

RESEARCH ARTICLE

Cable Tension Estimation System for Cable-Stayed Structures Using FPGA and Accelerometer Based on the Flat Taut String Method

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Abstract

One of the critical aspects of Structural Health Monitoring (SHM) systems is cable tension estimation, particularly in cable-stay structures. This study compares two tension estimation approaches: a direct method using a load cell and an indirect method based on vibration response analysis through an accelerometer -FPGA system. The developed system utilizes an Altera DE0-Nano FPGA board to acquire acceleration signals from the ADXL345 sensor via SPI and simultaneously transmits the data to a host computer via UART. The data is collected in real time and externally analyzed using the Welch Fast Fourier Transform (FFT) algorithm. The extracted fundamental frequency is then applied to the flat taut string theory to estimate cable tension. The experiment was conducted on an isolated test rig under various tension conditions, with ground truth measurements obtained from a calibrated load cell. The results indicate that the system offers reliable estimation performance, especially in the high-tension group, achieving a mean relative error of 1.2% and a coefficient of determination (R^2) of 0.984 in (f_1) compared to load cell readings. It also demonstrates good measurement consistency, with an average repeatability error of 1.55%. Despite using the low-cost ADXL345 sensor with a measured average Signal-to-Noise Ratio (SNR) of approximately 25.9 dB, the system exhibits sufficiently high accuracy and reliability. Therefore, the proposed accelerometer -FPGA-based approach is considered a viable, non-invasive, and efficient alternative for cable tension estimation in SHM applications.

Keywords: ADXL345 accelerometer, cable tension, DE0-Nano, FPGA, taut string

I. INTRODUCTION

Cable tension measurement in structures, such as suspension or cable-stayed bridges, is a crucial component of Structural Health Monitoring (SHM) systems [1]. In general, tension measurement methods are categorized into two types: direct methods, such as load cells installed in series with the cable, and indirect methods based on the cable's natural vibration frequency [2].

While direct methods offer high accuracy, they are often difficult to implement once the cables are permanently installed, mainly due to limited access to the anchorage system. In contrast, vibration-based indirect methods enable tension estimation without any physical modification to the cable [3]. Accelerometers can be attached non-invasively to active cables, making this approach ideal for long-term monitoring.

In a previous study, Zhang et al. (2021) [5], an accelerometer and the flat taut string theory to convert the frequency derived from the FFT into cable tension. However, all computations were performed offline on a PC, and the system lacked real-time data processing and FPGA involvement, resulting in high system latency. Bono et al. (2025) [6] proposed a wireless accelerometer architecture with a "sensor-to-cloud" approach, emphasizing low power consumption and data synchronization. While this study shared similarities in real-time data acquisition, the processing

remained microcontroller-based per base station, rather than utilizing FPGA acceleration.

Sliti and Boudriga (2021) [7] designed an SHM system for buildings using Fiber Bragg Grating (FBG) sensors and an FPGA to estimate external vibrations. However, the system did not employ real-time processing via FPGA, nor did it provide tension estimation, and relied on expensive sensors. Debora et al. (2018) [8] comprehensively evaluated vibration-based methodologies for cable tension estimation and concluded that the flat taut string theory simplifies the estimation process, although considerations must be made for the structural complexity of larger bridges.

Alves et al. (2024) [10] proposed a vibration-based cable tension estimation method using MEMS accelerometers with wideband capability up to 3000 Hz. Their approach employed frequency-domain analysis to extract modal frequencies, demonstrating that the flat taut string theory can effectively simplify the estimation process. However, the study also emphasized that this theory may face limitations when applied to complex structural geometries, such as multi-span bridges or cable-dense environments. In contrast, this study focuses on a controlled laboratory-scale test rig and integrates FPGA-based real-time acquisition, enabling deterministic sampling and practical validation against load cell references.

A systematic review by PMC (2022) [4] also confirmed that most SHM systems today still rely on conventional approaches in both data processing and sensor configuration. Few studies have integrated hardware architectures such as an

FPGA with frequency-based estimation techniques for direct cable tension measurement. The research by Santoso (2020) [1] and Cho et al. (2013) [3] explored the use of modern technologies, such as accelerometer sensors, and the Taut String and Beam String theories for tension estimation in cable-stayed bridges. One of the key findings demonstrated that these theories could achieve cable force estimation errors of less than 7.0%.

This study proposes a novel approach to cable tension estimation in cable-stayed bridges by integrating a MEMS-based accelerometer sensor with an FPGA-based data acquisition system. The system is capable of acquiring real-time acceleration data via SPI, processing it in parallel on the FPGA, and transmitting it to a host computer via UART for further analysis using FFT. Cable tension is then estimated based on the extracted natural frequency and analyzed using the taut string theory. Validation was conducted through direct measurement using a load cell on a custom-designed test rig, resulting in a relative error below 6% and a high coefficient of determination, indicating strong accuracy and system consistency.

The novelty of this research lies in the implementation of a real-time cable tension estimation system based on an accelerometer and an FPGA using the taut string method. The proposed system is non-invasive, cost-effective, and has been experimentally validated against a calibrated load cell.

II. METHODS

This section describes the methodology used for the development and testing of the real-time cable tension estimation system. The process begins with the design of a data acquisition system based on an FPGA and an accelerometer sensor, followed by cable vibration signal acquisition, frequency analysis using FFT, and tension estimation based on the taut string theory. To validate the measurement results, an isolated test was conducted using a laboratory-scale test rig equipped with a strain gauge sensor as a reference for comparing the estimated tension. The strain gauge system was calibrated using a load cell to ensure measurement accuracy and consistency.

A. Flat Taut String Theory

The dynamic testing method is used to estimate cable tension through frequency and mode shape analysis, utilizing the dynamic characteristics of the cable to determine its

internal tension. The natural frequency (f) of a tensioned cable can be mathematically expressed as Equation (1):

$$f = \frac{1}{2L} \sqrt{\frac{T}{\mu}} \quad (1)$$

Where L is the cable length. T is the cable tension, and μ is the mass per unit length of the cable. From this relation, the tension T can be derived directly from frequency measurements as shown in Equation (2):

$$T = 4L^2 \mu f^2 \quad (2)$$

In the context of SHM, the dynamic testing method is essentially a form of Vibration-Based Monitoring (VBM), which commonly utilizes vibration sensors such as accelerometers to measure structural vibrations and detect changes in the natural frequency. This technique involves measuring the dynamic response of the structure to external excitation.

The Flat Taut String method is one type of dynamic testing used for cable tension estimation. The taut string theory estimates cable tension by analyzing the cable's natural vibration frequencies. The mathematical formulation of the taut string method, as shown in Equation (3), uses the first vibration mode frequency as the basis for tension estimation.

$$f = \frac{1}{2L} \sqrt{\frac{T}{\mu}} \quad (3)$$

Where f_1 It is the first mode frequency. L is the cable length. T is the cable tension. μ is the mass per unit length of the cable. Based on equation (3), solving for T , we obtain (4):

$$T = 4mL^2 \left(\frac{f_n}{n}\right)^2 \quad (4)$$

For the f_n , the general form becomes equation (5).

$$f_n = n \cdot f_1 = n \cdot \frac{1}{2L} \sqrt{\frac{T}{\mu}} \quad (5)$$

B. Cable-Stayed Tension Estimation System Using an FPGA and Accelerometer

The cable tension estimation system for cable-stayed structures developed in this study utilizes a combination of an FPGA and an accelerometer sensor. The proposed FPGA-based cable tension estimation system using an accelerometer is functionally illustrated in Figure 1

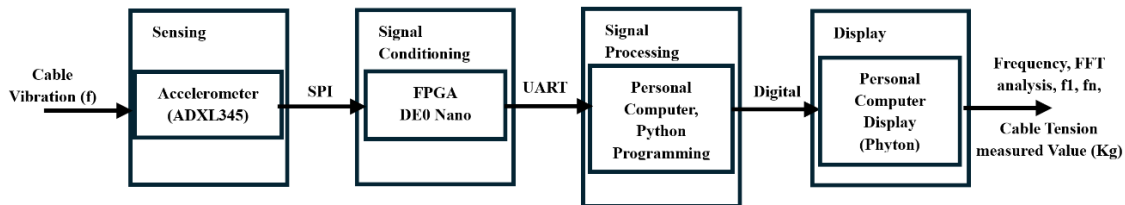


Fig. 1. Block diagram of the Accelerometer-FPGA system for steel cable tension estimation.

Based on the functional diagram, the accelerometer-FPGA-based cable tension estimation system begins with the measurement of cable vibrations (frequency) using an accelerometer sensor. The vibration data is transmitted to the FPGA via the SPI interface, where signal conditioning is performed. The processed data is then forwarded to a

computer via UART for digital analysis using Welch's FFT algorithm to determine the fundamental frequency (f_1, f_n). This frequency is subsequently used to calculate the cable tension in kilograms using the theoretical taut string model, and the results are displayed through a computer-based visual interface.

1. MEMS Accelerometer Sensor

The accelerometer sensor used in this system is the ADXL345, a digital 3-axis MEMS-based sensor with 13-bit resolution and a measurement range of up to $\pm 16g$. This sensor was selected due to its wide availability, comprehensive documentation, low power consumption, and compatibility with FPGA platforms via the SPI interface. To maintain signal quality and avoid increased noise at low frequencies—critical for cable tension estimation—an output data rate (ODR) of 1600 Hz was chosen as the optimal compromise between resolution and signal-to-noise ratio (SNR).

Based on experimental results and datasheet references (Analog Devices)[9], the X-axis was selected as the primary data source due to its lower noise level (~ 5.0 mg RMS) compared to the Z-axis (~ 6.1 mg RMS), despite the mechanical excitation direction being closer to the Z-axis. The X-axis acceleration data is transmitted in 16-bit format via SPI to the DE0-Nano FPGA, where it is framed and forwarded to a computer through UART for further analysis using Python.

2. FPGA Handling

FPGA was chosen as the primary acquisition platform due to its capability to handle data in parallel, synchronously, and in real time. In this system, the DE0-Nano board is used to initialize the ADXL345 sensor and read X-axis acceleration data via SPI communication. The X-axis was selected for acquisition due to its lower noise level compared to the Z-axis, while still effectively representing the cable's excitation direction. The Output Data Rate (ODR) was set to 1600 Hz as a compromise between signal quality and frequency resolution without significantly increasing noise.

The RTL (Register Transfer Level) design is modularly structured into several key components, including:

- **spi_ee_config**: sensor initialization and data acquisition from ADXL345 via SPI
- **uart_system**: UART transmission controller at 115200 bps

- **led_driver**: LED indicators for sensor and UART status/debugging
- **FSM and timer**: for synchronized data transmission at 1600 Hz

The X-axis data acquired from ADXL345 is transmitted in raw binary format (two bytes: low and high) via UART, rather than in ASCII format. This minimizes transmission overhead and allows the system to stream 1600 raw data samples per second, directly matching the sensor's ODR. As such, the FPGA serves as an effective real-time acquisition system that forwards data to the host computer without requiring large buffering. The PC then receives and processes the data in real time using Python for logging, FFT computation, and tension estimation.

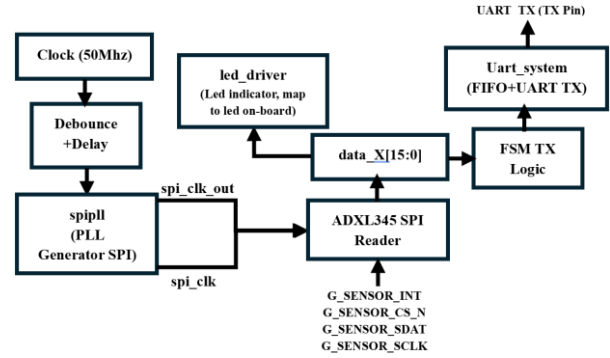


Fig. 2. Flow diagram of FPGA system design for steel cable tension estimation.

The FPGA system architecture (shown in Fig. 2) is modular, encompassing SPI clock generation via PLL, ADXL345 X-axis data handling over SPI, acceleration-to-LED display conversion, and UART-based digital data transmission to the PC. Each function is executed in parallel and orchestrated by internal FSM (Finite State Machine) logic, ensuring stable and synchronized acquisition at 1600 Hz. Figure 3 shows the RTL viewer output generated from the Verilog programming, illustrating the implementation of the data acquisition system design on the FPGA.

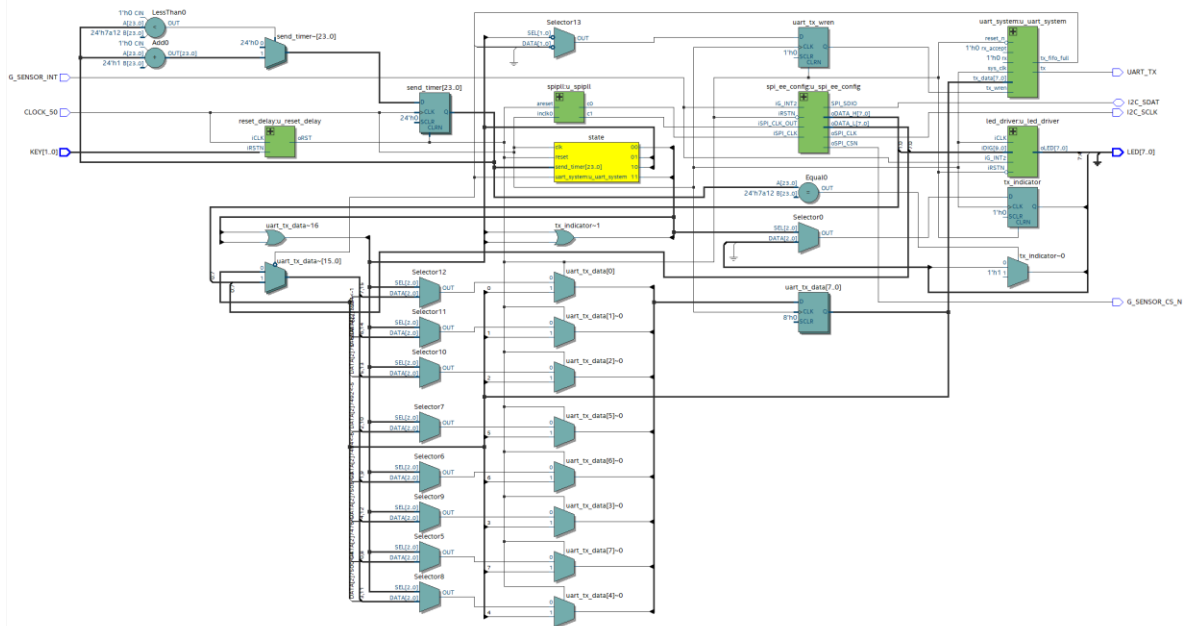


Fig. 3. RTL Viewer of the top module in the accelerometer-FPGA-based cable tension estimation system.

3. Real-Time Processing

Once the data is transmitted via UART to the host PC, real-time acquisition, logging, and analysis are executed using a dedicated Python script. The main script performs the following tasks in real time:

- Opens the serial port and reads raw data from the FPGA
- Converts the binary stream into numeric values and logs them into an Excel .xlsx file
- Displays the time-domain (time series) waveform in real-time plots
- Computes and displays the frequency spectrum using Welch's method based on Fast Fourier Transform (FFT), including signal segmentation, Hann windowing, and spectral averaging, to obtain a stable Power Spectral Density (PSD) robust against noise
- Estimates cable tension based on the dominant frequency using the flat taut string formula

As shown in Fig. 4, the data from the accelerometer-FPGA system is received via UART and handled by the main script, which operates in parallel using multithreading. One dedicated thread is responsible for reading UART data and storing it in both a buffer and an Excel file for time-domain data logging. Simultaneously, another thread processes the data every 30 seconds using Welch's method to produce the frequency spectrum (FFT), displays the result, and extracts up to six visible fundamental frequencies while discarding false peaks either manually or automatically. Once the fundamental frequencies are determined, the script calculates cable tension using the Taut String Theory, storing the results as part of the analysis output. A separate Python script is used for manual analysis of previously logged data. This auxiliary tool allows verification of the results and validation of the tension estimation in cases where anomalies may be suspected during real-time acquisition.

The implementation results of the FPGA- and accelerometer-based cable tension estimation system for cable-stayed structures are shown in Figure 5.

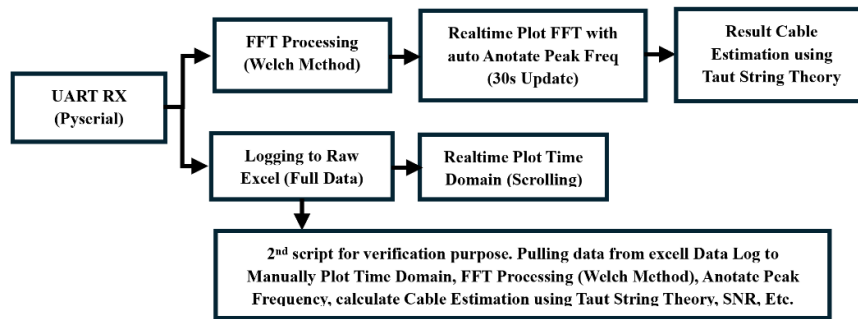


Fig. 4. Flow diagram of data handling in the steel cable tension estimation system.

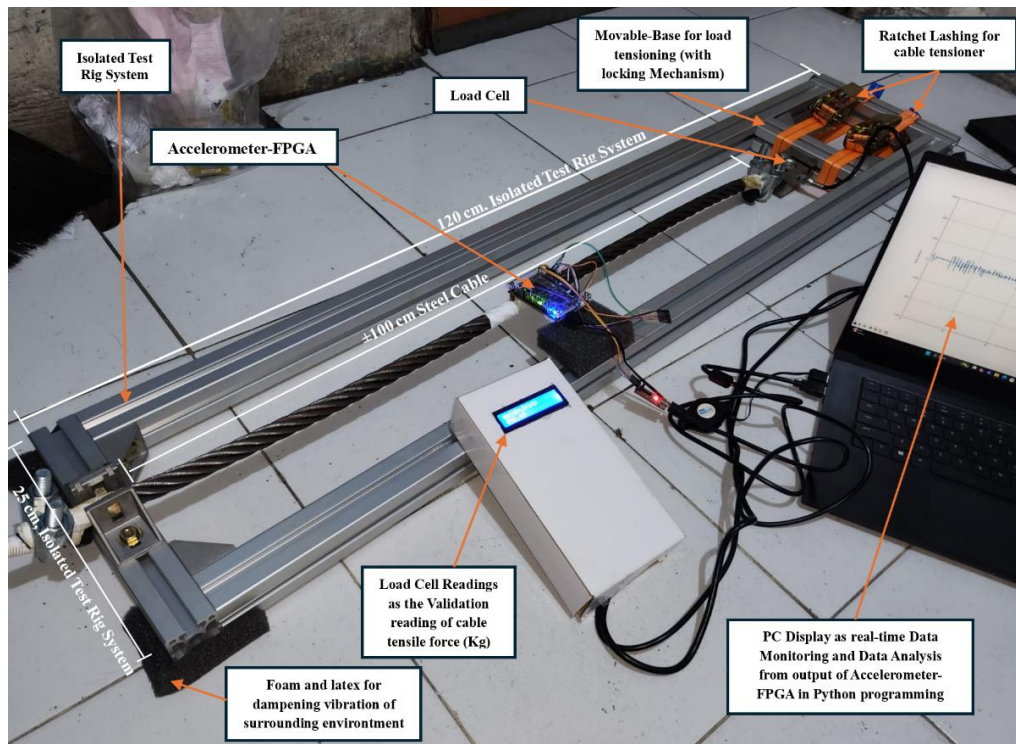


Fig. 5. Final implementation of the Cable-Stayed Tension Estimation System Using an FPGA and Accelerometer with components such as the accelerometer-FPGA module, Load Cell, Load Cell Display, and PC Display for data monitoring.

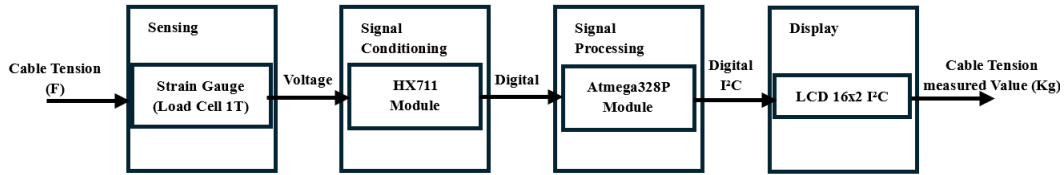


Fig. 6. Block diagram of the load cell system as a reference for cable tension measurement.

The system consists of an isolated test rig measuring 120 cm in length, with a 100 cm steel cable employed in a 6×37 strand configuration with a total diameter of 10 mm, effective mass per unit length $\mu=0.3695\mu=0.3695$ kg/m serving as the test object, equipped with a load cell for measuring actual tensile force. The rig frame is constructed using heavy-duty 4040 aluminum extrusions, providing high tensile strength, and includes an adjustable mechanical mount with a ratchet lashing mechanism for cable tension control. The system also features foam and latex padding as vibration dampers to minimize environmental interference and maintain measurement stability. Load cell readings are displayed on a digital screen, while estimated tension values and frequency spectra are visualized on a computer. This implementation demonstrates that the system can operate in a stable, real-time, and accurate manner, serving as a non-invasive solution for cable tension monitoring.

C. Calibration and Validation

Calibration and validation were conducted to ensure the reliability of the system in measuring cable tension. Calibration focused on the load cell system used as the measurement reference, which employed a strain gauge sensor conditioned by an HX711 module and processed by a microcontroller, with results displayed on an LCD. Figure 6 presents the functional diagram of the cable tension measurement system using the load cell, which serves as the calibrator for this system. Although the load cell was factory-calibrated, additional verification was performed using the Reference Measurement method by comparing the readings with a commercially calibrated digital scale.

Figure 7 shows a photo of the additional verification process, where a mass of 2713 grams resulted in a reading of -2.72 kg, with an average error of less than 0.7%, indicating that the system is sufficiently accurate to be used as a reference comparator.

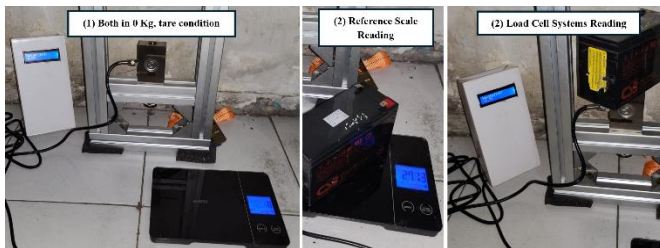


Fig. 7. Reference comparison between a factory-calibrated digital scale and the load cell system: (1) both systems at 0 Kg tare, (2) Reference scale reading, (3) Load cell system reading.

The validation of the FPGA- and accelerometer-based cable tension estimation system was carried out by comparing the estimated tension results with measurement data obtained from the load cell. The validation also included signal quality analysis, such as frequency stability and measurement

repeatability. This process ensures that the vibration-based estimation system can provide consistent and accurate results, making it suitable for real-time structural health monitoring.

The load cell readings are in kilograms (kg) by default, and the main accelerometer-FPGA system uses kilonewtons (kN). The following conversion equation (6) is applied:

$$force(kN) = \frac{Mass(kg) * 9.80665}{1000} \quad (6)$$

Verification results indicated that the load cell system was sufficiently accurate (error < 0.7%) and could be reliably used as a reference without requiring recalibration. Therefore, validation efforts were focused on the accelerometer-FPGA system. The validation of the accelerometer-FPGA system includes the following aspects:

- **Signal-to-Noise Ratio (SNR):** This evaluates the quality of the vibration signal from the accelerometer. SNR is calculated by comparing the power of the vibration signal (during excitation) to the background noise level (at rest), as shown in Equation (7) :

$$SNR_{dB} = \log_{10} 10 \left(\frac{P_{Signal}}{P_{noise}} \right) \quad (7)$$

- **Repeatability:** This test measures the system's ability to produce similar tension estimations under the same loading conditions.
- **Relative Error and Linear Regression (R^2):** To compare the estimated results with the load cell values to evaluate accuracy and correlation.

The full test procedure using the isolated rig is conducted through systematic stages to ensure accuracy and repeatability. First, the rig and cable system are fully assembled, including securing the steel cable and adjustable load cell. The system is initially set upright and left undisturbed for an hour to stabilize, followed by calibration (tare = 0) to remove gravitational bias. The rig is then laid horizontally on cushioning, and cable tension is adjusted using a ratchet lashing mechanism to reach the desired load. Once the target tension is achieved, the rig is locked and allowed to settle for another hour. The main monitoring system—comprising the accelerometer-FPGA, and PC running the Python script—is then activated to acquire time-domain data under no excitation for SNR evaluation. Afterward, dynamic excitation is manually applied to the cable using a mallet, and the resulting vibration response is analyzed for tension estimation based on natural frequency extraction. This process is repeated at multiple tension levels, with recalibration and stabilization performed at each stage to ensure experimental validity. Through these validation steps, the performance and reliability of the proposed cable tension estimation system can be quantitatively confirmed before being applied on a broader scale deployment.

III. RESULTS AND DISCUSSION

This section presents the implementation results and analysis of the accelerometer- and FPGA-based cable tension estimation system for cable-stayed structures. The results include the system's performance in vibration signal acquisition, frequency analysis using FFT, and tension estimation based on the taut string model. Additionally, the estimated results are validated against load cell measurements as a reference, including relative error analysis, coefficient of determination (R^2), and repeatability testing.

A. Noise SNR Accelerometer

Signal quality evaluation was performed by calculating the Signal-to-Noise Ratio (SNR) of the accelerometer sensor and comparing it between idle and excited conditions. The graph in Figure 8 illustrates the time-domain output signal amplitude of the accelerometer under excitation, measured on the steel cable section of the isolated test rig.

In Table II, the SNR testing in this study was conducted under three conditions: on the cable within the isolated rig, on a wooden table, and on the aluminum frame. Table I shows that the system could produce signals suitable for tension estimation, with all SNR values exceeding 20 dB.

TABLE I SNR MEASUREMENT RESULTS UNDER VARIOUS CONDITIONS

Condition	Average SNR	SNR Range	Error Relative	Standard Deviation (dB)
Isolated Test Rig (Cable)	25,57	22,54 - 28,81 ($\pm 6,27$)	6,77	1,73
Thick-WoodTable	27,74	23,6 - 31,49 ($\pm 7,89$)	9,94	2,75
Isolated Test Rig (Frame)	24,48	20,51 - 26,44 ($\pm 5,93$)	5,8	1,42

a. Each condition was measured with 20 repetitions; the displayed values are summaries

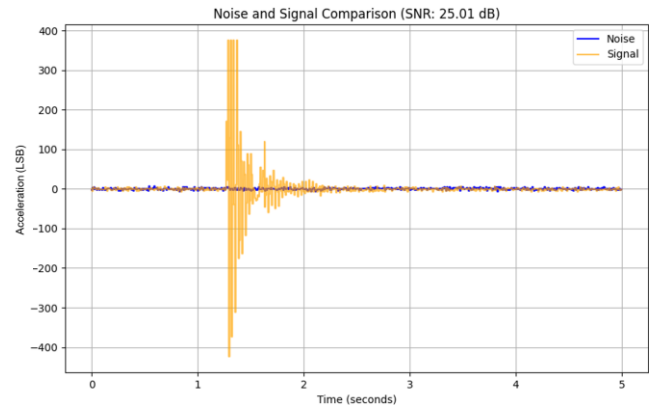


Fig. 8. Time-domain plot of the accelerometer signal: before excitation (blue) and after excitation (yellow).

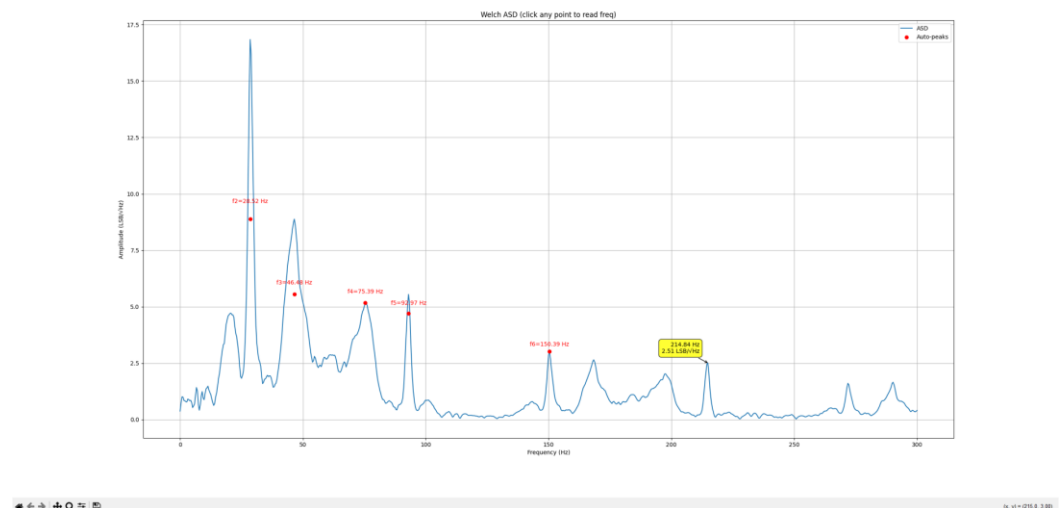
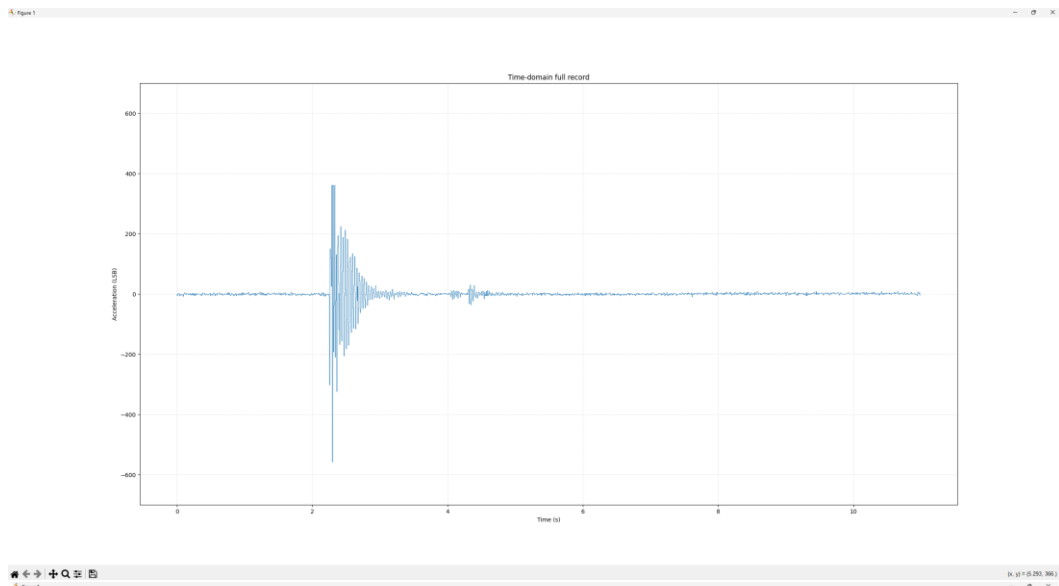


Fig. 9. Display in Python UI with two parallel display windows, Display of external real-time data processing.

The wooden table yielded the highest SNR but exhibited less stability, while the aluminum frame offered the most consistent results despite a lower SNR. The cable rig condition provided a balanced outcome with an SNR of 25.57 dB and a relative error of 6.77%, making it the most representative test condition. The overall average SNR across all conditions was 25.95 dB, demonstrating the system's reliability in distinguishing excitation signals from noise in real time.

B. Real-Time Processing Validation

The external real-time data processing, implemented using Python programming, is shown in Figure 9 as the Python UI display during acceleration data acquisition from the Accelerometer-FPGA system in the time domain (LSB; $\pm 2g \approx \pm 512$), along with the real-time analysis of the signal's fundamental mode or other modal frequencies using Welch's FFT method. Figure 10 illustrates an example of the Terminal/Console Log interface in the Python program, which displays real-time tension estimation results, modal frequency identification, and SNR calculation.

```

PROBLEMS 27 OUTPUT DEBUG CONSOLE TERMINAL PORTS
>>
μ = 0.3695 kg/m
Mode 1: f = 28.52 Hz → T = 1.202 kN
Mode 2: f = 46.48 Hz → T = 0.798 kN
Mode 3: f = 75.39 Hz → T = 0.933 kN
Mode 4: f = 92.97 Hz → T = 0.799 kN
Mode 5: f = 150.39 Hz → T = 1.337 kN
Mode 6: f = 168.36 Hz → T = 1.164 kN

Estimasi tegangan rata-rata ≈ 1.039 kN
Deviasi standar antar-mode ± 0.227 kN

```

Fig. 10. Terminal/Console Log display in Python showing the real-time calculation Taut String Theory Formula from the Python program.

It is important to note that Figures 9 and 10 are part of a continuous experimental session. During this test (1-meter cable length), the load cell system recorded a cable tension of 105.5 kg, which can be converted into kilonewtons using Equation (6), resulting in 105.5 kg = 1.0346 kN.

These results demonstrate that the full implementation—comprising the accelerometer-FPGA system, Load Cell reference system, and Python-based real-time processing—functions correctly and cohesively. The Python script logs the data, plots the acceleration signal, and concurrently processes the signal using Welch's method to produce the frequency spectrum (FFT). The script then identifies the top 6 visible fundamental frequencies (as shown in Figure 9), removing any false peaks either manually or automatically. Once the 6 modal frequencies are extracted, the system proceeds to calculate the estimated cable tension using the Taut String Theory formula using equation (4), with the result immediately displayed (as seen in Figure 10).

If uncertainties arise during real-time acquisition, a separate Python script can be used for manual analysis. This includes verification of the FFT results, manual annotation of frequency peaks, and tension estimation validation—based on the automatically saved Excel log files.

C. System Testing Result

The testing of the cable tension estimation system, which combines an accelerometer and an FPGA, was conducted under various actual tension conditions measured using a load

cell. The analysis focused on four main aspects: estimation of the cable's vibration frequency for tension calculation, comparison of the estimated results with load cell data, evaluation of relative error and regression quality, and repeatability testing to assess the system's consistency.

1. Cable Tension Estimation

Cable tension estimation was performed by calculating the fundamental frequency of the cable vibration signal using FFT and comparing it with load cell data to evaluate the system's accuracy. Table II presents the results of cable tension estimation across various tension levels.

TABLE II RESULTS OF CABLE TENSION ESTIMATION AT VARIOUS TENSION LEVELS

Sample Number	Cable Length	f_1 (Hz)	f_2 (Hz) (Optional)	f_3 (Hz) (Optional)	Est Tension f_1 (kN)	Est Tension f_2, f_3 (kN)
1	0.97	28.52	44.53	92.97	1,131	1,052
2	0.97	28.52	39.84	92.97	1,131	1,006
3	0.97	28.91	44.53	92.97	1,162	1,062
4	0.97	28.91	48.05	92.58	1,162	1,097
5	0.97	28.52	50.00	92.97	1,131	1,112
6	0.97	28.52	51.17	92.97	1,131	1,126
7	0.97	28.52	51.56	93.36	1,131	1,134
8	0.97	28.91	44.92	92.97	1,162	1,067
9	0.97	28.52	46.48	92.97	1,131	1,073
10	0.97	28.91	46.88	92.97	1,162	1,087
11	0.97	28.91	57.81	92.97	1,162	1,220
12	0.97	29.69	46.88	91.80	1,226	1,097
13	0.97	30.08	47.27	91.80	1,258	1,113
14	0.97	28.52	47.27	93.36	1,131	1,085
15	0.96	28.12	56.25	93.36	1,077	1,158
16	0.96	28.12	55.86	93.36	1,077	1,153
17	0.96	29.69	54.69	92.19	1,201	1,169
18	0.96	30.47	60.94	91.41	1,265	1,265
19	0.96	29.30	55.86	92.19	1,169	1,173
20	0.96	29.69	55.47	92.19	1,201	1,178
21	0.96	29.69	56.25	92.19	1,201	1,188
22	0.96	29.69	55.86	92.19	1,201	1,183
23	0.96	28.91	57.03	92.58	1,139	1,181
24	0.96	29.30	56.64	92.58	1,169	1,186
25	0.96	29.30	55.08	92.19	1,169	1,163
26	0.96	30.08	57.03	91.80	1,233	1,205
27	0.96	29.69	54.30	91.80	1,201	1,160
28	0.96	29.30	54.69	91.80	1,169	1,155
29	0.96	30.08	56.64	91.80	1,233	1,200
30	0.96	29.69	55.86	91.18	1,201	1,174
31	0.96	33.20	65.62	98.83	1,502	1,482
32	0.96	33.20	63.67	98.83	1,502	1,453
33	0.97	36.33	72.61	103.72	1,836	1,777
34	0.97	36.72	72.66	104.30	1,875	1,797
35	0.97	36.72	72.66	103.20	1,875	1,786
36	0.97	36.33	74.61	103.91	1,836	1,813
37	0.97	36.33	75.39	103.91	1,836	1,827
38	0.97	35.94	71.09	103.12	1,796	1,732
39	0.97	35.94	71.48	104.30	1,796	1,751
40	0.97	36.72	77.34	104.69	1,875	1,883
41	0.97	36.33	75.78	105.08	1,836	1,846
42	0.97	36.33	76.56	103.16	1,836	1,839
43	0.97	35.94	76.56	103.52	1,796	1,830
44	0.97	36.33	76.95	103.52	1,836	1,850
45	0.97	35.94	75.78	105.64	1,796	1,839

Based on the test data, the accelerometer-FPGA-based cable tension estimation system demonstrated satisfactory performance across various actual tension levels. Tension estimation was calculated using the fundamental frequency (f_1) and later compared with load cell readings as the validation reference.

As shown in Table II, the system consistently identified different tension levels based on the detected natural frequency (f_1). Samples 1 to 14 exhibited fundamental mode frequencies around 28–30 Hz, corresponding to estimated tension values ranging from 1.006 to 1.220 kN. In contrast,

samples 33 to 45 showed higher fundamental frequencies (around 35–36 Hz), with higher estimated tensions ranging from 1.732 to 1.883 kN.

This trend aligns with the flat taut string theory, which states that the higher the cable tension, the higher the resulting natural frequencies (f_1, f_2, f_3). The consistent relationship between frequency and tension further supports the validity of this estimation method. Additionally, the uniformity of frequency values within the same tension group indicates that the system is sufficiently sensitive to capture dynamic changes in the cable caused by external excitation and is not significantly affected by random noise.

These results provide initial justification that the cable-Stayed Tension Estimation System Using an FPGA and Accelerometer is not only capable of accurately detecting the fundamental frequency mode but also stable in estimating cable tension across different cable lengths and tension levels.

2. Comparison with Load Cell

TABLE III CABLE TENSION ESTIMATION VS LOAD CELL READINGS

Sample Number	Est Tension f_1 (kN)	Est Tension f_1, f_2, f_3 (kN)	LoadCell (kN)
1	1,131	1,052	1,035
2	1,131	1,006	1,035
3	1,162	1,062	1,035
4	1,162	1,097	1,035
5	1,131	1,112	1,035
6	1,131	1,126	1,035
7	1,131	1,134	1,035
8	1,162	1,067	1,035
9	1,131	1,073	1,035
10	1,162	1,087	1,035
11	1,162	1,220	1,035
12	1,226	1,097	1,035
13	1,258	1,113	1,035
14	1,131	1,085	1,035
15	1,077	1,158	1,100
16	1,077	1,153	1,100
17	1,201	1,169	1,130
18	1,265	1,265	1,130
19	1,169	1,173	1,130
20	1,201	1,178	1,130
21	1,201	1,188	1,130
22	1,201	1,183	1,130
23	1,139	1,181	1,130
24	1,169	1,186	1,130
25	1,169	1,163	1,130
26	1,233	1,205	1,130
27	1,201	1,160	1,130
28	1,169	1,155	1,130
29	1,233	1,200	1,130
30	1,201	1,174	1,130
31	1,502	1,482	1,500
32	1,502	1,453	1,500
33	1,836	1,777	1,834
34	1,875	1,797	1,834
35	1,875	1,786	1,834
36	1,836	1,813	1,834
37	1,836	1,827	1,834
38	1,796	1,732	1,834
39	1,796	1,751	1,834
40	1,875	1,883	1,834
41	1,836	1,846	1,834
42	1,836	1,839	1,834
43	1,796	1,830	1,834
44	1,836	1,850	1,834
45	1,796	1,839	1,834

To validate the accuracy of the FPGA–Accelerometer-based tension estimation system, a direct comparison was conducted against the load cell system readings as the standard reference. Table III shows that for the tension range of Samples 1–14, the estimated values ranged from 1.006 to 1.258 kN, while the load cell readings remained stable around 1.035 kN (approximately 105.6–105.4 kg during measurement). The deviation in these samples generally

ranged from ± 0.1 to 0.18 kN or approximately 10–17%, with some estimated values slightly overshooting.

In contrast, for the higher tension range (Samples 33–45), the estimated values ranged from 1.732 to 1.883 kN, with the load cell reference remaining stable around 1.834 kN. The estimation system tended to provide values closer to the load cell readings in the higher tension range compared to the lower range. This discrepancy may be attributed to the system's sensitivity to frequency modes, which can still be influenced by local noise or imperfections in the cable excitation.

Overall, these differences remain within a reasonable margin for non-invasive dynamic measurements. The results indicate that the accelerometer–FPGA system is capable of producing quantitative tension estimations that are consistent and comparable to standard measurement tools (load cell), making it suitable for practical monitoring applications, particularly in systems permanently installed, mainly due to limited access to the anchorage system.

Overall, the observed deviations remain within reasonable limits for non-invasive dynamic measurements. These results suggest that the accelerometer–FPGA system can produce quantitatively comparable and directionally consistent tension estimates relative to standard measurement devices (load cells), making it a viable tool for practical monitoring—especially in systems where permanent load cell installation is not feasible.

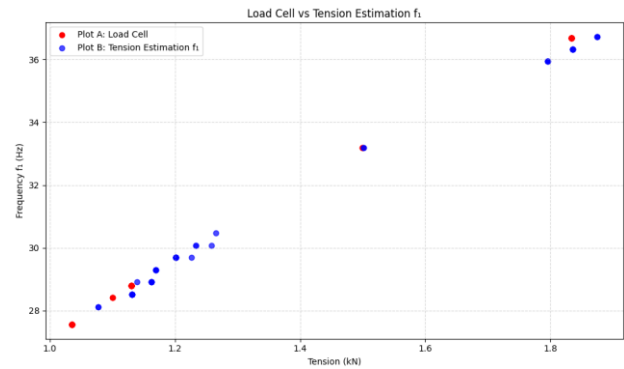


Fig. 11. Comparison graph of Load Cell vs. Estimated Tension (f_1).

The comparison between the estimated tension values using the fundamental frequency (f_1) and the load cell readings demonstrate a strong correlation and a consistent trend. Most of the estimated values fall within a close range of the actual values, with relatively small deviations. The comparison graph in Figure 11 illustrates that the estimation system is capable of consistently tracking variations in actual tension.

With an average relative error of 4.28% across tension estimates in (f_1, f_2, f_3) and a maximum error of 21.54%, the system provides sufficiently accurate results for experimental applications. These values indicate that the accelerometer–FPGA-based approach can serve as a valid alternative for monitoring cable tension without the need for invasive sensor installation.

3. Relative Error and Regression

Table IV presents a direct comparison between the estimated cable tension results from the Accelerometer–FPGA system and the actual readings from the load cell, along with the calculated relative error for each sample. Although

the relative error for a few samples reached up to 21.54%, the overall average relative error across all samples was 5.98%. This was primarily influenced by lower cable tension ranges, where small variations in the fundamental frequency led to large deviations in the estimated values due to the sensitivity of the nonlinear equation at low frequencies.

In higher tension ranges (approximately ± 1.8 kN), the relative errors were generally smaller—below 5% for most samples—with an average relative error of only 1.2% for high-tension samples using f_1 . This indicates that the system is likely more stable and accurate in medium to high steel cable tension ranges, aligning with the clearer signal characteristics observed when the cable is excited with greater force.

TABLE IV RELATIVE ERROR IN CABLE TENSION ESTIMATION

Sample Number	Est Tension $f_1 f_2 f_3$ (kN)	Est Tension f_1 (kN)	Error Relative $f_1 f_2 f_3$ (%)	Error Relative f_1 (%)	LoadCell (kN)
1	1,052	1,131	1,643	9,275	1,035
2	1,006	1,131	2,802	9,275	1,035
3	1,062	1,162	2,609	12,271	1,035
4	1,097	1,162	5,990	12,271	1,035
5	1,112	1,131	7,440	9,275	1,035
6	1,126	1,131	8,792	9,275	1,035
7	1,134	1,131	9,565	9,275	1,035
8	1,067	1,162	3,092	12,271	1,035
9	1,073	1,131	3,671	9,275	1,035
10	1,087	1,162	5,024	12,271	1,035
11	1,220	1,162	17,874	12,271	1,035
12	1,097	1,226	5,990	18,454	1,035
13	1,113	1,258	7,536	21,546	1,035
14	1,085	1,131	4,831	9,275	1,035
15	1,158	1,077	5,273	2,091	1,100
16	1,153	1,077	4,818	2,091	1,100
17	1,169	1,201	3,451	6,283	1,130
18	1,265	1,265	11,947	11,947	1,130
19	1,173	1,169	3,805	3,451	1,130
20	1,178	1,201	4,248	6,283	1,130
21	1,188	1,201	5,133	6,283	1,130
22	1,183	1,201	4,690	6,283	1,130
23	1,181	1,139	4,513	0,796	1,130
24	1,186	1,169	4,956	3,451	1,130
25	1,163	1,169	2,920	3,451	1,130
26	1,205	1,233	6,637	9,115	1,130
27	1,160	1,201	2,655	6,283	1,130
28	1,155	1,169	2,212	3,451	1,130
29	1,200	1,233	6,195	9,115	1,130
30	1,174	1,201	3,894	6,283	1,130
31	1,482	1,502	1,200	0,133	1,500
32	1,453	1,502	3,133	0,133	1,500
33	1,777	1,836	3,108	0,109	1,834
34	1,797	1,875	2,017	2,236	1,834
35	1,786	1,875	2,617	2,236	1,834
36	1,813	1,836	1,145	0,109	1,834
37	1,827	1,836	0,382	0,109	1,834
38	1,732	1,796	5,562	2,072	1,834
39	1,751	1,796	4,526	2,072	1,834
40	1,883	1,875	2,672	2,236	1,834
41	1,846	1,836	0,654	0,109	1,834
42	1,839	1,836	0,273	0,109	1,834
43	1,830	1,796	0,218	2,072	1,834
44	1,850	1,836	0,872	0,109	1,834
45	1,839	1,796	0,273	2,072	1,834

The R^2 value for the tension estimation using (f_1, f_2, f_3) reached 0.984, as shown in Figure 12, demonstrating that the Accelerometer-FPGA system is highly capable of capturing nearly all the tension variations measured by the load cell. Figures 12 and 13 show that the data points are tightly clustered around the linear regression line, indicating a strong linear relationship between the estimated tension values and the load cell readings.

These findings reinforce the validity of the fundamental frequency-based estimation method as an accurate and reliable approach under the testing conditions used. Although the experiments were limited to five tension levels, the high coefficient of determination still provides strong evidence supporting the feasibility of this frequency-based estimation

method, at least within the load range represented in this test setup.

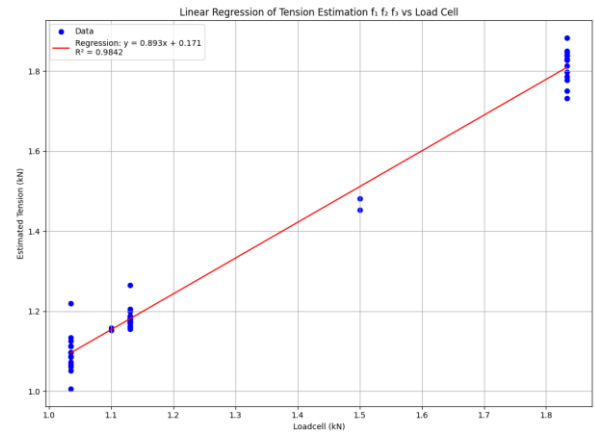


Fig. 12. Linear Regression of Tension Estimation (f_1, f_2, f_3) VS Load Cell.

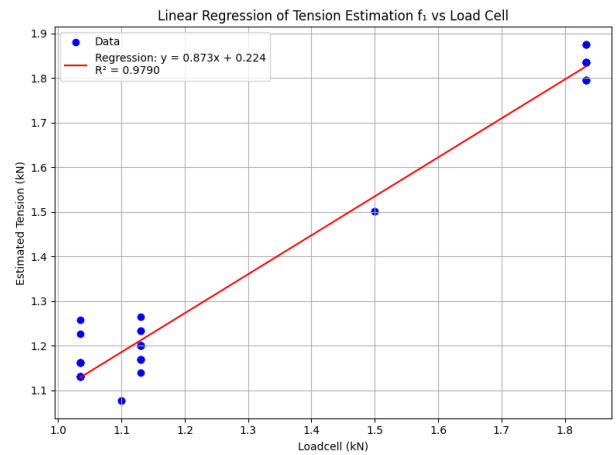


Fig. 13. Linear Regression of Tension Estimation (f_1) VS Load Cell.

It should be noted that the regression analysis was conducted using five primary tension groups, due to mechanical and safety limitations of the isolated test rig; the ratchet lashing system, in particular, is easily broken. These five levels were carefully selected to represent low- and high-tension ranges, which are sufficient to evaluate the performance of the estimation system across meaningful dynamic conditions. Although more data points across intermediate tension levels would improve statistical granularity, the current distribution still produces a strong linear correlation ($R^2 = 0.963$), validating the effectiveness of the frequency-based tension estimation method under the given constraints. This limitation will be addressed in future work by expanding the test rig design and incorporating better and finer tension increments to improve regression spread.

4. Repeatability

To ensure the system's consistency in estimating tension under identical loading conditions, repeated tests were conducted for five tension groups: Group Tension 1 (~ 1.035 kN) which in the sample Number 1-14; Group Tension 2 (~ 1.1 kN) which in the sample Number 15-16; Group Tension 3 (~ 1.130 kN) which in the sample Number 17-30; Group Tension 4 (~ 1.5 kN) which in the sample Number 31-32; Group Tension 5 (~ 1.834 kN) which in the sample Number 15-25 as you can see in Tables IV.

As shown in Table V, all groups exhibited very low standard deviations (around 0.004 kN – 0.049 kN, respectively), with relative error between repetitions around 1.4% – 4.5% and the average relative error of repeatability was 1.55%, indicating excellent system repeatability.

TABLE V REPEATABILITY OF CABLE TENSION ESTIMATION

Tension f_1				
Group Tension	Average Tension Estimation (kN)	Tension Estimation Range (kN)	Error Relative	Standard Deviation (kN)
1	1,158	1,131 - 1,258 (± 0.127)	3,371	0,039
2	1,077	1,077 - 1,077 (± 0.000)	0,000	0,000
3	1,197	1,139 - 1,265 (± 0.126)	2,724	0,033
4	1,502	1,502 - 1,502 (± 0.000)	0,000	0,000
5	1,833	1,796 - 1,875 (± 0.079)	1,639	0,030

Tension (f_1, f_2, f_3)				
Group Tension	Average Tension Estimation (kN)	Tension Estimation Range (kN)	Error Relative	Standard Deviation (kN)
1	1,158	1,006 - 1,220 (± 0.214)	4,461	0,049
2	1,156	1,153 - 1,158 (± 0.005)	0,306	0,004
3	1,184	1,155 - 1,265 (± 0.110)	2,298	0,027
4	1,468	1,453 - 1,482 (± 0.029)	1,397	0,021
5	1,813	1,732 - 1,883 (± 0.151)	2,355	0,043

It is important to note that the relative error values discussed in this section differ in context from those in Section 3 (Relative Error and Regression). In repeatability testing, the relative error is calculated based on the spread between multiple estimation results under the same tension condition, not the deviation from load cell readings. Therefore, even though the average relative error against the load cell reached 21.54% in Section 3—mainly due to systematic offset—in this section, the system demonstrates high internal consistency with minimal estimation fluctuation. This suggests the system is reliable and stable for repeated measurements, and that most deviations from the estimation are due to fixed systematic bias, not measurement instability. Variations observed are more likely caused by manual excitation inconsistencies and the dynamic behavior of the steel cable, for which the vendor did not provide complete manufacturer specifications, rather than by instability of the acquisition system itself.

The error in the low-tension range is primarily attributed to the nonlinearity of the tension-frequency relationship at lower fundamental frequencies, combined with manual excitation inconsistency, intrinsic cable dynamics, and affected by local noise around the lab. To tackle and reduce this error, future work may involve controlled excitation mechanisms (e.g., modal hammers), the use of lower-noise accelerometers such as the ADXL355, and better noise dampening in the rig itself. The flat taut string model may also be enhanced by including correction factors for cable bending stiffness in small-scale systems.

IV. CONCLUSION

This study successfully developed a non-invasive cable tension estimation system that integrates an ADXL345

accelerometer with an FPGA-based acquisition platform. By applying Welch's FFT method and the flat taut string theory, the system effectively detects the fundamental vibration frequency for tension estimation in real time. Experimental validation using a calibrated load cell demonstrated high accuracy, particularly in the high-tension range (~1.8 kN), where the average relative error was just 1.2% and the R^2 coefficient reached 0.984.

Repeatability analysis confirmed the system's measurement stability, with a low average relative error of 1.55% across tension groups, indicating that observed deviations were primarily due to external factors such as manual excitation or cable variability. The system also maintained an average SNR above 25 dB under various test conditions, confirming robustness against environmental and structural noise.

Overall, the proposed FPGA–accelerometer-based system offers a reliable, portable, and cost-efficient alternative to traditional load cell methods for cable tension monitoring. These results provide a strong foundation for broader implementation in structural health monitoring (SHM), especially in cable-stayed bridges and similar infrastructure. Future improvements may include automated excitation, lower-noise sensors, better noise dampening in the rig itself, and refined modeling to address bending stiffness in small-scale setups.

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