneous ToF measurements for bolts of equal length. As Poisson’s ratio in structural steel is generally considered a constant, and the elastic modulus cannot change without a corresponding change in shear modulus, a bi-wave UT approach mitigates the impact of material variation on accuracy. ToF ratios of the shear and longitudinal waves enable a robust ML model to be built on a subset of bolts in a laboratory and that model to translate to the field on bolts of similar properties (see Figure 1).

Machine Learning

Many variables impact the velocity of a wave as it travels through a bolt. Consequently, data needs to be collected from the many scenarios that a bolt could experience in the field (see Data Collection Method section). This results in large datasets (tens of thousands of samples) to analyse. ML excels at detecting patterns in large datasets and can be carefully engineered by humans with deep knowledge of bolt and ultrasonic wave behaviour. Therefore, ML is a prime candidate for building a model to estimate bolt tension.

Data Collection Method

The work focuses on grade 10.9 (DASt 021 standard) steel bolts and studs. Two bolts (M42×235mm and M42×330mm) and one stud (M56×400mm) were chosen. Ten samples of each geometry were acquired from which one was removed from the sample set as a holdout. Data was collected a) from 0–75% of yield stress, b) at temperatures of 0–40°C, c) using a torque wrench and tensioner, d) from minimum to maximum possible clamp length, e) at head and tail measurement orientations, and f) from no bending to 4-degree bending according to IEC 61400. No surface treatment of the bolt surface was performed.

Model Building Method

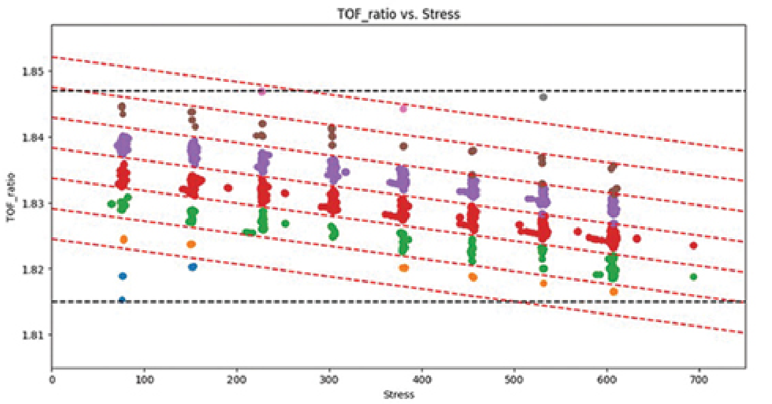
Over 31,000 training data samples were collected. The samples then underwent quality checks to ensure the data met modelling standards. For example, signal-to-noise ratio, signal amplitude, metadata, and other variables were considered. To ensure robust model training and generalisation, a K-fold cross-validation strategy was employed for both training and hyperparameter tuning. Data was stratified by unique bolt, ensuring that all data points from a single bolt were grouped within the same fold, preventing data leakage across folds. At each level, a statistical breakdown of the model performance was output, enabling performance to be tracked across groups and relative to performance requirements/goals. Once the model's performance was stable and satisfactory, blind testing was performed on bolts unknown to the model.

Challenge #1: Bolt Bending

Bolts experiencing bending have specific zones in compression and tension. Also, a wave may enter a bolt experiencing bending at normal incidence but be reflected at an angle. These factors cause deformation of ultrasonic waveforms relative to waveforms in bolts that are not experiencing bending. Further, research indicates that bending can impact the amplitude of the waveform and cause phase shifting. Naturally, this presents a challenge when measuring the axial load using UT and must be accounted for in data collection and by ML.

Challenge #2: Cycle Skip

'Cycle skip' is a common issue when estimating ToF. ToF calculations estimate the time difference between the first and second ultrasonic echoes, i.e. the first and second time the wave reflects off the back surface of the bolt and is detected at the transducer. However, as an ultrasonic wave travels through a bolt it has a spatial impulse response. This response can change shape due to sidewall and bottom surface reflections, causing the shape of the first and second echo to differ. Depending on the method employed for estimating the ToF, errors attributed to respective peak shift in the spatial response can be observed, usually in multiples of a wave period. This can occur in both longitudinal and shear waves, causing a series of shifted trends or 'bands' in the ToF ratios relative to tension. See Figure 2, which shows multiple colour-coded bands of ratios relative to stress (MPa).



Solution

To overcome the two challenges a stacked model was implemented, which combines several base models to hone the performance of the tension measurements. The stack determines whether bending is present and sends the data to a deep learning model for tension measurement. If no bending is present, a band classifier determines the ToF ratio band to which the data belongs. Each band has a multivariable linear regression associated with it and once the band is selected the data is passed to the corresponding model for tension measurement.

Results

Holdout testing (witnessed by DNV, an international accredited certification body) was performed on sample bolts from each geometry, whose ‘identity’ was unknown to the model. The model was installed into Predictant’s Bolt iQ device and testing was conducted across the spectrum of variables described in the Data Collection Method section. Measurements were taken between 15% and 75% (at increments of 10%) of yield stress and tension/stress was estimated in real time. More than 400 measurements were made. The average error during the holdout testing was determined to be −5.51MPa. As verified by DNV, the model was able to achieve less than 5% error, relative to yield stress, with 93.32% confidence, and better than 8% error, relative to yield stress, with 99.73% confidence.

Further Reading

Koshti, A. 1998. Ultrasonic measurement of the bending of a bolt in a shear joint. Experimental Mechanics 38, 270–277.

Johnson, G., Holt, A.C. and Cunningham, B. 1986. An ultrasonic method for determining axial stress in bolts. Journal of Testing and Evaluation 14(5), 253–259.

Biography of the Author

Joshua Scott is the Director of Research and Innovation for Predictant. He has a background in physics and mechanical engineering and is an inventor on several non-destructive testing-related patents. He is responsible for leading a team of researchers who develop non-destructive techniques to resolve real-world problems.

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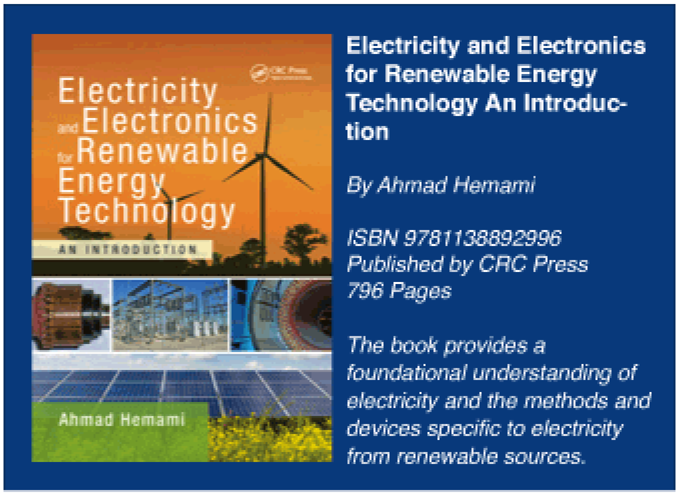

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