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Design and Experimental Analysis of a Low Cost Test Bed for Motorcycle Disc Brake Energy Performance

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Abstract

This study aims to design, fabricate, and experimentally evaluate a low-cost test bed for assessing the energy performance of motorcycle disc brake systems. The prototype was developed to provide a practical laboratory-scale platform for studying braking energy characteristics, disc geometry variations, and friction material behavior under controlled conditions. The research applied a design and development methodology using the concept screening method to select the most efficient configuration based on manufacturability, cost, and operational simplicity. The final model was designed using SolidWorks and fabricated by combining commercial components and machined raw materials. Experimental tests were performed using a three-phase electric motor at variable operating frequencies of 10, 20, 30, and 40 Hz, with a constant lever pressure of 4.409 Nm. The electrical energy generated during braking was measured to evaluate energy conversion performance. The results indicated that higher motor frequencies (10–30 Hz) produced greater current, voltage, power, and braking energy outputs, with a maximum recorded energy of 9,718.4 J at 30 Hz. However, at 40 Hz, a decline in braking efficiency was observed due to dynamic instability at higher rotational speeds. This study demonstrates the feasibility of a simple, affordable, and effective disc brake test bed capable of replicating real braking conditions. It offers a valuable tool for analyzing braking energy behavior and serves as a foundation for future research on regenerative braking systems for lightweight electric vehicles.

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INTRODUCTION

Motorcycles are among the most prevalent means of transportation, especially in developing nations, because they offer low operating costs, fuel efficiency, and high mobility in congested areas (Detter, 2015; Ehebrecht et al., 2018; Pojani & Stead, 2015). In Indonesia, for instance, more than 120 million motorcycles were officially registered in 2016, illustrating the essential role of this vehicle category in everyday commuting and small-scale logistics. However, the increasing number of motorcycles correlates with a higher incidence of road accidents, many of which are associated with the malfunction or inefficiency of braking systems (Rizzi et al., 2015; Savino et al., 2019; Yousif et al., 2020). Since the braking mechanism is responsible for converting kinetic energy into thermal energy through frictional contact between the disc and the brake pad, its performance directly determines safety, stability, and overall vehicle control (*A Review of Braking Performance and Dynamic Performance of Brake Discs*, 2025; Borawski et al., 2021; Ilie & Cristescu, 2022). Therefore, continuous improvement and evaluation of motorcycle braking systems remain a critical focus within mechanical and transportation engineering research.

Disc brakes have gradually replaced drum brakes in modern motorcycles due to their superior thermal management, structural simplicity, and responsiveness (García-León et al., 2019). They also enable more consistent braking under variable load and environmental conditions (Ruan et al., 2016; Shi et al., 2024; Z. Zhang et al., 2017). Nevertheless, braking performance is influenced by several design parameters, such as disc diameter, surface pattern, ventilation structure, and the composition

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of friction materials (Kumar & Kumaran, 2019; Raghunathan et al., 2024; Sathyamoorthy et al., 2022). Experimental analysis of these parameters under controlled conditions is essential to enhance braking reliability and energy efficiency (Li et al., 2016; Wu et al., 2021; Xu et al., 2016). Conventional testing procedures, which often involve full-scale dynamometer setups or on-road evaluations, tend to be costly and technically demanding (Jaworski et al., 2022). Consequently, these methods are less feasible for small laboratories or educational institutions, creating a need for simpler, low-cost testing systems that can accurately simulate real braking scenarios.

A compact and affordable test bed provides a viable alternative for investigating braking dynamics without the limitations of large-scale infrastructure (*On scaled-down bench testing to accelerate the development of novel friction brake materials*, 2022; Saiteja et al., 2022; Siegel et al., 2018). Such a system can facilitate experimental measurements of power dissipation, energy conversion, and braking stability at different operating frequencies, while also supporting educational objectives in mechanical design and energy studies (Dong et al., 2019; Hosseini et al., 2023; Szumska, 2025; W. Zhang et al., 2023). Developing an accessible test bench using a combination of readily available materials and straightforward manufacturing methods not only reduces production costs but also encourages innovation in academic environments (Huang et al., 2015; Steenhuis & Pretorius, 2017). Furthermore, the use of standardized testing parameters allows for reliable data comparison across future studies in braking performance and energy recovery.

Most existing studies on braking technology emphasize large-scale dynamometer evaluations, advanced friction materials, or electronic control mechanisms, rather than direct energy performance assessment in small-scale systems. Research by (*On scaled-down bench testing to accelerate the development of novel friction brake materials*, 2022) introduced a scaled-down bench for evaluating friction materials, while (*Testing of alternative disc brakes and friction materials regarding brake wear particle emissions and temperature behavior*, 2021) and (*Analysis of the Test Bench Design Influence on the Cooling Performance of a Rail Vehicle Brake Disc*, 2023) focused on emissions and cooling characteristics of disc brakes. A test platform for high-speed rail systems, which is unsuitable for lightweight vehicles. Meanwhile, studies in motorcycle braking, such as those by Huang and Shih (2010), (Teoh, 2011), (Rizzi et al., 2015), and (*Analysis of the minimum swerving distance for the development of a motorcycle autonomous braking system*, 2013), primarily addressed safety enhancement through hydraulic or automatic braking control. While these works contribute to the development of safer braking systems, they rarely explore experimental quantification of energy conversion or the design of affordable test benches applicable to two-wheeled vehicles. The present study aims to design, construct, and experimentally validate a low-cost test bed to evaluate the energy performance of motorcycle disc brake systems. By integrating concept-based design screening, three-dimensional modeling using SolidWorks, and controlled laboratory testing under variable motor frequencies, this research provides a practical approach for assessing braking energy efficiency. The developed prototype is expected to serve as both an educational apparatus and a research platform, offering a foundation for future advancements in regenerative braking and energy recovery technologies for lightweight electric vehicles.

METHOD

Research Site and Period

The study was conducted at the Mechanical Engineering Laboratory, Universitas Lampung. The design and fabrication processes were carried out between July 2017 and January 2018. The overall research framework combined conceptual design, prototyping, and experimental testing to develop and evaluate a functional test bed for motorcycle disc braking systems

Conceptual Design and Development

The research began with a conceptual analysis of the motorcycle braking system. Literature studies were conducted to identify essential system requirements and design constraints. Several alternative configurations were generated to fulfill the primary function of simulating disc brake performance under variable load and speed conditions.

Three preliminary design concepts were proposed based on the choice of motor type, transmission system, and braking mechanism:

- Concept 1: DC motor with chain drive transmission.

- Concept 2: DC motor with pulley and belt transmission.
- Concept 3: DC motor with direct coupling and integrated current-cutoff mechanism.

Each concept was evaluated using the concept screening method (Ulrich & Eppinger, 2003) through a weighted matrix considering cost, assembly ease, component simplicity, and operational safety. Concept 3 achieved the highest cumulative score and was selected for further development due to its low fabrication cost, minimal component count, and ease of maintenance

Fabrication and Assembly Process

The selected design was modeled using SolidWorks software and optimized through the Design for Manufacturability (DFM) approach to reduce production complexity. Fabrication involved combining ready-made and raw materials. Mild steel was used for the frame, shaft housing, and brake mounts. Machining and welding processes were performed to ensure structural rigidity and precise alignment. Components such as the AC motor, couplings, and caliper units were integrated into the structure. Assembly followed a sequential approach: preparation of raw materials, machining, component finishing, and final assembly. The DFM principles guided the process to minimize waste, reduce assembly time, and maintain alignment accuracy.

Test Bed Components

The test bed consisted of a three-phase AC motor (0.75 kW, 220/380 V, 50 Hz) connected through a rigid coupling to a rotating shaft that held the disc brake system. The brake assembly included a Honda 22 cm diameter disc and front caliper pads designed for automatic scooters. The braking force was applied manually through a lever calibrated to exert a torque of 4.409 Nm. Instrumentation included a digital multimeter to measure electrical parameters—voltage (V), current (A), and power (W)—at different operating frequencies (10 Hz, 20 Hz, 30 Hz, and 40 Hz). These frequencies were controlled using a variable frequency inverter (VFD) attached to the motor system.

Experimental Procedure

Each experiment was conducted by operating the motor at a specific frequency, maintaining a constant lever pressure during braking. The energy generated during braking was calculated from electrical measurements using the following equations:

P = V \times I

E = P \times t

where P denotes electrical power (W), V is voltage (V), I is current (A), and t is braking duration (s). Each frequency setting was tested three times to ensure repeatability, and mean values were used for further analysis. Data were recorded under steady-state conditions when the motor reached stable rotational speed (up to 2400 rpm at 40 Hz) before brake application. Observations included fluctuations in voltage, current, and power output during braking

Data Analysis and Validation

The recorded data were processed statistically to determine mean and deviation values for each variable. Graphical analyses were used to visualize relationships among motor frequency, power, and braking energy. Calibration of measuring instruments was performed prior to testing, and multiple repetitions ensured data reliability. Structural stability and safety of the test bed were verified at each stage to minimize mechanical error and ensure reproducibility.

RESULTS AND DISCUSSION

Prototype Performance and System Integrity

The constructed motorcycle disc brake test bed successfully demonstrated the expected operational reliability and structural stability. The apparatus integrated a 0.75 kW three-phase induction motor, a rigid coupling, and a 220 mm hydraulic disc brake mounted on a mild steel frame. The system was designed to operate across four motor frequencies (10 Hz, 20 Hz, 30 Hz, and 40 Hz), with a constant brake lever torque of 4.409 Nm. Throughout the experiments, the structure exhibited minimal vibration and mechanical deflection, indicating robust alignment between the rotating shaft and the brake disc.

Figure 1. The Fabricated Test Bed Prototype

This configuration met the study's objective of developing a low-cost yet effective system to simulate real braking conditions. The results confirmed that the mechanical design provided both rigidity and repeatability—critical parameters also emphasized in similar brake performance rigs developed by (*Analysis of the Test Bench Design Influence on the Cooling Performance of a Rail Vehicle Brake Disc*, 2023), where system stability was found essential to ensure consistent energy measurements.

Electrical Power and Braking Energy Performance

The average electrical parameters (voltage, current, and power) were measured under each operating frequency using a digital multimeter and data logging system. Table 1 presents the summary of experimental results. The average electrical parameters (voltage, current, and power) were measured under each operating frequency using a digital multimeter and data logging system. Table 1 presents the summary of experimental results.

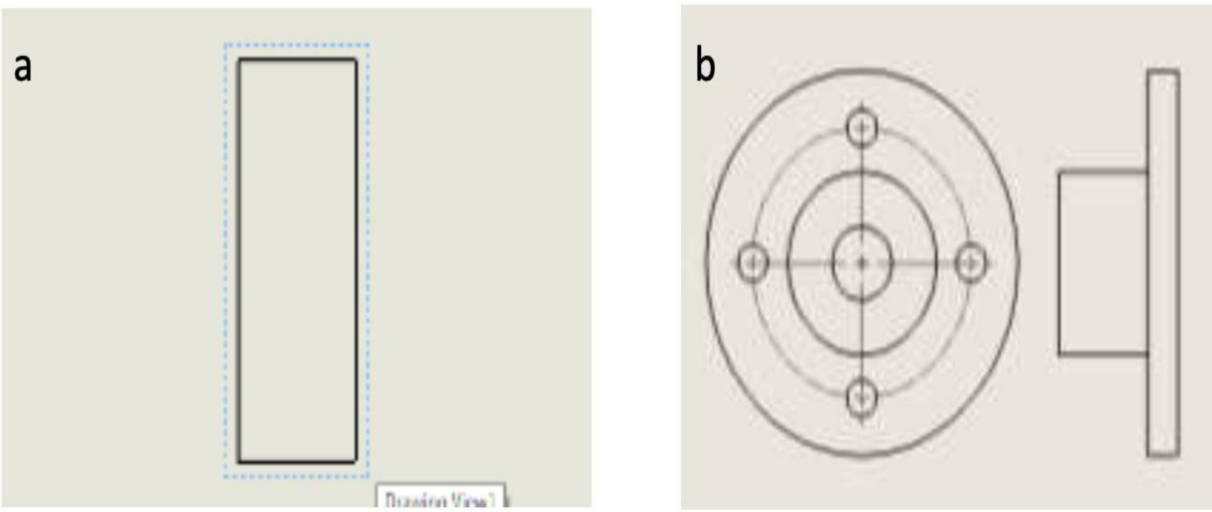

Figure 2. Circuit schematic for electrical measurement

Table 1. Experimental results of power and braking energy under different frequencies

Frequency (Hz)	Average Voltage (V)	Average Current (A)	Average Power (W)	Braking Duration (s)	Total Energy (J)
0	19.5	0.68	35.93	112	1,077.9
20	31.2	1.41	111.17	103	3,335.0
30	45.3	2.15	323.95	100	9,718.4
40	38.2	1.74	294.53	92	8,835.9

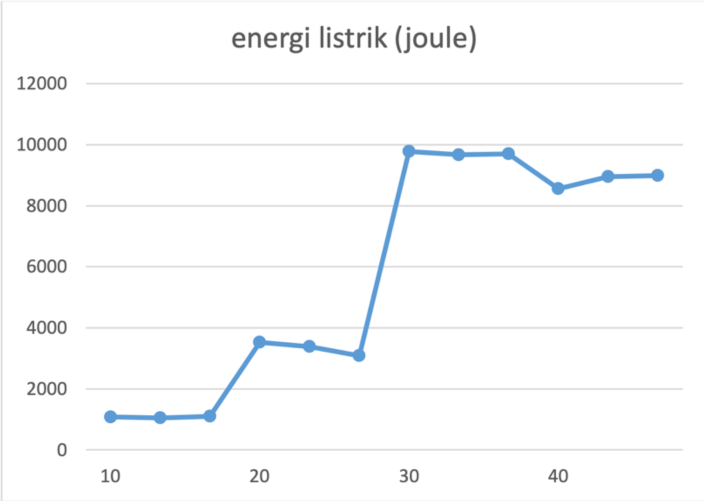

Figure 3. Relationship between motor frequency and braking energy

The data reveal a positive correlation between motor frequency and electrical power up to 30 Hz. As the rotation speed increased, both current and voltage values rose, resulting in a significant increase in power and total energy output. However, a decline occurred at 40 Hz, where the mean power and energy values dropped by approximately 9% compared to the 30 Hz condition. This performance drop can be attributed to excessive rotational speed (~2400 rpm), leading to dynamic imbalance and uneven frictional contact between the brake pad and the disc. Similar non-linear behavior has been reported (*On scaled-down bench testing to accelerate the development of novel friction brake materials*, 2022), who observed that braking energy dissipation efficiency peaks at moderate rotational speeds due to optimal contact pressure distribution. At higher speeds, vibration-induced micro-slip and thermal effects reduce effective torque transmission.

Energy Conversion Behavior and Dynamic Effects

The calculated electrical energy followed the theoretical relationship E = P \times t. The highest total energy (9,718.4 J) was obtained at 30 Hz, confirming that this frequency represents the most efficient balance between kinetic energy input and frictional dissipation. At 10–20 Hz, insufficient rotational inertia resulted in lower energy conversion, while at 40 Hz, the shorter braking duration and unstable pad–disc contact decreased total output despite higher voltage.

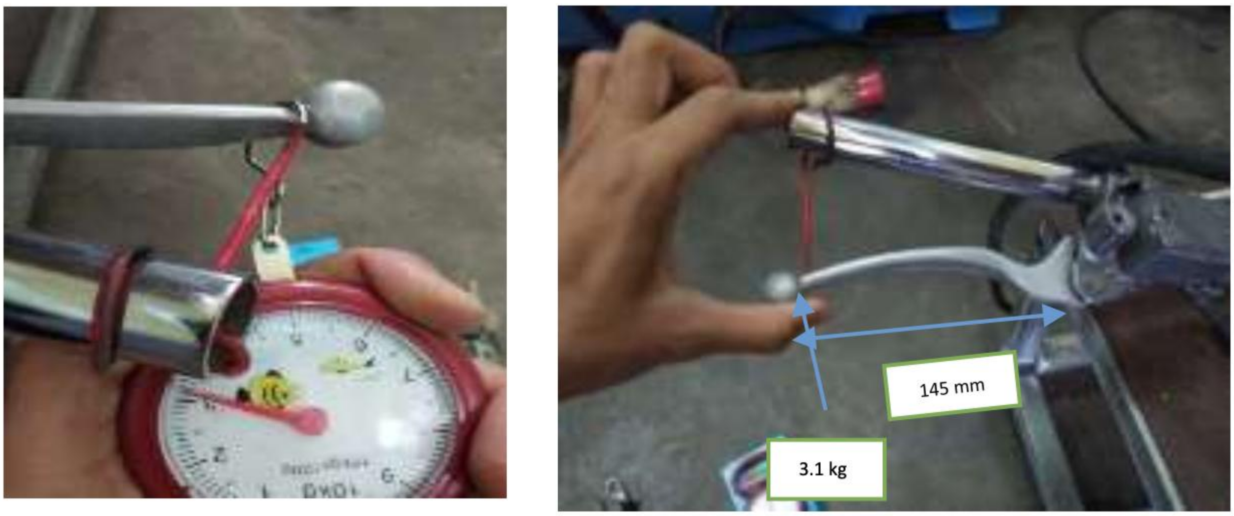

Figure 4. Close-up of the braking setup during energy measurement

This pattern aligns with the findings of (*Testing of alternative disc brakes and friction materials regarding brake wear particle emissions and temperature behavior*, 2021), who emphasized that excessive rotational velocity increases heat generation and frictional instability, reducing the proportion of mechanical work converted into electrical or measurable output. The dynamic vibration observed at 40 Hz corresponds to a transition into an unstable frictional regime often referred to as *friction fade* that also limits consistent braking force.

Comparative Analysis with Previous Studies

To contextualize these results, Table 2 compares the current study's energy and power outcomes with selected literature on braking system testing and energy analysis.

Table 2. Comparison of present study with selected previous works

Author / Year	Test Bed Type	Variable Studied	Peak Energy / Power Output	Observed Limitation	Main Contribution
This study (2025)	Mechanical–electrical hybrid for motorcycle disc brakes	Frequency (10–40 Hz)	9,718.4 J / 323.9 W	Instability above 30 Hz	Demonstrated affordable, efficient brake energy analysis
Singireddy et al. (2022)	Mini dynamometer with sensors	Disc temp. & friction coeff.	~10.2 kJ	High complexity & calibration cost	Validated speed–energy proportionality
Hesse et al. (2021)	Thermal brake rig	Speed & cooling performance	—	Heat-induced fade	Identified optimal operating window for thermal stability
Zan et al. (2019)	Rail brake test bed	Torque vs. braking time	11.4 kJ	Large-scale setup	Provided mechanical torque–energy model
Pavelčík et al. (2023)	High-speed vibration test rig	Friction stability & dynamics	—	Instability >3000 rpm	Quantified vibration–energy loss relationship

Compared to high-cost dynamometer systems, the present design delivers similar analytical capability using standard measurement instruments and manual lever actuation. This simplicity makes it particularly suitable for educational laboratories and applied research in small-scale mechanical engineering contexts. Furthermore, while prior studies primarily focused on temperature or torque-based metrics, the present work directly quantified braking energy in Joules, providing a more tangible link between mechanical and electrical energy domains.

Technical Implications and Future Applications

The non-linear performance pattern emphasizes that braking efficiency peaks at moderate frequencies, beyond which frictional and thermal instability become dominant. These results confirm the theoretical behavior of energy dissipation in frictional systems where performance is limited by surface temperature rise and loss of uniform contact pressure. This study also demonstrates that low-cost test beds can reliably capture essential energy parameters, making them valuable tools for both research and academic instruction. With further modifications, the system could serve as an experimental platform for regenerative braking studies, by coupling the electrical output to a capacitor or energy storage module. This aligns with emerging directions in lightweight electric vehicle research, where small regenerative systems can significantly enhance energy efficiency.

Discussion

The discussion of the motorcycle disc brake test bed results reveals a coherent relationship between motor frequency, electrical power, and braking energy. As outlined in the experimental data, increasing the motor frequency from 10 Hz to 30 Hz led to a substantial rise in voltage, current, and power, producing maximum energy output of approximately 9,718 J at 30 Hz, before slightly declining to 8,835 J at 40 Hz. This pattern supports the theoretical principle that braking power depends on the product of torque and angular velocity, in which moderate rotational speeds optimize mechanical-to-electrical energy conversion. The observed decline at 40 Hz corresponds to the onset of dynamic imbalance and partial frictional loss at around 2,400 rpm, where excessive vibration reduces contact uniformity between the brake pad and disc. Comparable results were reported (*Testing of alternative disc brakes and friction materials regarding brake wear particle emissions and temperature behavior*, 2021), who demonstrated that higher rotational velocities cause surface vibration and temperature escalation that diminish braking torque stability.

Similarly, (*On scaled-down bench testing to accelerate the development of novel friction brake materials*, 2022) confirmed that braking efficiency peaks at mid-range frequencies due to optimal pressure distribution, declining thereafter as frictional fade occurs. The present results also indicate that at high frequency, a portion of mechanical energy is dissipated as heat and micro-vibrations rather than being converted to measurable electrical power a condition consistent with the thermal degradation model. Thus, the prototype effectively identifies the operational limit where energy conversion becomes unstable, confirming that braking systems exhibit non-linear efficiency behavior under varying rotational speeds. Compared to large-scale test, this low-cost test bed provides similar analytical insights into energy transfer with accessible instrumentation, making it suitable for educational laboratories and small-scale research. The findings underscore the mechanical and thermal interplay governing disc brake performance, establishing 30 Hz as the optimal operational frequency for energy efficiency and demonstrating the test bed's reliability in capturing the fundamental dynamics of frictional energy transformation.

Implication

The implications of this study extend beyond the immediate evaluation of a motorcycle disc brake system and offer substantial contributions to both engineering research and practical innovation in sustainable mobility technologies. The findings demonstrate that braking efficiency follows a non-linear trend governed by the interplay between mechanical stability, thermal behavior, and dynamic frictional response. Identifying 30 Hz as the optimal operational frequency provides a foundational benchmark for the design of braking systems that aim to maximize energy conversion while minimizing vibration-induced losses and thermal degradation. From a technological perspective, this insight is crucial for the development of regenerative braking mechanisms in lightweight electric vehicles, where the recovery and storage of braking energy can significantly enhance overall system efficiency and reduce energy consumption. Furthermore, the success of this low-cost, modular test bed highlights its potential as an accessible educational and research platform, bridging theoretical understanding and empirical experimentation for students and engineers in the field of mechanical design and energy systems. Its ability to replicate real braking phenomena with minimal resource requirements supports wider adoption in academic laboratories, especially in developing regions where access to advanced instrumentation is limited. The study also reinforces the importance of integrating thermomechanical analysis into brake system design, suggesting that future improvements should incorporate torque and temperature sensors to capture the full spectrum of energy dissipation mechanisms. Ultimately, this research underscores the value of affordable, scalable engineering solutions that not only enhance safety and performance but also align with the global transition toward energy-efficient and environmentally sustainable transportation technologies.

Limitation and Suggestion for Further Research

Despite the promising outcomes of this study, several limitations must be acknowledged to contextualize its findings and guide future investigations. The most notable limitation lies in the absence of direct measurements of braking torque, surface temperature, and frictional coefficient, which restricts the analysis of the thermomechanical behavior underlying the observed energy fluctuations. Without these parameters, it is difficult to fully quantify the proportion of mechanical work converted into heat versus that transformed into electrical output. In addition, the application of a manually operated braking lever, although calibrated to a constant torque, may introduce minor variations in applied force that could affect data repeatability under higher frequency conditions. The prototype's structural design, while sufficiently rigid for moderate speeds, also exhibited minor vibration at 40 Hz, suggesting the need for further mechanical refinement and enhanced damping to improve measurement stability. For future research, it is recommended to incorporate torque sensors, thermocouples, and data acquisition modules capable of real-time monitoring to capture transient variations in braking force and temperature distribution. The integration of a controlled actuator system could also standardize braking pressure and minimize operator-related inconsistencies. Expanding the study to include various disc materials, pad compositions, and ventilation patterns would provide deeper insights into how surface microstructure influences energy dissipation and braking efficiency. Furthermore, coupling the electrical output of the test bed to an energy storage unit such as a capacitor bank or battery system—would enable the evaluation of regenerative braking potential and its applicability to small electric or hybrid vehicles. Addressing these limitations will enhance the analytical robustness of the test bed, broaden its experimental capability, and strengthen its contribution to the field of sustainable vehicle engineering and energy recovery research.

CONCLUSION

The study successfully designed, fabricated, and evaluated a low-cost experimental test bed for assessing the energy performance of motorcycle disc braking systems. The prototype demonstrated reliable operational stability and consistent energy measurement across variable motor frequencies, confirming its mechanical integrity and experimental feasibility. The results revealed that braking energy and electrical power increased proportionally with frequency up to 30 Hz, where peak energy output of approximately 9,718 J and maximum average power of 323.95 W were achieved. Beyond this point, specifically at 40 Hz, both parameters declined due to the onset of dynamic vibration, partial slip, and thermal effects, indicating an optimal operating range for efficient energy conversion. These findings validate the theoretical relationship between angular velocity and braking energy while emphasizing the critical influence of mechanical and thermal stability on performance efficiency. Moreover, the test bed's simplicity, modularity, and cost-effectiveness make it particularly valuable for educational laboratories and small-scale research environments, offering an accessible tool for studying the dynamics of frictional energy transformation and for developing future regenerative braking concepts. Overall, the study establishes a practical foundation for future engineering applications and experimental modeling aimed at improving braking system efficiency, sustainability, and energy recovery in two-wheeled vehicle technologies.

AUTHOR CONTRIBUTIONS STATEMENT

Imam Rosyid, as the corresponding author, was primarily responsible for conceptualizing the research framework, conducting the experimental design, data acquisition, and analysis of the motorcycle disc brake test bed performance. He also led the manuscript preparation, drafting, and revision process. Yanuar Burhanuddin contributed to the supervision of the research design and provided expert guidance on mechanical system modeling, data interpretation, and validation of the experimental setup. He also reviewed and refined the analytical framework to ensure the methodological rigor and scientific coherence of the study. Ahmad Su'udi assisted in the development of the test bed fabrication process and the evaluation of energy performance measurements. He contributed to the theoretical discussion, critical manuscript review, and verification of experimental accuracy.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. All contributions were conducted independently and without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The research was carried out solely for academic and professional purposes.

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