

Energy spectral analysis of wire breaks in post-tensioned tendons for wind turbines

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1 Introduction

In 2021, onshore wind turbines in Germany contributed over 15% to the country's total gross electricity generation, making them one of the most essential components of Germany's clean energy transition [1]. The efficiency of power generation in wind turbines is greatly influenced by the hub height, as it affects the wind speed at the rotor blades. Generally, a higher hub height results in increased economic efficiency, with a rule of thumb suggesting a yield increase of up to 1% per meter of hub height [2]. To achieve greater hub heights, the use of prefabricated hybrid towers has gained popularity in recent years [3]. These towers combine a prestressed concrete tower with an attached steel tube tower, offering modularity and cost-efficiency in transportation and assembly. The concrete tower is constructed using precast segments and is externally post-tensioned to ensure structural stability. Maintaining the proper condition of the tendons is crucial for tower safety and performance. Conventional methods like visual inspection and magnetic stray field measurement [4] are often time-consuming and limited due to restricted access. To address these limitations, alternative non-destructive testing (NDT) techniques based on structure-borne sound are being explored. Acoustic emission (AE) testing as a promising NDT technique involves investigating acoustic signals emitted by the structure when subjected to stress or deformation. It serves as a valuable tool for the detection of structural changes such as crack formation and wire breaks. Extensive research has been dedicated to AE analysis of tendon wire breaks. [5] presents a comprehensive AE feature analysis of wire breaks in several prestressed bridge girders. In [6], the acoustic wave propagation due to tendon wire breaks is investigated through laboratory experiments as well as long-term AE monitoring of concrete structures in situ. Also, wire break-like signals generated using a rebound hammer are detected and analyzed in [7]. This study focuses on the spectral analysis of wire breaks in externally post-tensioned tendons, commonly employed in hybrid wind turbine towers. The wire breaks are conducted under controlled boundary conditions of a laboratory setting. All wire break events were recorded with conventional AE sensors with a main sensitivity between 25 and 80 kHz.

2 Methodology

Acoustic emission (AE) refers to the release of elastic waves resulting from structural alterations within a material subjected to stress. Figure 1 illustrates the principle of AE measurements, which involves the propagation of emitted waves through the material and their detection using appropriate measuring instruments. Piezoelectric sensors are commonly employed to acquire AE signals by converting the detected mechanical values (e.g. velocity or acceleration) into electrical voltages. Subsequently, through processes such as amplification, filtering, and digitization the analog signals are transformed into digital format and stored for further analysis. AE analysis can be classified into two categories: parameter-based and signal-based approaches, depending on the storage format, as depicted in figure 1. In parameter-based analysis, AE parameters such as peak amplitude or signal energy are utilized to evaluate the characteristics associated with the observed structural changes. In contrast, signal-based analysis involves the use of the entire waveform to interpret and classify fracture mechanics. Several investigation

methods, originally developed in seismology, have been successfully applied in material research [8] and condition monitoring [9], including techniques such as magnitude squared coherence (MSC) for quantifying signal similarity and moment tensor inversion (MTI) for determining fracture types.

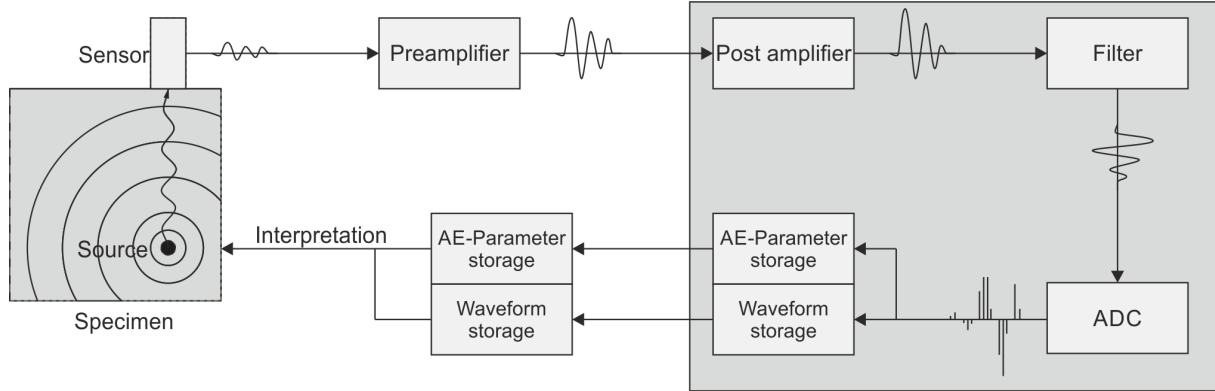


Figure 1: Principle of measurement and analysis of acoustic signals

This study presents a methodology for signal-based energy spectral analysis of tendon wire breaks. The discrete Fourier transform (DFT) is employed to extract the energy spectrum from the recorded signals $Rec(t)$. The DFT operates by converting a discrete-time sequence of signal samples into its frequency representation. The transformed signal in the frequency domain $Rec(f)$ can be expressed as follows:

$$Rec(f) = \mathcal{F}\{Rec(t)\} = \sum_{n=0}^{N-1} Rec(n \cdot \Delta t) \cdot e^{-2\pi f i n \Delta t} \quad (1)$$

with $f = \frac{m}{N \cdot \Delta t}$ ($m = 0, 1, 2, \dots, N - 1$)

where N represents the sum of the samples and Δt denotes the sampling interval. In signal processing, the energy of a discrete-time signal is defined as the sum of the squared magnitude of the signal's samples in the time domain. Notably, Parseval's theorem establishes a fundamental relationship between the energy of a signal and its spectral energy density. According to this theorem, the signal's total energy is equivalent to the sum of the energy contributions across all frequency components present in its spectrum. Consequently, the energy $E(f)$ of a discrete signal at a specific point can be quantified as the squared magnitude of the corresponding frequency component in the signal's spectrum, multiplied by the sampling interval and scaled by the factor $1/N$:

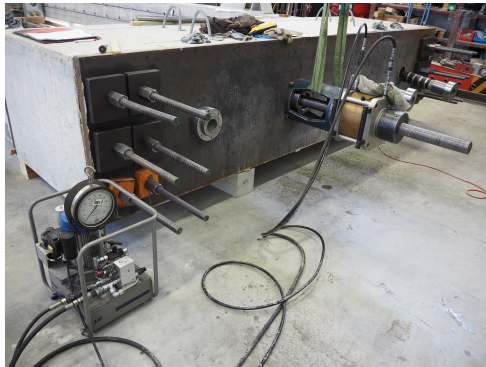
$$E(f) = \frac{1}{N} \cdot |Rec(f)|^2 \cdot \Delta t = \frac{1}{N} \cdot \left| \sum_{n=0}^{N-1} Rec(n \cdot \Delta t) \cdot e^{-2\pi f i n \Delta t} \right|^2 \cdot \Delta t \quad (2)$$

with $f = \frac{m}{N \cdot \Delta t}$ ($m = 0, 1, 2, \dots, N - 1$)

3 Experiments

To conduct the experiments on tendon wire breaks, a specially designed test rig measuring 12 m x 4 m was constructed. The test frame consisted of two longitudinal and two transverse reinforced concrete (RC) beams, providing a robust structural frame. Four SUSPA EX30 type tendons, each comprising 30 parallel wires, were individually post-tensioned to 700 kN. A steel plate measuring 4 m x 0.85 m x 0.05 m was affixed to one of the transverse RC beams, with stressing anchors located on it, replicating the transition section of a real hybrid tower (figure 2a). At the opposite end, each tendon was mounted to a specific anchor set supplied by Max Bögl, creating fixed anchors on this side (figure 2b). These fixed anchors were integrated into the RC beam, emulating the configuration commonly observed in the concrete foundation of a real hybrid tower, where fixed tendon anchors are typically embedded. The experiment setup thus reproduces key aspects of a hybrid tower system, enabling the investigation and analysis of tendon wire breaks under controlled laboratory conditions that closely resemble real-world scenarios.

The experiments involve severing 30 wires in each of four post-tensioned tendons, resulting in 120 wire breaks in total. To capture the AE signals produced by each wire break, 24 piezoelectric sensors were installed on the test



(a)



(b)

Figure 2: (a) Stressing anchors of the tendons; (b) Fixed anchors of the tendons mounted with the specific anchor set supplied by Max Bögl

Figure 3 illustrates the arrangement of sensors employed during the experiments conducted on tendon four. Eight sensors were placed directly on the tendon, another eight on the RC beam connected with fixed anchors, and the remaining eight sensors on the steel plate on the other RC beam. For the purpose of data collection, three measuring systems were employed, each comprising eight measuring channels.

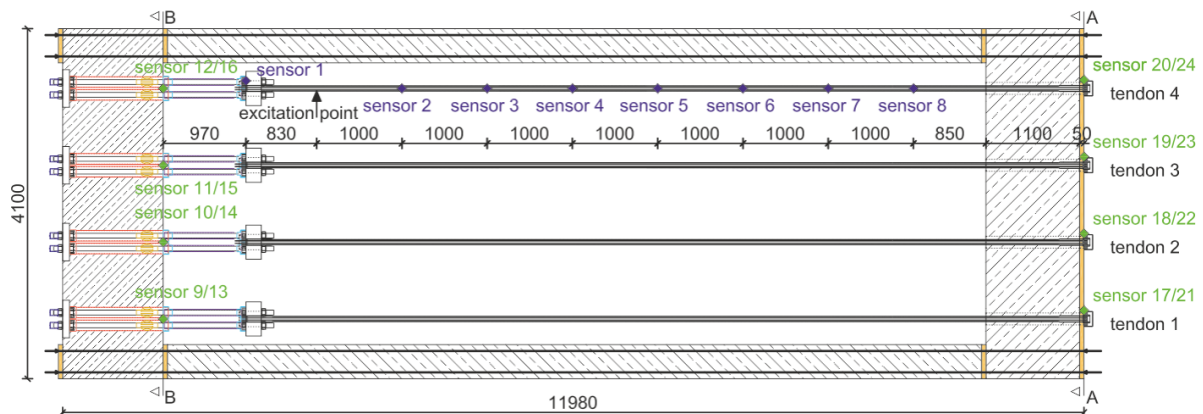


Figure 3: Layout of piezoelectric sensors for wire break experiments on tendon four

4 Some results and future work

This study presents an energy spectral analysis based on a case study involving 30 wire breaks conducted on tendon four. Figure 4a illustrates the energy distribution across frequencies for a single wire break detected at sensor position 9, with the normalized cumulative energy distribution represented by a red line. Additionally, figure 4b provides an overview of the normalized cumulative energy distribution across frequencies for all 30 wire breaks in tendon 4, measured at the same sensor position 9. The sensor position for the analysis is arbitrarily chosen to serve as an illustrative example of the results. The findings indicate that the wire break energy concentrates within a low-frequency range, with frequencies between 5 and 20 kHz contributing to over 90% of the total energy. Future work will encompass a statistical analysis of the energy distribution, considering all 120 wire breaks recorded across all 24 sensor positions.

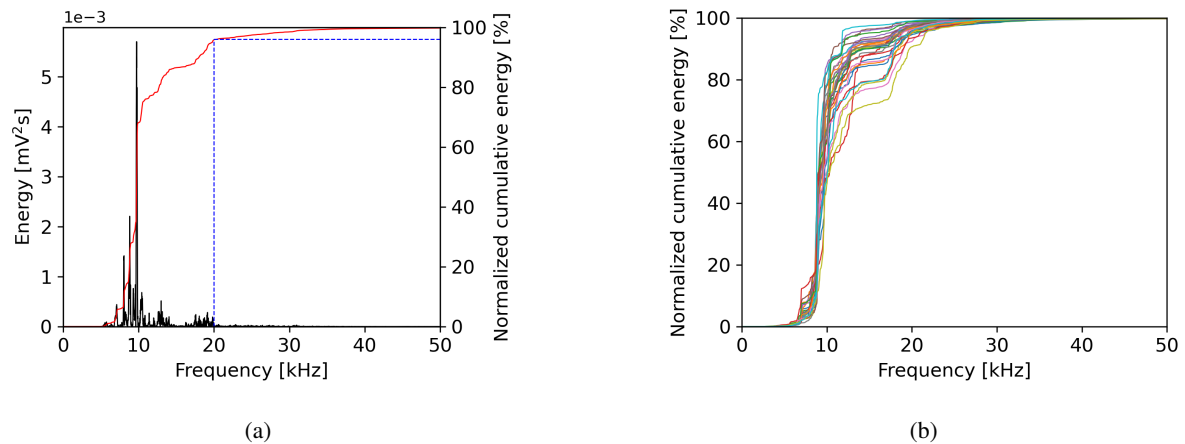


Figure 4: (a) Energy spectrum of a single wire break in tendon 4; (b) Normalized cumulative energy distribution of all 30 wire breaks in tendon 4

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