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Research Article

Design and Testing of Twin-Disk Friction Torque Test Rig Using Quality Function Deployment and Function Analysis Methods Approach

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A B S T R A C T

Fatigue failure is the most common failure in gears besides failure due to friction and wear on the surface of the gear. To determine the failure phenomenon that occurs in gears, testing can be done on the gear, but the testing will be expensive. So it is necessary to test on a laboratory scale to understand the failure mechanism of gears by designing and making a twin-disk friction torque test rig. The design process used an approach model developed by the National Aeronautics and Space Administration (NASA) to maximize user desires with the Quality Function Deployment (QFD) method approach and to be able to meet technical needs with the Function Analysis Methods (FAM) approach. The results of the design that has been done provide the design of a twin-disk friction torque test rig that has met user needs and, from the test results of the test rig's performance, has met the expected functional requirements as a test tool. From the results of tests that have been carried out on changes in load and slip ratio, the friction torque will increase with increasing load and slip ratio. While the friction coefficient will decrease with increasing load, and vice versa, with increasing slip ratio, the friction coefficient will increase. The data generated from the measurements are consistent, so the test rig can be used to measure friction torque.

1. INTRODUCTION

Fatigue failure is a common failure in machine components such as gears, where two tooth surfaces interact with each other under repeated and continuous impact loads, causing material degradation of the gear contact surfaces [1], [2]. Furthermore, friction and wear failure can occur between two tooth surfaces of gears in contact and moving relative to each other, under both adequate and limited lubrication conditions, which are key factors affecting the performance and service life of these gear components [3]. The phenomenon of fatigue, friction, and wear-induced gear failure needs to be investigated to understand the failure mechanisms. Therefore, experimental testing is needed to understand the fatigue, friction, and wear failure mechanisms on the gear surfaces. Direct testing of gears is often hampered by the high cost and complexity of the testing process. Variations in operating conditions such as changes in load, rotational speed, and lubrication type complicate direct fatigue, friction, and wear testing. Therefore, a simpler and more economical alternative method is needed to study the friction and wear mechanisms in gears so that it is possible to understand the failure mechanisms of gears more effectively and efficiently by making a twin-disk friction torque test

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rig on a laboratory scale. Before the friction test rig is made, it is necessary to carry out a design process and then test the performance of this twin-disk friction torque test rig.

The design process is a systematic approach used to design tools or machines in a structured and planned manner [4]. The National Aeronautics and Space Administration (NASA) have developed steps in the engineering design process [5]. According to NASA, the design process is an iterative and gradual process that begins with defining the problem and its constraints, followed by brainstorming and prototyping solutions, and then testing, evaluating, and refining the design. This engineering design process includes identifying objectives, researching solutions, selecting the best approach, building and testing prototypes, and then refining based on results and feedback. The main goal of this approach is to produce a design that not only meets technical requirements but also considers aspects of efficiency, reliability, and sustainability.

One of the most important steps in the design process is defining the problem by identifying user needs. User wants and needs are the problems being addressed or goals being achieved with the product. However, wants and needs are often vague, subjective, conflicting, and may not be explicitly stated or easily observed, and may change over time or vary across contexts and situations. Therefore, product designers need effective methods and tools to explore, analyze, prioritize, and validate user wants and needs. Quality function deployment (QFD) is a systematic method for translating customer needs into the design and production requirements of a specific product or service [6]. It uses a structured approach, often visualized through a house of quality matrix, to ensure that customer feedback, or the "voice of the customer," is integrated throughout the development process. The house of quality (HOQ) is a tool that helps designers connect and validate the relationship between user needs and design specifications or engineering requirements. The HOQ is a matrix that shows the relationship between customer desires and how the product can meet those desires. The ultimate goal is to build high-quality products and processes that satisfy customers while increasing efficiency and reducing rework.

To meet the technical requirements of the twin-disk friction torque test rig, functional analysis methods were used. Functional analysis methods for machine design involve breaking down the machine into its core functions, which can then be used to develop the product structure and identify potential improvements [7]. Key methods include the functional analysis systems technique (FAST), which breaks down functions into smaller elements for in-depth investigation, and the functional analysis diagram (FAD), which visually represents the relationships between components. Other approaches include the use of "black box" models to analyze inputs and outputs and the APTE method, which uses diagrams such as the octopus diagram to identify functions [8].

In this paper, the design and testing of a twin-disk friction torque test rig will be carried out. The needs of this twin-disk friction torque test rig allow for control of parameters such as speed, load, slip ratio, rotation cycle, and lubrication conditions so that friction characteristics and wear rates can be measured accurately. Moreover, the twin-disk friction torque test rig enables investigators to quantify frictional torque generation, in addition to determining friction coefficients and wear characteristics, during the evaluation of diverse materials subjected to varying operational parameters. This methodology provides researchers with a comprehensive assessment of material performance under authentic service conditions. The approach taken for the design process in order to maximize user desires is the quality function deployment (QFD) method approach and to be able to meet technical needs with the function analysis methods (FAM) approach.

2. METHODOLOGY

In the design process of the twin-disk friction torque test rig, the design process involves several main interrelated stages based on the design process developed by NASA to ensure optimal and functional design. The stages or steps that are very important in the design process of this twin-disk friction torque test rig: First is identification of needs. Identification of needs is the initial step in the design process that aims to determine the main parameters of the test based on the research objectives. Important parameters that are considered include the slip ratio between the disks, maximum rotation speed, maximum normal load, and type of disk material, as well as measurement parameters such as friction coefficient and material wear level. The slip ratio is a key parameter because it describes the difference in relative speed between the disks in rolling-sliding contact conditions. In addition, this identification of needs also includes determining the specifications of the tool to ensure its suitability for realistic test conditions. The second aspect pertains to the technical specifications. In the technical specifications stage, predetermined parameters are used to formulate detailed tool specifications. These technical specifications include the capacity of the single drive motor used to rotate the test disc, variations in pulley diameter to produce the desired slip ratio, a normal load mechanism for flexible load regulation, and a high-accuracy torque sensor mounted on the transmission shaft. This torque sensor functions not only to measure torque but also to assist in analyzing the working system of the two simultaneously rotating discs made of different materials. Third is the preliminary design concept. Before starting 3D design using software such as SolidWorks, a preliminary design concept is created to provide an overview of the tool configuration and layout of the main components. This concept includes a simple manual or digital sketch showing the position of the drive motor, pulley-belt transmission system, test disc, and normal load mechanism, as well as the torque sensor and rotary encoder. The purpose of this preliminary design concept is to facilitate the visualization process before entering the more detailed design stage. Fourth is material selection. Material selection is based on superior mechanical and tribological properties to ensure the tool's durability under harsh operating conditions. AISI 1045 steel was chosen as the test disc material due to its high mechanical strength and resistance to friction and wear. In addition, hollow steel is used for the support frame due to its structural strength, while S45C steel is selected for the transmission shaft to ensure rigidity and resistance to dynamic loads. Lastly is design evaluation and optimization. Evaluation is conducted on the initial design to ensure that the tool meets the technical specifications and functions according to the test objectives. The evaluation process involves manual analysis of the configuration of key components based on technical data, such as the drive motor capacity, pulley-belt transmission ratio, and load distribution on the support frame. If deficiencies are found in the initial design, optimization is carried out by improving the component configuration or replacing certain materials to increase the tool's efficiency and accuracy.

2.1. Functional Requirements

Functional requirements are the requirements that must be met in the manufacture of test equipment, based on an evaluation of the weaknesses of existing equipment. The functional requirements include (a) accuracy of friction torque measurement, (b) adequate load capacity, (c) ease of operation, (d) cost efficiency, and (e) compatibility with various types of materials.

2.2. Function Analysis Methods (FAM)

The Function Analysis Method (FAM) is a method for systematically describing the main functions of a system. In the twin-disk friction torque test rig, the FAM describes the functional flow, from the drive, transmission, test material, and load control to torque and output measurements. Figure 1 below shows the FAM for this system.

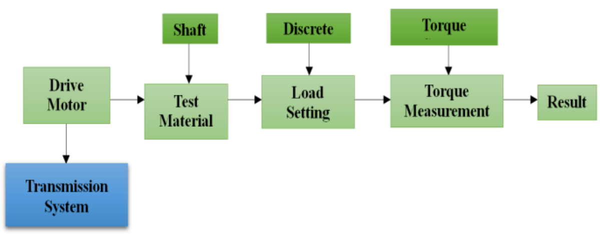

Figure 1. Methodological approaches for functional evaluation of twin-disc friction test rig.

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2.3. *Design Requirement and Objective Tree*

Design requirements that include technical specifications of the twin-disk friction torque test rig, such as torque measurement, slip ratio setting, and surface wear measurement. QFD is used to connect customer needs with engineering characteristics, as well as determine priorities in the design of the twin-disk friction torque test rig based on the analysis of customer needs and the required technical characteristics. The QFD of the twin-disk friction torque test rig design can be seen in Figure 2.

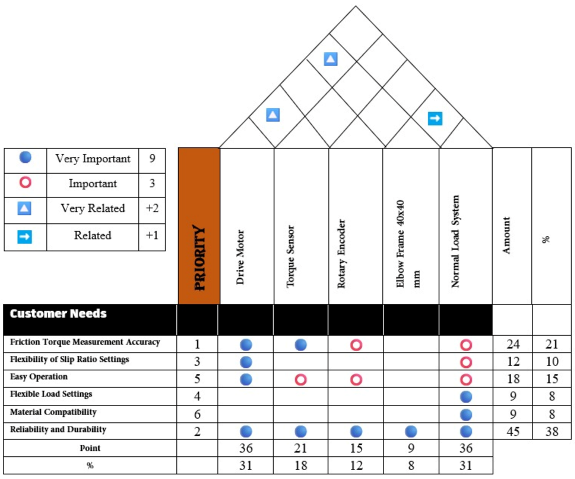

Figure 2. The QFD of the twin-disc friction torque test rig

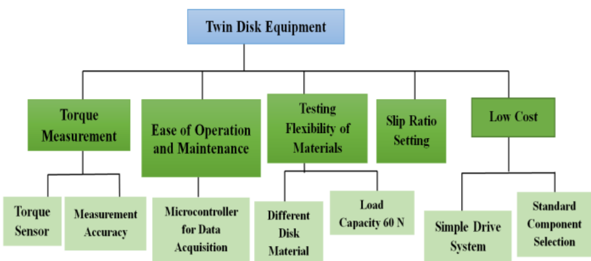

Figure 3. The objective tree of the twin-disc friction torque test rig

The objective tree method is used to map the main objectives and sub-objectives in designing a twin-disk friction torque test rig, describing the relationship between the test objectives and the design elements that support them, as shown in Figure 3.

Table 1. Morphology chart methods

Criterion	Alternative Design 1	Alternative Design 1	Alternative Design 1
Number of electric motors	One motor	Two motors	One motor
Drive system	Pulley and belt	Two independent motors	Pulley and chains
Slip ratio setting	Adjusted by changing the diameter size of the pulley	Each motor has a different speed	Adjusted by changing the gear diameter size
Torque measurement	Torque transducer for measuring torque	Torque transducer for measuring torque	Torque transducer for measuring torque
Testing flexibility	Limited to small slip ratio variations	Flexible, wider slip ratio variation	Limited to small slip ratio variations
Test accuracy	Quite accurate, suitable for basic simulations	More accurate, simulates more realistic testing	Quite accurate, suitable for basic simulations
Cycle data collection	Rotary encoder to measure the number of shaft rotations	Rotary encoder to measure the number of shaft rotations	Rotary encoder to measure the number of shaft rotations
Design complexity	Simple and cost-effective	More complex	Simple and cost-effective
Testing application	Suitable for basic and simple testing	Suitable for testing with larger slip ratio variations	Suitable for basic testing with easy slip setup

2.4. *Morphological Chart Methods (MCM)*

The morphological chart method (MCM) is an approach used to compare several alternative designs based on relevant technical criteria. In this context, MCM is applied to evaluate three different design concepts, considering operational efficiency, system reliability, parameter adjustment capability, measurement accuracy, and applicability in various test scenarios. With this method, each design is analyzed objectively, which helps in more informed decision-making. The following is presented in Table 1: a comparison of alternative designs that illustrates the evaluation of the three design concepts.

2.5. *Generating Alternative*

This section will generate alternative designs for a Twin Disk friction torque test rig, developing various options for the drive system, slip ratio settings, and torque and wear measurement methods. Each design alternative considers operational ease and the test rig's ability to accurately test materials. These designs will be evaluated based on criteria such as measurement accuracy, setup flexibility, and the test rig's compatibility with various materials.

From the results of the MCM method above, 3 alternative designs were generated, as in Figure 4, which consist of: **Alternative Design 1**: In this design concept, one motor is used to drive both discs through a crossed belt drive transmission system, ensuring that both discs rotate in opposite directions. This motor rotates both discs using pulleys and belts of different sizes to regulate the slip ratio between the two discs. The slip ratio is regulated by changing the size of the pulley, thus allowing for variations in rotational speed without the need to change the speed of the motor. This system offers a simple and cost-effective design because it only uses one motor. A torque transducer is installed to measure the torque generated by friction between the discs, providing accurate measurement data. A rotary encoder is used to measure the number of shaft revolutions, ensuring accuracy in the measurement of rotational speed. **Alternative Design 2**: In the alternative design concept using two motors, each motor drives one disc independently. This design provides more precise control over the slip ratio between the two discs, allowing for regulation of the speed of each motor to create more realistic test conditions. With two motors working independently, the speed difference between the two discs can be adjusted more flexibly, providing a wider variety in test simulations.

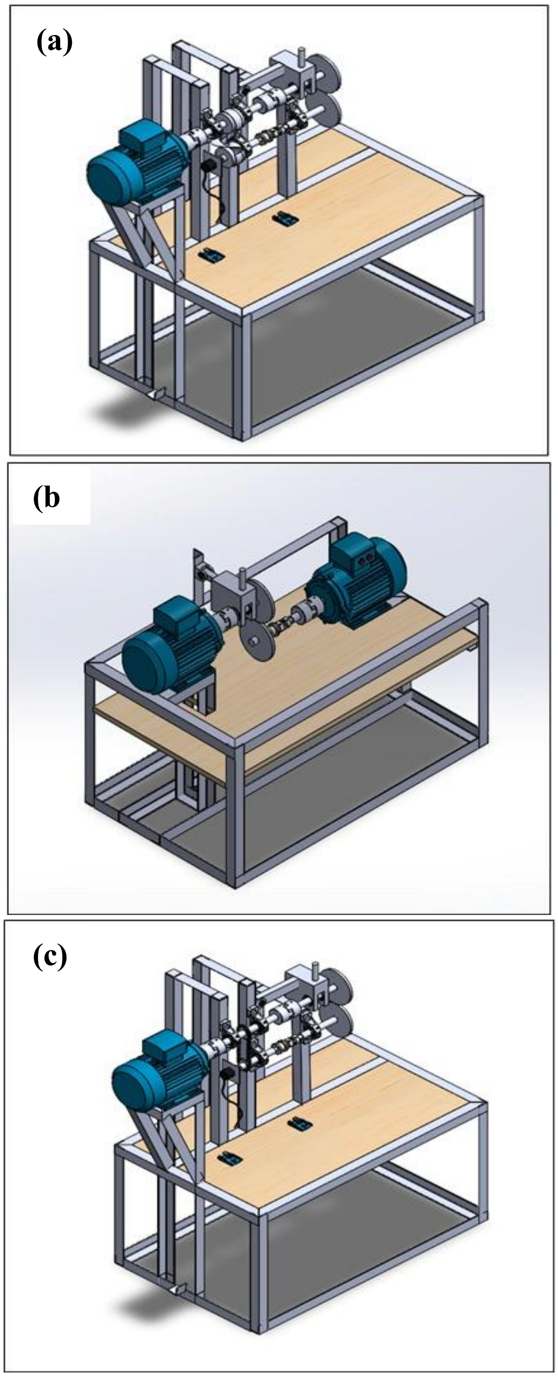

Figure 4. Generating alternative design (a) alternative design 1, (b) alternative design 2, and (c) alternative design 3.

This drive system is more complex but provides higher accuracy in creating friction that matches real-world conditions, such as in clutch or brake systems. A fixed torque transducer is mounted on a fixed spindle, which measures the torque resulting from the speed difference between the discs. This design concept is more suitable for applications that require more varied slip ratio testing and is more realistic in material testing simulations. **Alternative Design 3**: In this design concept, a single motor is used to drive both discs through a transmission system using gears and chains. This motor rotates both discs in the same direction using a transmission system consisting of gears and chains of different sizes to regulate the slip ratio between the two discs. The slip ratio is adjusted by changing the size of the gear or chain, allowing for variations in rotational speed without the need to change the speed of the motor. This system offers a simple and cost-effective design because it uses only one motor. A torque transducer is installed to measure the torque generated by friction between the discs, providing accurate measurement data. A rotary encoder is used to measure the number of rotations of the spindle, ensuring accuracy in the rotational speed measurement.

2.6. Weighted Objective Matrix (WOM)

Once the design concept is developed, the next step is to select the best design using the weighted objective matrix (WOM). This method helps us compare various design alternatives by assigning a value to each option based on predetermined criteria. With WOM, we can weigh each criterion to determine the most appropriate design. This method is often used to assist decision-making involving design choices or alternatives. The main components of a WOM include selected criteria, criterion weights, assessments, and scores.

2.7. Determining Dimensions

In the manufacture of a twin-disk friction torque test rig, several calculations need to be performed to determine the correct component dimensions and suit the needs of the tool. This dimensional calculation aims to ensure that each component used can function optimally and support the overall performance of the tool. The calculations performed include: **Motor Power Calculation**: To determine the motor power required to drive the disc at the desired speed and the resulting load, the calculation is carried out based on the required torque and the rotational speed of the disc. **Transmission System**: To determine the speed difference between the two discs, the slip ratio calculation is carried out by adjusting the diameter of the pulley or gear. This calculation ensures that the desired slip ratio is achieved, which regulates the rotational speed between the driving disc and the driven disc. Utilizing the determined slip ratio, one must identify and implement the suitable pulley or gear dimensions to attain the requisite velocity differential, thereby ensuring optimal functionality of the transmission system in accordance with the operational parameters of the twin-disk tribological testing apparatus. **Torque Sensor and Rotary Encoder**: Calculation of the torque and rotational speed measurement range is carried out to ensure the tool measures accurately within the appropriate range. Select a torque sensor that can handle the maximum torque of the motor without losing accuracy and ensuring optimal performance. Additionally, choose a rotary encoder capable of measuring the rotational speed of the discs with high accuracy, ensuring that both sensors provide accurate data as required. **Load System**: The normal load applied to the twin disc tribology tester is 50 N, which simulates realistic contact pressure between the discs.

2.8. Performance Test

The performance test of the test rig is to assess whether the twin-disc friction torque test rig system that has been created is able to function properly and in accordance with its design objectives. Several aspects tested include: calculation of friction torque and friction coefficient. The dynamic torque sensor is used as the main sensor to measure the torque that occurs in the twin-disc friction torque test rig system. This sensor works by converting the amount of mechanical torque on the rotating shaft into a digital signal that can be analyzed electronically. The torque value obtained is used as the basis for calculating the friction force through a mechanical approach. The relationship between the torque value and the friction coefficient is an important aspect in this study, because the friction coefficient is one of the main parameters analyzed. In addition, the rotary encoder is a sensor that functions to measure the amount of rotation that occurs on the shaft. This sensor works by detecting changes in angular position and converting it into an electrical signal that represents the amount of rotation. The rotary encoder is used to record the number of shaft rotations, which is the main reference in this study and will be linked to the torque value and the calculation of the friction coefficient.

3. RESULTS AND DISCUSSION

3.1. Decision Matrix

In the initial stage of designing the twin-disk friction torque test rig, three alternative designs were developed and evaluated based on technical and practical parameters. The evaluation was conducted using the weighted objective matrix (WOM) method, with the design criteria used including ease of manufacture, low cost, frame stability, ease sensor integration, and modification flexibility. Each alternative design was scored on each criterion based on the technical assessment, and then the total weighted score was calculated. The evaluation results are presented in Table 2.

Table 2. Assessment of design alternatives using the WOM method

Criterion	Weight (%)	Design 1	Design 2	Design 3
Easy to make	25	5 5x25 = 125	4 4x25 = 100	3 3x25 = 75
Low cost	20	4 4x20 = 80	3 3x20 = 60	5 5x20 = 100
Frame stability	20	5 5x20 = 100	4 4x20 = 80	3 3x20 = 60
Ease of sensor integration	15	4 4x15 = 60	4 4x15 = 60	3 3x15 = 45
Flexibility of modification	20	4 4x20 = 80	3 3x20 = 60	3 3x20 = 60
Total Weighted Score	**100**	**445**	**365**	**345**

Based on the evaluation results, Design 1 was selected as the final design because it obtained the highest weighted score, namely 445. This design demonstrated advantages in terms of frame stability and ease of sensor integration, while maintaining cost efficiency and ease of fabrication. With these advantages, Design 1 was deemed the most feasible to be realized in the manufacturing and testing phase of the twin-disk friction torque test rig.

3.2. Main Component and Sensor Specifications for Data Acquisition

In the design and testing process of the twin-disk friction torque test rig, component selection was carried out carefully based on technical requirements, market availability, and efficiency in system integration. The main components used include the drive motor, transmission system, shaft, test disc, and support frame. Each component has its own specifications and functions that support the performance of the tool in measuring frictional torque and visualizing surface wear due to frictional forces. The drive motor used is a three-phase electric motor with a power specification of 1.5 kW (2 HP) and a nominal speed of 1400 rpm. This motor is capable of producing sufficient torque to withstand frictional forces due to the speed difference between the two discs (slip ratio), as well as providing stable and consistent rotation of the lower disc during the testing process. The transmission system uses pulleys made of high-strength steel material, which is fabricated through a precision turning process. This process aims to ensure rotational balance and minimize vibration during the test rig's operation. The pulleys are connected by a flat belt that allows for efficient and stable power transmission between the shafts. The upper and lower shafts are made of S45C steel, using a turning process to obtain precise dimensions and compatibility with components such as bearings and pulleys. Key slots are also made to ensure the pulleys are locked properly. The lower shaft functions to rotate the disc, while the upper shaft supports the static disc and receives the load during testing. The test discs in this system are made of AISI 1045 steel with a diameter of 200 mm, as referenced in previous research. This material was chosen because of its strength and resistance to friction, as well as its ability to show signs of material wear visually during testing. One disc is fixed (static), while the other is rotated by the transmission system. The main frame structure is made of 40 × 40 mm L-angle iron, which is cut and

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welded to form a sturdy support frame. This frame supports the entire system, including the motor, transmission, shaft, disc, and sensors. Frame stability is crucial for maintaining the consistency of test results and avoiding interference from vibrations during operation.

The electronic system of the twin-disk friction torque test rig integrates several key components for data acquisition and visualization. The torque sensor used is the dynamic torque sensor DYN-200, which has an RS485 output and is connected to the Arduino Uno via a MAX485 converter module. This sensor functions to measure the frictional torque that occurs during testing and transmits the data digitally. In addition, the system is equipped with a rotary encoder that is used to record the Wiring system slip ratio calculation. Both the rotary encoder and the torque sensor are connected to the Arduino Uno as a data processing center, which then displays the readings directly via an I2C LCD as a visual interface. For digital data recording and further analysis, the system is integrated with PLX-DAQ, allowing real-time data transmission to Microsoft Excel.

3.3. *System Configuration and Integration*

To support the real-time friction torque data acquisition process, the system for this test uses a DYN-200 torque sensor connected to an Arduino Uno via an RS485 communication module (MAX485). Figure 5 shows the wiring configuration between the sensor, the converter module, the Arduino Uno, and the connection to a 24V DC power supply. This circuit is designed so that digital signals from the sensor can be sent stably to the microcontroller, then displayed and recorded directly via the PLX-DAQ software on a laptop. The design of component placement on the twin-disk friction torque test rig frame is arranged by considering mass distribution, structural stability, and ease of access to the sensor and electronic system to support maintenance efficiency and reliability during the testing process.

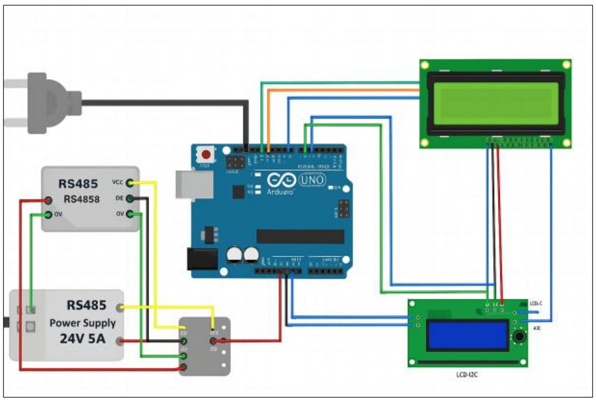


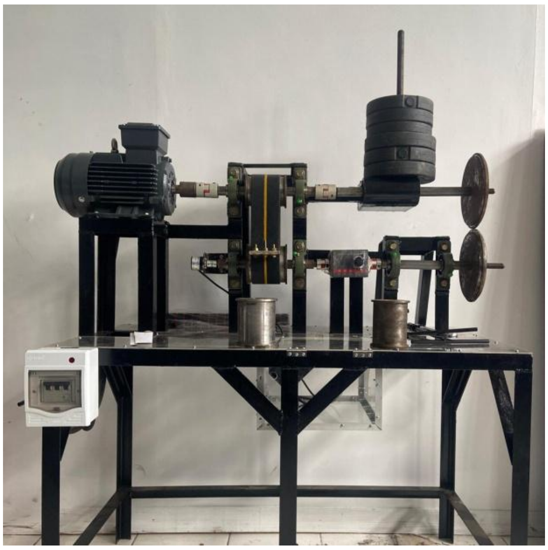
Figure 5. Wiring system

Based on the visual design and actual construction, the following are the placement and primary functions of each component. The three-phase electric motor is mounted horizontally on the upper left side of the frame on a sturdy steel mount. This position allows for efficient power transmission to the main drive system while maintaining a stable center of gravity. Two pulleys are mounted on the upper and lower shafts, respectively. They are connected by a flat belt, which serves to transmit rotation from the motor to the lower shaft and then to the upper shaft. The use of a flat belt was chosen because of its large contact area, resulting in smoother torque transmission and minimal slippage. The lower shaft is mounted horizontally parallel to the motor and is supported by two precision-machined bearing mounts. This shaft acts as the primary drive of the lower disk during testing. The upper shaft is positioned vertically directly above the lower shaft, forming a direct contact system between the upper and lower disks. The load housing attached to the upper shaft can be modularly loaded to simulate normal forces during testing. The DYN-200 type torque sensor is mounted on the lower shaft, between the test disk and the bearing seat. This location allows direct friction torque measurement with minimal mechanical interference and simplifies wiring to the control system. The electronic system is controlled by an Arduino Uno connected to the sensor via the MAX485 communication module. The entire control system is housed in a small electronic box placed on the bottom or side of the frame, protected from vibration and heat from the motor. The 24V 5A power supply is mounted on the back or bottom side of the frame. Cable management is done using ducting and cable ties to maintain neatness and system security and avoid interference with mechanical parts.

3.4. Fabrication and Assembly of Twin Disk Test Equipment

The upper and lower shafts are made of S45C steel and are machined to achieve dimensions suitable for the flexible coupling and pulley components to be installed. Keyways are also machined on specific shaft sections to ensure a strong connection and prevent slippage during torque transmission. The machining process is carried out with high precision to maintain rotational alignment and minimize vibration in the system during testing. The pulleys are made of solid aluminum and are precisely machined to produce a cylindrical shape and keyholes for locking the shafts. This process ensures that the pulleys are firmly attached and rotate stably during operation. The iron pipe undergoes internal machining processes to modify the bearing's external diameter, thereby guaranteeing proper and reliable positioning within the pipe assembly. Furthermore, snap ring grooves are made on the inside and outside to lock the bearings in place to prevent them from shifting during operation.

The main frame of the test equipment is made from L-shaped angle iron that is cut to the required size and then assembled with welded joints to form a strong and stable support structure. The motor is mounted on the frame using an L-shaped angle iron mount. Power from the motor is transmitted through a flexible coupling that is directly connected to the lower shaft, then continues to the pulley and flat belt transmission system with adjustable tension. The shaft is mounted horizontally on the frame using a seat-type bearing to maintain rotational stability. The end of the shaft is machined so that the test disk can be installed and locked precisely using Ø16 mm locking bolts. The two disks are placed on the upper and lower shafts as a friction contact pair according to the test requirements. The DYN-200 torque sensor is integrated with the Arduino Uno via the RS485 communication module (MAX485). Torque data is sent serially to a laptop using PLX-DAQ and displayed in real-time in Microsoft Excel. This system allows for direct torque monitoring during the test process. Figure 6 shows the front and side views of the twin disk test equipment after installation.



(a) Front view

(b) Side View

Figure 6. (a) Front view and (b) side view of twin disk-friction torque test rig

3.5. Performance Test of Twin Disk Test Equipment

Testing was conducted to verify the performance of the twin-disk friction torque test rig in reading the frictional torque due to contact between the disk surfaces given a certain load. The main objective of

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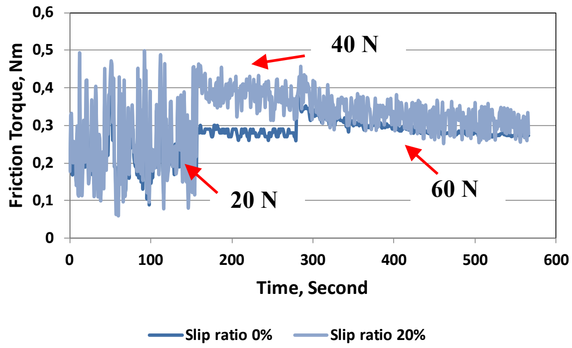
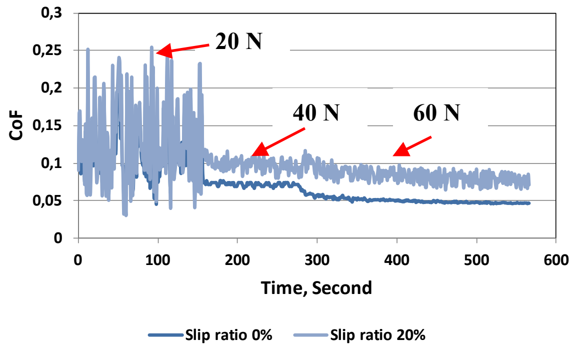
this test is to ensure that the sensor system is able to work accurately and stably when the load is applied under different test conditions. The test method is carried out by applying a gradual load ranging from 20 to 60 N vertically on the upper shaft, which presses the upper test disk against the lower test disk. The test was carried out in two slip ratios, namely: (a) 0% slip ratio, where both disks rotate together without a difference in rotational speed (relative static conditions), and (b) 20% slip ratio, where there is a difference in rotational speed between the disks to simulate dynamic friction conditions. Each variation in load and slip ratio was recorded to measure the frictional torque that occurs using a DYN-200 torque sensor. Data was sent to PLX-DAQ and recorded in real-time for further analysis to determine the friction coefficient.

Figure 7 is a real-time graph of frictional torque versus time for three types of loads at two slip ratio conditions (0% and 20%). The figure shows the change in frictional torque during the test and the differences in frictional torque and CoF due to variations in slip ratio and load. At a load of 20 N, there were significant torque fluctuations at both slip ratio conditions. At a slip ratio of 0%, the torque pattern appeared more random and unstable, while at a slip ratio of 20%, fluctuations persisted but tended to be slightly more regular. This indicates that at light loads, the surface contact tends not to be fully stable, and the influence of slip on frictional stability is not yet dominant. This is because the contact is very small, resulting in high vibration due to the low system stiffness [9].

At a load of 40 N, the torque pattern showed a stable and increasing trend, especially in the no-slip condition (0%). Torque at 0% slip showed a consistent upward trend, indicating an increase in frictional force over time. Meanwhile, at a slip ratio of 20%, the torque remained lower with greater fluctuations, indicating frictional variations due to differences in relative speeds between the contact surfaces. This begins to demonstrate the significant effect of slip on friction behavior.



(a) Friction torque



(b) CoF

Figure 7. Performance test of twin disk test equipment with different load dan slip ratios (a) friction torque and (b) CoF

At a load of 60 N, the system exhibits greater stability. At a slip ratio of 0%, the friction torque exhibits a constant pattern approaching its peak value, indicating that the surfaces have reached full contact. Conversely, at 20% slip, although the torque value remains below 0% slip, fluctuations occur repeatedly. This indicates that the influence of slip becomes more significant at higher loads, with more dynamic friction due to increased contact pressure and relative friction velocity.

The effect of load on friction torque can be seen from Figure 8, where the friction torque increases with the increase in the applied load, as well as the slip ratio; the higher the slip ratio, the more the friction torque will increase. At the same load, the 20% slip condition consistently produces a higher friction torque than the no-slip condition. This indicates that the difference in rotational speed between the discs contributes significantly to the increase in friction torque. The friction coefficient (μ) is inversely proportional to the load. However, it is important to note that at each load level, the friction coefficient value at 20% slip is greater than that at 0% slip. The consistency of the results in both graphs provides validation of the measurement system and the performance of the tool, which successfully detects and records changes due to variations in load and slip accurately [10], [11].

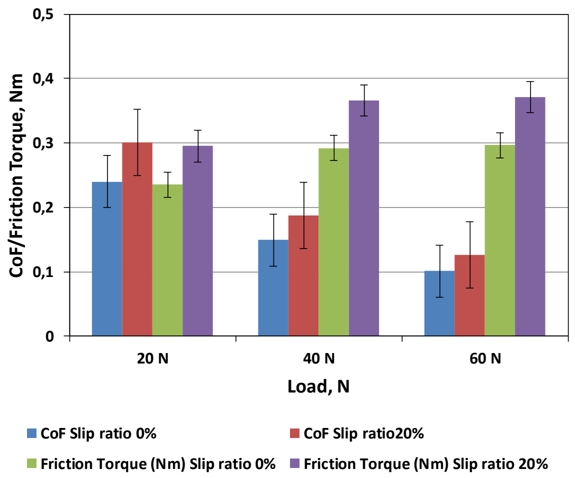


Figure 8. Friction torque and CoF for different loads and slip ratios

The DYN-200 sensor demonstrated stable and responsive reading performance to increasing loads throughout the test. The resulting torque data was consistent with the applied load conditions and showed a logical trend. No significant delays were observed in data readings, and the received signal was clear of noise, indicating the acquisition system was operating reliably.

4. CONCLUSION

Based on the design and testing results, several conclusions can be drawn:

a. The twin-disk friction torque test rig was successfully designed and manufactured to specifications capable of testing frictional torque, friction, and surface wear. This device's design allows for variations in load and slip ratio and is equipped with sensors that can record torque and cycle data in real time. The resulting data is consistent and logical, thus supporting the validity of the measurement system and the overall performance of the device.

b. Based on the test results for changes in load, frictional torque was shown to have a proportional relationship with the load magnitude; the greater the applied load, the greater the frictional torque produced. The slip ratio showed a significant effect on frictional torque, with a 20% slip ratio producing higher frictional torque compared to the no-slip condition (0%). This finding indicates that differences in rotational speed between the discs play a significant role in improving torque transfer capability. Friction coefficient testing showed that the friction coefficient is inversely proportional to the load, but the friction coefficient value at 20% slip remained higher than at the no-slip condition (0%).

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