Research Article / Araştırma Makalesi

Adıyaman University
Journal of Engineering Sciences
Adyü J Eng Sci 2025;12(25):143-158
Adıyaman Üniversitesi
Mühendislik Bilimleri Dergisi
Adyü Müh Bil Derg 2025;12(25):143-158
https://doi.org/10.54365/adyumbd.1652866

Automation of a Multi-Station Rotary Bending Fatigue Test Machine with PLC Control System

Çok İstasyonlu Döner Eğilmeli Yorulma Test Makinesinin PLC Kontrol Sistemi ile Otomasyonu

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Abstract

Rotating bending fatigue tests are crucial for assessing material fatigue strength in both industrial and academic contexts. While standards such as the AISI and ISO define test methodologies, automation and control mechanisms have not been sufficiently investigated. This study presents the automation of a 22-station fatigue testing system with PLC control. Inductive sensors detect real-time specimen fractures, transmitting signals to the PLC, which autonomously tracks cycles, identifies failures, and terminates tests. A rotary encoder (40 pulses/rev) refines cycle monitoring, whereas an HMI panel enables real-time visualization and parameter adjustments. This automation system significantly improves test accuracy, reliability, and repeatability, offering substantial advantages for material fatigue assessments in industrial and academic applications.

Keywords: *Rotating bending fatigue test, PLC control, Automation, HMI interface*

Öz

Döner eğilmeli yorulma testleri, hem endüstriyel hem de akademik bağlamlarda malzeme yorulma mukavemetini belirlemek için çok büyük öneme sahiptir. AISI ve ISO gibi standartlar test yöntemlerini tanımlasa da, bu testlerin otomasyon süreçleri yeterince araştırılmamıştır. Bu çalışma 22 istasyonlu bir yorulma test sisteminin ve PLC kontrollü otomasyonunu içermektedir. Endüktif sensörler, gerçek zamanlı numune kırılmalarını tespit ederek, PLC'ye sinyaller iletir, böylece PLC döngüleri otonom olarak izler, arızaları tanımlar ve testleri sonlandırır. 40 pulse/rev çözünürlüklü bir rotary encoder hassas çevrim izlemesi sağlarken, HMI paneli anlık veri takibi ve parametre düzenlemelerine imkân tanımaktadır. Bu otomasyon sistemi, test doğruluğunu, güvenilirliğini ve tekrarlanabilirliğini önemli ölçüde artırarak endüstriyel ve akademik uygulamalarda malzeme yorulma analizleri için ciddi avantajlar sunar.

Anahtar Kelimeler: *Döner eğilme yorulma testi, PLC kontrolü, Otomasyon, HMI arayüzü*

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Received (Geliş Tarihi):06.03.2025, **Accepted (Kabul Tarihi):** 16.04.2025

1. Introduction

In industrial use, damage occurs mostly when materials are loaded under variable loads. Predicting the behaviour of materials under such dynamic loading is very important in the field of structural design. Engineering materials that are damaged under dynamic loads much lower than their current static strength; such a dynamic failure mechanism is called fatigue. Rotating bending fatigue tests are used to determine the fatigue strength of materials and play a critical role in industrial and academic research [1, 2]. These tests determine the fatigue characteristics of rotating machine elements under cyclic loading as a result of the bending effect [3, 4]. A great deal of information is available on the application procedures of these tests, such as many standards (AISI and ISO) and a considerable amount of academic work. However, there is not enough information in the literature in the field of control of the test systems that perform these tests.

Electronic components may vary depending on the specific system design, but the principles of cycle counting methods are generally similar for rotary bending fatigue test setups. One widely adopted method reported in the literature relies on proximity sensors that generate signals each time a predetermined reference point on a rotating spindle completes a revolution, incrementing the cycle count accordingly [1-3, 5, 6]. Moving beyond this conventional method, Yamamoto et al. [4] introduced an alternative approach employing photoelectric sensors. Similarly, Gentile et al. [7] utilized high-precision encoders integrated with computer-controlled real-time data acquisition systems for cycle-counting tasks. Small (e.g., 6 or 10 digits) LCD screens are generally preferred for data display in single specimen test systems [2, 5]. However, digital counters are also frequently used for cycle counting [1, 2, 5, 6, 8]. Yamamoto et al.[4] developed a system consisting of four test stations, each equipped with a separate 16x2 LCD screen, to independently monitor specimen cycle life in a multispecimen test configuration. To improve operational ease and optimize data management, this research team subsequently integrated a human–machine interface (HMI) panel into the setup to simplify the data input and output processes [9]. Similarly, Gentile et al. provided a data display process involving real-time data transfer via computer connections [7]. Unlike other studies, Isakov et al. [3]. used a data acquisition system (DAQ) instead of a microcontroller-based controller and preferred to perform all data processing during the test through this system. Other studies in the literature do not provide details about the control system, and some of them do not even use advanced control elements such as microcontrollers.

Today, the design and control approaches of a rotating bending fatigue test system are largely standardized, but the need for more advanced control systems that can meet industrial needs is increasing. Since statistical repeatability is of critical importance in fatigue testing, significant efforts are being made to develop multistation test systems in terms of both mechanical and electronic control. Particularly critical is the ability to rapidly and synchronously acquire and display data from each testing station. The methodologies demonstrated by Gentile and Yamamoto provide notable frameworks for achieving synchronized data processing and visualization in multistation rotating bending fatigue tests[4, 7, 9]. Moreover, the ability to independently manage multiple concurrent experiments within a single machine environment continues to drive innovation, inspiring novel and industrially viable test system designs.
With the aim of addressing this gap in the literature, this study describes an automation process in a rotating bending fatigue test unit consisting of 22 stations. Employing a PLC-based automation architecture facilitates precise real-time data acquisition and streamlines algebraic computations, significantly improving overall operational accuracy and efficiency[10]. During the cyclic loading of the specimen at the machine stations, the PLC monitors the life span values in real time. Moreover, the PLC is also used to detect damage and autonomously terminate the test.

The HMI panel is integrated into the system for external data input and reading existing data in the test unit. Certain control commands are given through the HMI panel, while at the same time, it is possible to make some parametric operating settings. Instantaneous monitoring of rotary encoder data with a resolution of 40 pulses/rev, which enables precise tracking of speed counting, is also carried out through this interface.

Additionally, to detect the presence of damage to the specimens in the automation process, inductive sensors are placed at each station. In the case of damage to the test specimens, which are monitored in real time via PLC, the life data are permanently determined as the number of cycles and the other stations continue the test. After the test, the life data of the specimen can be displayed via the HMI panel. Inductive sensor signals are monitored instantaneously at each station during the test, and when the specimen breaks at all stations, the machine stop command is automatically derived via the PLC algorithm.
In this study, the completed electronic equipment, machine automation and operating characteristics of a rotating bending test unit consisting of 22 stations are analysed. The findings and the contribution of the machine to the literature are discussed in section 4.

2. Materials and methods

The literature reveals that most existing systems rely on manual or semiautomated testing processes. These systems are typically limited to testing a small number of specimens, with cycle counting performed via manual counters or basic digital sensors.

In this context, the fully assembled 22-station rotating bending fatigue test device, as depicted in Figure 1, distinguishes itself from existing methods because of its high efficiency, fully automated operation, and precision data acquisition capabilities. This section presents the electrical connections of the machine, the mechanical assembly of its electronic components, and an analysis of its operational characteristics.

Figure 1. Final assembled configuration of the test unit.

2.1. Inductive sensor

Inductive sensors are widely used for detecting metals and other conductive materials that enter their generated electromagnetic field. These sensors produce a signal upon detecting a suitable object within a specific sensing range. The generated signals are utilized to monitor and control the specimen status in the automation process of the test unit.

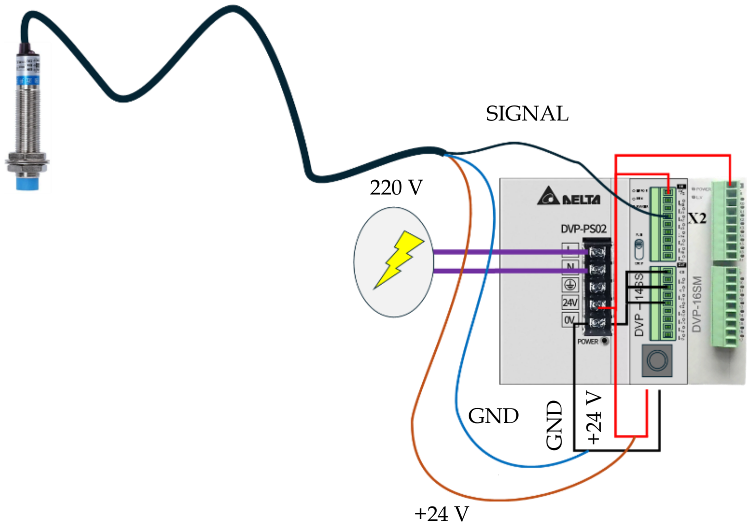


Figure 2. Schematic representation of the wiring diagram between the PLC and inductive sensor

In the test unit with 22 stations, the sensors positioned on the idler weights of the specimens provide very effective control to check the rupture conditions. In the automation process using a Delta DVP 14-SS series PLC, one inductive sensor was used at each test station. The wiring diagram of the inductive sensor used in the study for the PLC is shown in Figure 2.

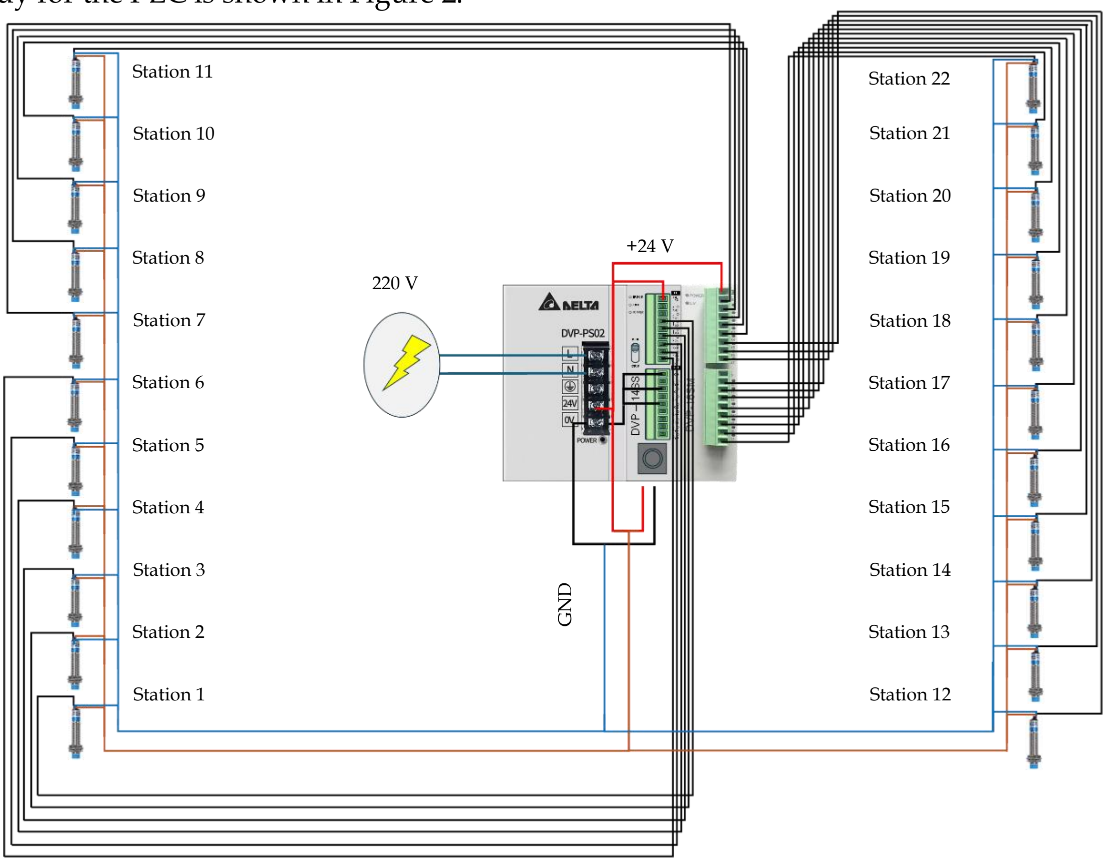


Figure 3. Schematic representation of the PLC connections for inductive sensors across all machine stations.

A comprehensive wiring schematic illustrating the integration of inductive sensors across all 22 test stations is presented in Figure 3. This schematic provides an overview of the connection architecture and sensor distribution throughout the testing system.

The mechanical framework of the test unit is designed to ensure effective monitoring across multiple stations. In this configuration, specimens are subjected to loading through idler weights attached to their free ends. These idler weights serve as a mechanism for applying force during fatigue testing. Inductive sensors are strategically positioned above these weights, enabling the precise detection of specimen conditions throughout the test. A schematic representation of the mechanical placement of sensors within the multistation setup is provided in Figure 4.

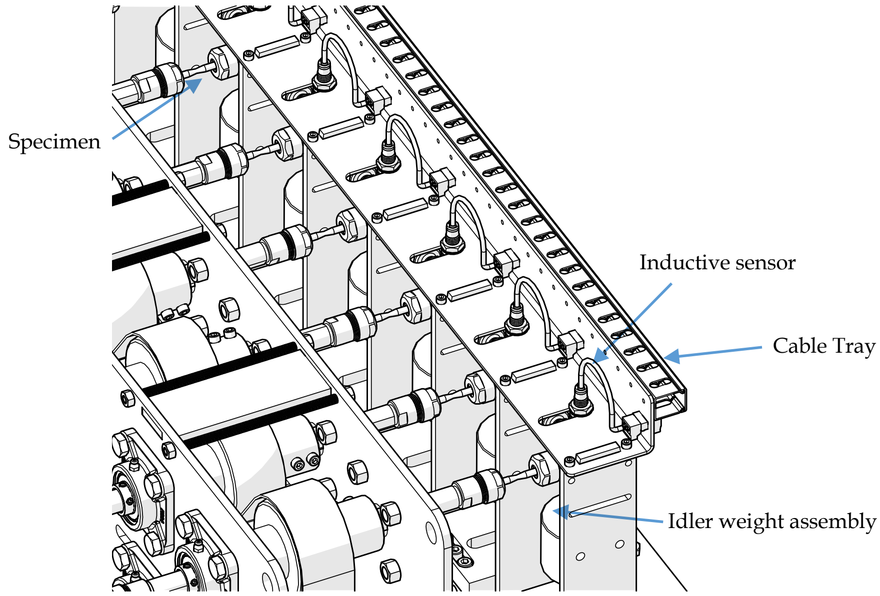


Figure 4. Methodology for the mechanical integration of inductive sensors in a multistation fatigue testing machine.

While the specimen remains intact, the inductive sensor generates a signal, activating the indicator light. Upon reaching a determined cycle count and subsequent specimen fracture, the sensor signal is interrupted, causing the indicator light to turn off. This process is schematically represented in Figure 5. The specimen status at each station is controlled in real time with the signal generated in this way. When a specimen fractures, the ongoing cycle count is instantly logged as permanent data, and counting ceases for the corresponding station, even as the machine continues operation. Consequently, the fatigue life of a material, measured in cycles, is precisely determined.

Within the PLC-based automation system, this methodology ensures comprehensive tracking of specimen failures across all stations. Additionally, a self-terminating mechanism was integrated, allowing the test unit to automatically halt upon completion of all the fatigue tests.

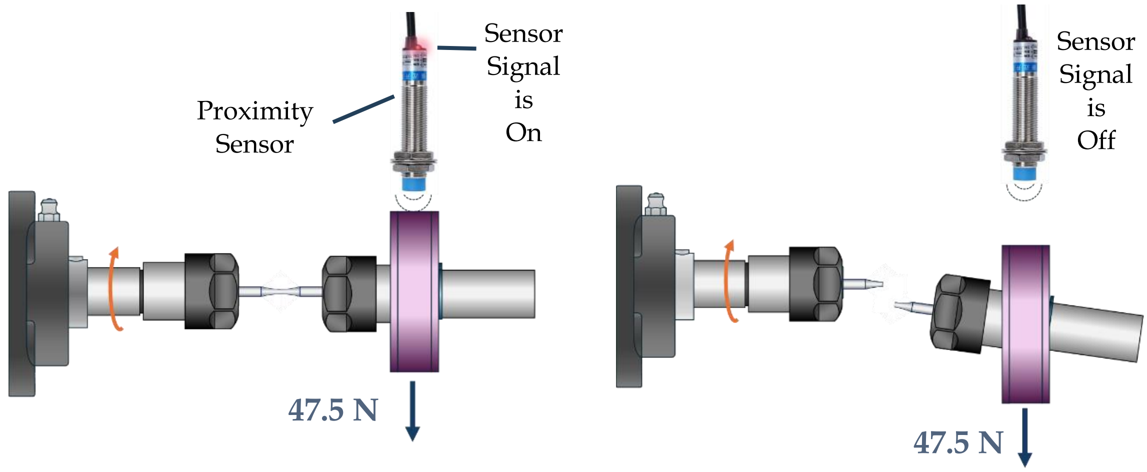


Figure 5. Specimen status detection via an inductive sensor signal: (a) Intact specimen, (b) Fractured specimen.

2.2. Rotary Encoder

The rotary encoder is a critical component in motion tracking applications, providing high-precision feedback by converting mechanical movement into electrical signals. This enables continuous and accurate monitoring of key parameters such as speed, position, and direction in rotating systems. In this study, an Autonics E50S-8-40-3-N-24 incremental rotary encoder was employed to facilitate precise cycle counting. A detailed wiring schematic illustrating the integration of the rotary encoder with the PLC is presented in Figure 6, outlining the necessary electrical configuration for seamless data acquisition and system functionality.

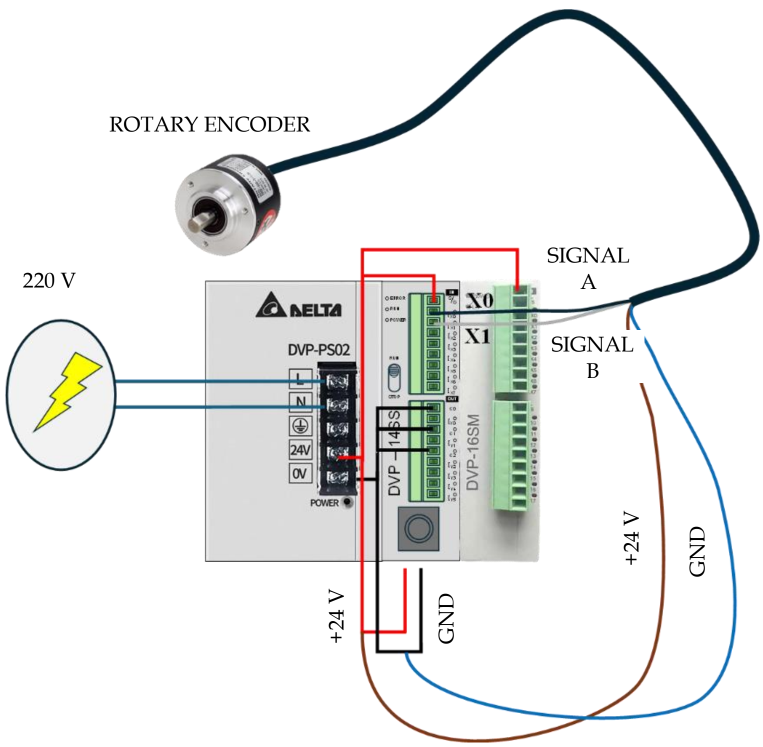


Figure 6. Schematic diagram of rotary encoder integration with the PLC.

For the mechanical installation of the rotary encoder onto the machine body, a dedicated mounting bracket and an encoder housing were designed. Figure 7 illustrates the systematic integration of the rotary encoder into the sheet metal frame of the machine. Additionally, a detailed perspective view of the encoder's attachment to the main drive shaft is presented in Figure 8.

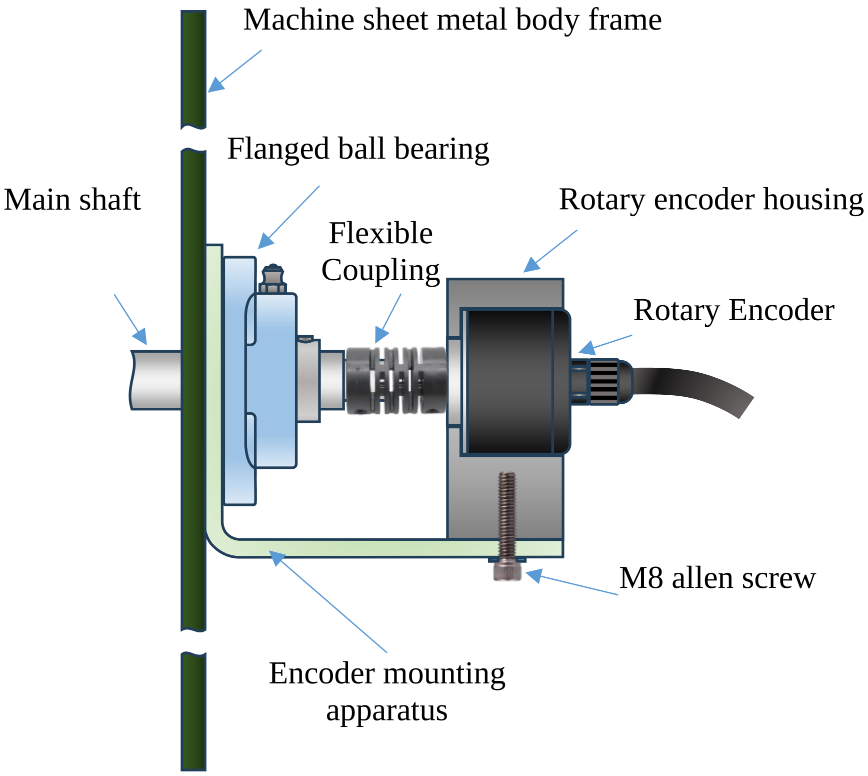


Figure 7. Schematic representation of the rotary encoder's mechanical integration with the machine's metal frame.

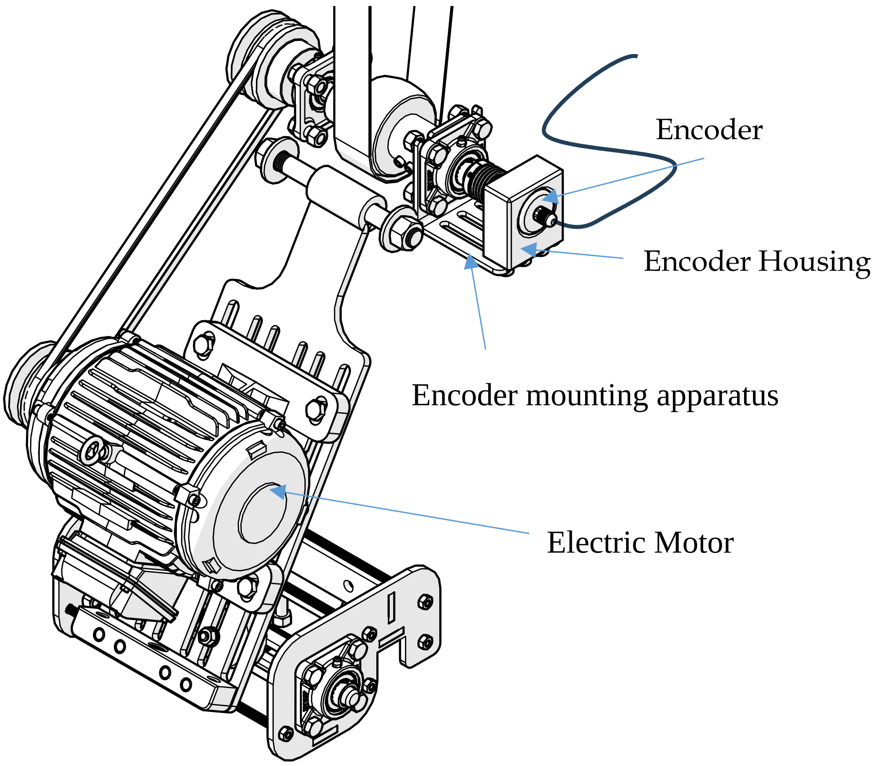


Figure 8. Mounting configuration of the rotary encoder on the main drive shaft

A 32-bit counter from the PLC registers was utilized for encoder-based cycle counting. These registers support bidirectional counting up to ±2,147,483,647. To accurately determine the number of rotations, a rotary encoder with a resolution of 40 pulses per revolution was employed. The counting limit of the test unit is defined in Equation (1).

$$\begin{aligned} Count\ limit &= 2147483647\ pulse * \frac{1}{40\,\frac{pulse}{rev}}; \\ &= 53\ 687\ 091\ rev \end{aligned} \tag{1}$$

On the basis of this limit, the machine can achieve over 53 million cycles, making it suitable for evaluating the fatigue behavior of nearly all metal types via this well-established system.

2.3. AC Motor Drive (VFD System)

A variable frequency drive (VFD) is a power electronics device designed to regulate the speed, torque, and direction of AC motors. Unlike conventional direct grid-connected motor systems, which operate exclusively at full speed and require mechanical braking, VFD technology enables precise digital control of motor speed profiles. In the test unit, a Delta VFD-M 5.5 kW drive was implemented for motor control (Figure 9).

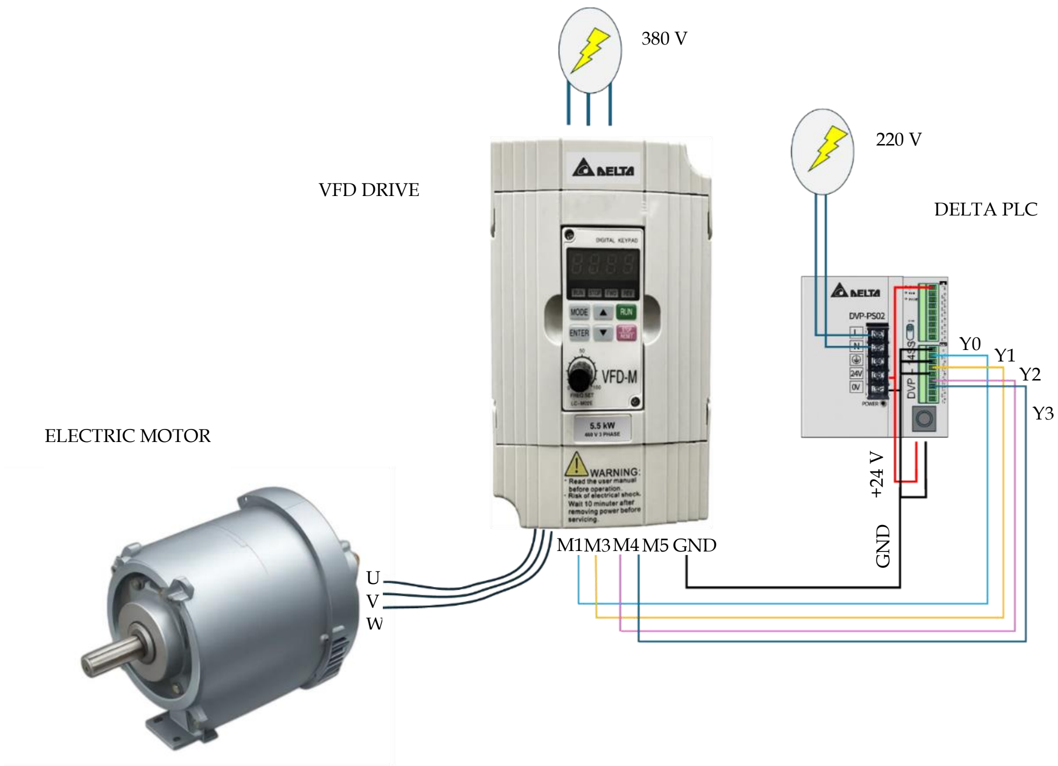
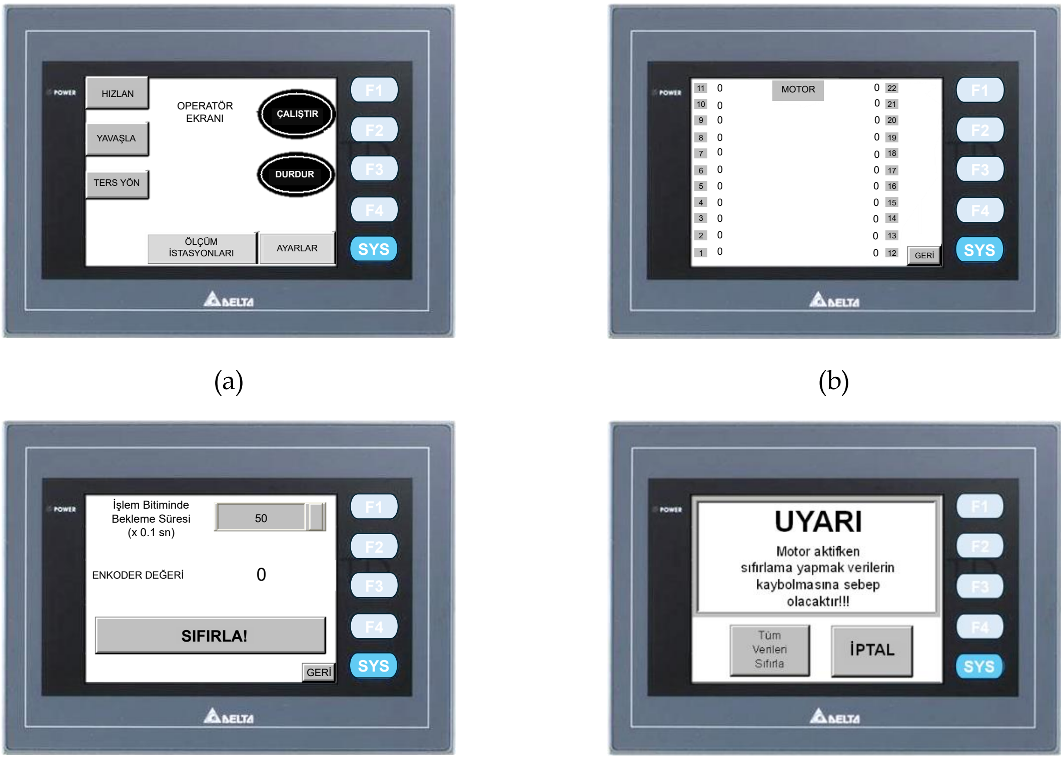


Figure 9. Schematic representation of the motor driver connection to the PLC and AC motor.

2.4. HMI Interface Panel

The human–machine interface (HMI) panel serves as the primary interaction point between the operator and the PLC controlling the fatigue testing system. Through this interface, operators can monitor system status, adjust parameters, and execute control commands in real time. The developed control system uses a Delta DOP-AS38-BSTD series HMI panel.



(a) (b) (c) (d)

Figure 10. Designed HMI control screens: (a) main control screen, (b) station-wide cycle count display, (c) encoder reset and preshutdown delay configuration, and (d) encoder reset confirmation screen.

The HMI panel is connected to the PLC via the RS485 industrial communication protocol, ensuring seamless data exchange. Its core functionalities include the following:

- **Start/stop control:** Operators can initiate or halt the test process via the touchscreen interface. The main control screen, designed for this function, is shown in Figure 10(a).
- **Parameter Configuration:** Users can reset encoder data and set automatic shutdown timing upon test completion. These adjustments are made through the HMI screens shown in Figures 10(b) and 10(c).
- **Real-time data monitoring**: The cycle count, sensor status, and system diagnostics are continuously displayed for operator oversight. The station data monitoring screen, designed for this purpose, is presented in Figure 10(b).

The integration of the HMI panel into the system enhances operator interaction, improving both the control and traceability of the fatigue testing process while optimizing operational efficiency. Figure 11 illustrates the overall connection architecture of the developed control system. The HMI panel enables operator interaction with the PLC, allowing external control of the system.

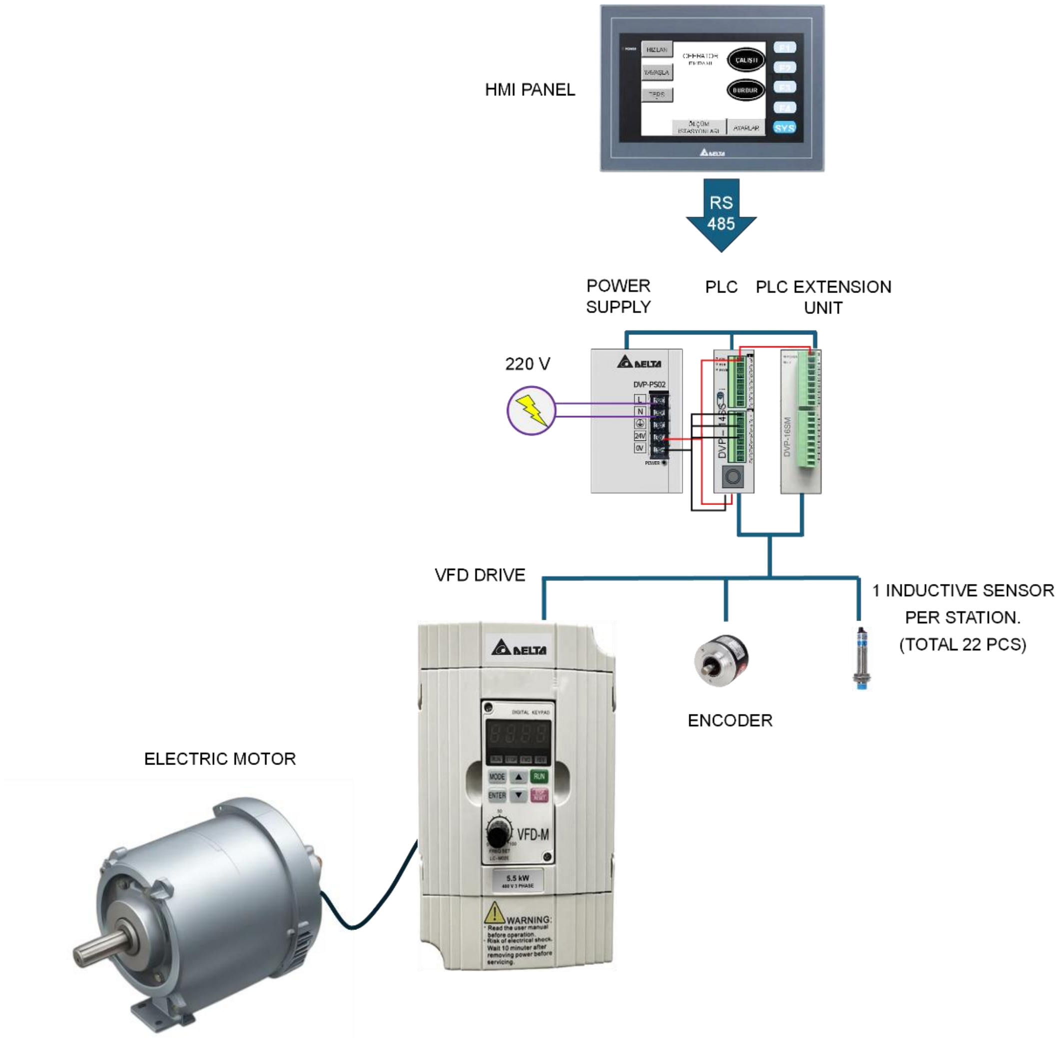


Figure 11. Control architecture comprising the HMI panel, Delta PLC, sensors, and motor drive.

The PLC derives power from a dedicated supply unit to ensure stable operation. Given the limited availability of digital input channels, a Delta DVP-16SM expansion module has been incorporated to increase the input capacity. The PLC continuously processes signals from 22 inductive sensors and a rotary encoder, facilitating real-time system surveillance and execution of critical control functions.

The output signals generated by the PLC are employed for parametric adjustments via a variable frequency drive (VFD). The VFD, in turn, interprets and executes these commands with high precision, modulating motor speed and direction accordingly.

Additionally, the HMI panel facilitates interaction with all system components via the PLC, enabling seamless data reading and writing operations. This architecture enhances operator control while optimizing process traceability and manageability. The complete operational framework of the system is outlined in the flow diagram presented in Figure 12.

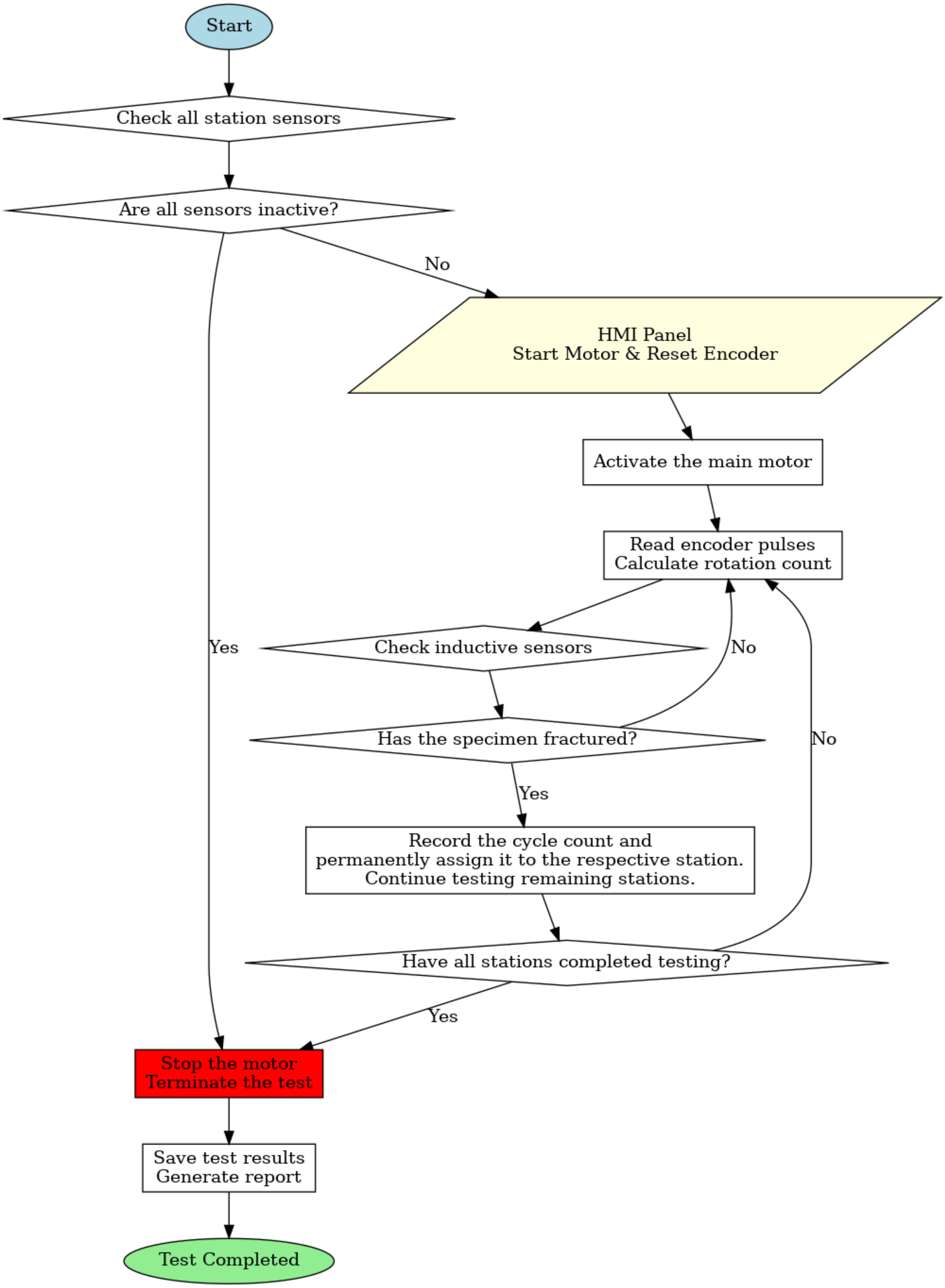


Figure12. Process flow chart

3. Results

3.1. Test specimens and preliminary fatigue test outcomes

AISI 304 stainless steel specimens were employed for preliminary fatigue assessments. The test samples were machined to precise geometrical specifications prior to testing, ensuring uniformity across all test stations. Figure 13 illustrates a pre-test specimen.

Figure 13. AISI 304 stainless steel specimen before fatigue testing.

After testing, clear distinctions were observed between fractured and unfractured specimens. The failed specimens exhibited visible surface cracks and complete breakage, whereas the surviving specimens endured cyclic loading within the endurance limit. The posttest conditions of these samples are presented in Figure 14.

Figure 14. Fractured and unfractured AISI 304 stainless steel specimens after the fatigue test and stress values applied to these specimens.

3.2. General observations from the S–N curve

To validate the accuracy and efficiency of the automated test system, preliminary fatigue tests were conducted on AISI 304 stainless steel specimens. The endurance limit was estimated on the basis of a set of seven stress levels recorded through a single trial per level. The resulting S–N curve is depicted in Figure 15.

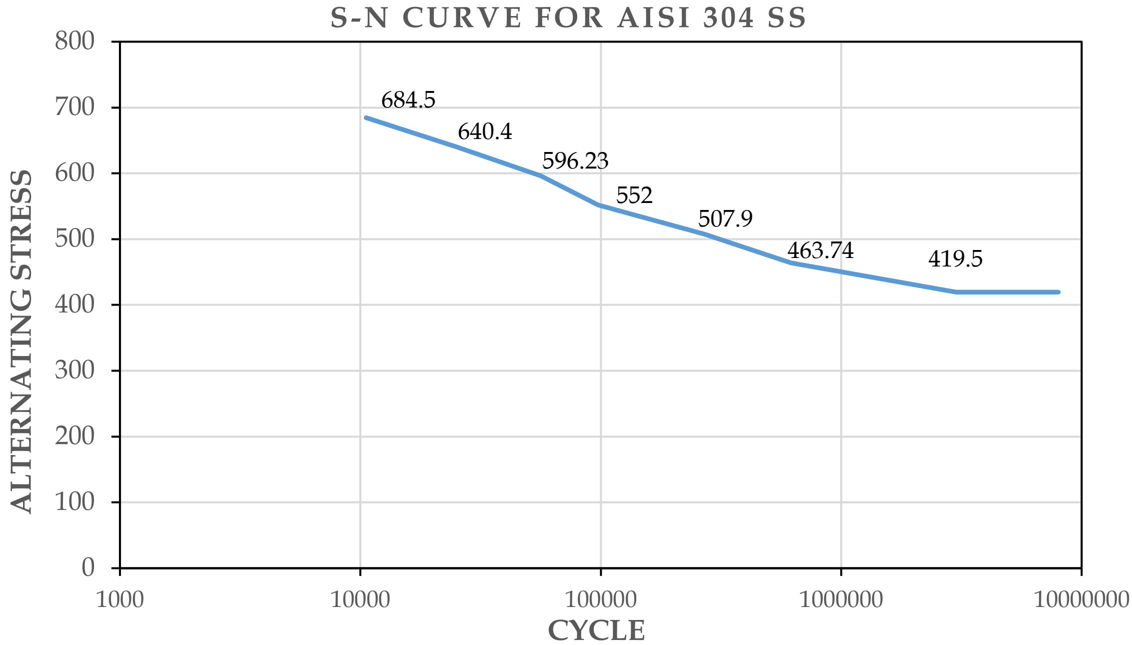


Figure 15. S–N curve for AISI 304 stainless steel, illustrating preliminary fatigue test results.

The results demonstrate a decreasing trend in fatigue strength with increasing cycle count, as expected in high-cycle fatigue scenarios. The endurance limit appears to stabilize at approximately 419.5 MPa, which is closely aligned with the literature. According to ASM Handbook Vol. 19 on Fatigue and Fracture, the endurance limit for 10% CW (cold-worked) AISI 304 stainless steel in rotating bending fatigue tests is reported to be 60 ksi (approximately 414 MPa)[11]. The similarity between the obtained endurance limit and the reference value suggests that the developed system provides accurate and reliable fatigue data. While these preliminary findings confirm the effectiveness of the PLC-controlled system, a more extensive statistical evaluation of fatigue behavior will be conducted in a subsequent study. The gathered data confirm that the developed system provides a reliable platform for fatigue testing with high repeatability and accuracy.

4. Discussion

To contextualize the developed system within the literature, Table 1 presents a comparative analysis of various rotating bending fatigue testing machines. The table summarizes key technical aspects, including machine configuration, load application mechanisms, and automation features.

Table 1. Comparative analysis of existing studies

Study	Application Type of Rotating Bending Fatigue	#Specimen	Sensor for Counting	Cycle Tracking Method	Controller Type	Data Visualization.
Ali et al. *[1]*	4-Point Bending	1	Proximity sensor	8-digit counter	No Controller was Used	2x16 Lcd screen
Kattimani et al. *[2]*	4-Point Bending	1	Proximity sensor	6-digit counter	No Controller was Used	6 digit LCD screen
Isakov et al. *[3]*	4-Point Bending	1	Inductive sensor	DAQ System	IMC Cronos PL2 Data Acquisition System	Not Specified
Yamamoto et al. *[4]*	Dual-Spindle Cantilever Type Rot. Bending Fatigue	4	Photo sensor	Not specified		A total of four 4×16 LCD screens were utilized, with one screen allocated for each sample.
Alaneme [5]	Cantilever Type Rot. Bending Fatigue	1	Proximity sensor	6-digit counter	No Controller was Used	6 digit Lcd screen

Continuation of Table 1

Study	**Application Type of Rotating Bending Fatigue**	**#Specimen**	**Sensor for Counting**	**Cycle Tracking Method**	**Controller Type**	**Data Visualization.**
R. Mali* et al. *[6]	**4-Point Bending**	**1**	**Proximity sensor**	**6-digit counter**	**No Controller was Used**	**2x16 Lcd screen**
Gentile et al. *[7]*	4-Point Bending	5	Encoder	PC-based cycle counting of each specimen is done separately by using encoder	PC-based system is used	
Çipil et al. *[8]*	4-Point Bending	1	Lap Counter sensor	10-digit counter	No Controller was Used	2x16 Lcd screen
Yamamoto et al. *[9]*	Dual-Spindle Cantilever Type Rot. Bending Fatigue	4	Not specified	Not specified		HMI screen
Chauhan et al. *[12]*	4-Point Bending	1	Not specified	Not specified	No Controller was Used	Not specified
M. Banavasi et al. *[13]*	4-Point Bending	1	Not specified	Not specified		Not specified

The comparison highlights the distinctive advantages of the proposed system, particularly in terms of automation efficiency, real-time failure detection, and high-precision cycle tracking. These aspects are critical for ensuring reproducibility in fatigue testing.

The key advantages of the developed test unit can be analysed as follows:

I. **Automation**: Previous studies by Ali et al. [1], Kattimani et al. [2], Alaneme [5], Chauhan et al. [12], Çipil et al. [8], and R. Mali et al. [6] did not incorporate any automated control mechanisms in their experimental setups; instead, they relied solely on manual operation. Similarly, Yamamoto et al. [4, 9] and M. Banavasi et al. [13] did not provide any details regarding the control systems used in their investigations. In contrast, Isakov et al. [3] opted for an IMC Cronos PL2 Data Acquisition System as an alternative to conventional controllers. Gentile et al. [7] advanced beyond these approaches by implementing a computer-based application, enabling the controlled testing of five specimens in real time. Despite these advancements, the present study represents a significant improvement by enabling the autonomous testing of 22 specimens through a PLC-controlled system. This approach not only enhances the efficiency and precision of the testing process but also ensures repeatability through an industrial-grade control system. Moreover, pioneering studies integrate an industrial PLC control system within this testing framework.

II. **Precision in cycle counting**: Conventional methodologies for cycle counting typically employ apparatuses such as proximity sensors [1-3, 5, 6], photo sensors [4], and mechanical lap counters [8], each of which registers a single count per revolution. In their study, Gentile et al. [7] implemented a more sophisticated approach by using individual encoders for each specimen to improve counting accuracy. The system developed in this study introduces significant advancements by incorporating an industrial-grade rotary incremental encoder (40 pulses/rev), ensuring superior precision in cycle tracking. This encoder, which is directly coupled to the machine's main drive shaft through a precision coupling mechanism, substantially enhances the measurement accuracy. By centralizing cycle counting across all machine stations, a robust, repeatable, and high-precision monitoring framework is established.

III. **Enhanced failure detection**: In manually operated systems utilizing mechanical counters, the counting process ceases automatically upon specimen failure. In contrast, digital counters without a dedicated controller rely on cycle signals generated by sensors to increase the displayed count on an LCD screen [1, 2, 5, 6, 8]. In such cases, when a specimen breaks, the counting process is typically halted by triggering a switch or similar mechanism to stop the motor. However, in multispecimen applications, a more sophisticated solution is needed to manage this issue effectively. In the control system developed, inductive sensors, which are conventionally used for cycle counting, have been adapted to detect specimen breakage. When a specimen breaks, the corresponding station cycle data are immediately fixed, and counting is halted for that specific station while the remaining stations continue uninterrupted. Moreover, testing and cycle counting continue uninterrupted at the remaining stations. This failure detection mechanism is continuously monitored by the PLC across all stations. Once all the specimens fail, the test autonomously ceases operation.

IV. **Advanced real-time monitoring:** The methods used for data visualization in experimental studies vary significantly. In conventional approaches that use digital counters, tracking measurement data is typically conducted through a small LCD screen [1, 2, 4-6, 8]. Gentile et al. [7] successfully implemented a computer-based software system in their test setup, which evaluated five specimens, enabling real-time monitoring of cycle count data for all specimens.In the present study, which incorporates an industrial control system, an advanced human–machine interface (HMI) panel was integrated into the system. This integration facilitates real-time data visualization for fatigue testing across 22 stations. Additionally, the HMI panel serves as an interface for configuring machine parameters and executing critical operational commands, thereby enhancing system functionality and user control.

V. **Endurance limit consistency**: The experimentally determined endurance limit (419.5 MPa) aligns closely with literature-reported values for cold-worked AISI 304 stainless steel. According to ASM Handbook Vol. 19, the endurance limit for 10% CW AISI 304 stainless steel in rotating bending fatigue tests is approximately 60 ksi (~414 MPa). This strong agreement confirms the accuracy and reliability of the developed test system[11].

4.1. Machine Performance Evaluation

The automation system demonstrated superior operational efficiency by eliminating manual intervention in failure detection and cycle counting. The use of high-resolution rotary encoders and inductive sensors ensures precise real-time monitoring, significantly reducing measurement errors. Moreover, the HMI provides an intuitive platform for data acquisition, making the testing process seamless and user friendly.

5. Conclusion

The comparative evaluation of the fatigue testing systems highlights the unique advantages of the developed PLC-controlled multistation rotating bending fatigue test machine. The system's automated failure detection, real-time cycle tracking, and precise endurance limit estimation distinguish it from conventional fatigue test setups. The findings confirm that this system offers a highly repeatable, accurate, and efficient fatigue testing method applicable to both academic research and industrial applications.

Future research will focus on integrating additional control algorithms to refine the accuracy of cycle tracking and extend the machine’s applicability to various material types.

Acknowledgements

The project was supported by the Scientific Research Project (BAP) Unit of Gaziantep University.
Project Number: HUBF.DT.22.03

Declaration of Contribution

Kürşad Göv and İbrahim Göv contributed to the idea of automation with PLC, the creation of the research methodology, and the writing of the article, and Abdurrahman Doğan contributed to the installation of the hardware components in the article and the installation of the necessary software.

Conflict of interest declaration

The author(s) of the article declare that there are no personal or financial conflicts of interest within the scope of the study.

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