

Research Paper

Effect of Anti-lock Braking System Modulation Frequency on Flywheel-Based Energy Harvesting During Panic Braking

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Abstract

A considerable portion of braking energy in electric vehicles is dissipated as heat, especially during severe or panic braking. This study experimentally investigates the effect of anti-lock braking system (ABS) modulation frequency on flywheel-based energy harvesting during panic braking using a laboratory-scale Flywheel Regenerative Capture System (FRCS). The proposed setup integrates an ABS braking unit, a magnetic clutch, a flywheel, and an electrical generator to recover part of the braking energy while maintaining braking stability. Experiments were conducted at ABS modulation frequencies of 10, 20, 30, 40, and 50 Hz. Braking performance was evaluated using wheel-speed response, slip ratio, braking time, braking distance, flywheel rotational response, and generated electrical power. At an initial braking speed of 1000 rpm, the ABS braking process operated within a slip-ratio range of approximately 0.17–0.38, while the shortest braking distance under regenerative braking reached about 15.83 m at 40 Hz, compared with about 19.58 m at 10 Hz without regenerative braking. The 10 Hz setting produced the most stable deceleration pattern, the highest flywheel rotational response, and the highest electrical output, whereas higher frequencies increased fluctuation and reduced effective torque transfer to the generator. These findings indicate that ABS modulation frequency strongly influences both braking stability and flywheel-based energy harvesting performance. The study demonstrates the feasibility of integrating a flywheel regenerative capture system with ABS-controlled panic braking, providing a basis for further vehicle-scale development.

Keywords: ABS modulation frequency; Anti-lock braking system; Energy harvesting; Flywheel regenerative capture system; Panic braking; Regenerative braking

1. Introduction

Within the broader context of the renewable energy transition and sustainable energy systems, improving energy efficiency in electric vehicles (EVs) is essential to reducing overall energy demand and enhancing system sustainability. A substantial portion of a vehicle's kinetic energy during braking is typically dissipated as heat, representing a significant loss of usable energy. Regenerative braking systems (RBSs) offer a viable solution by converting part of this lost

energy into electrical energy that can be stored and reused. This energy recovery mechanism not only improves vehicle efficiency but also complements renewable energy use by reducing reliance on external energy supplies and supporting the integration of intermittent renewable sources into transportation systems [1], [2], [3]. Recent studies have shown that regenerative braking has evolved from conventional motor-based recuperation into more integrated architectures involving friction brakes, brake-by-wire systems, and hybrid energy-



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storage technologies, while still facing major challenges in safety, control coordination, and energy-efficiency optimization [4], [5], [6], [7].

In automotive applications, the braking problem is more complex than in general energy-recovery systems because braking performance must simultaneously meet energy-recovery, vehicle stability, and safety requirements. During severe or panic braking, the anti-lock braking system (ABS) plays a critical role in preventing wheel lockup and maintaining steering control [8], [9], [10]. Under such conditions, regenerative braking cannot be treated independently from wheel-slip control. Previous studies have shown that braking-energy recovery must be constrained by tire-road adhesion, braking stability, and safety-critical maneuvers [11], [12]. In particular, the integration of regenerative braking with ABS requires coordinated management of braking torque so that energy recovery does not degrade wheel-slip regulation and stopping performance [13], [14].

The interaction between ABS and regenerative braking has therefore become an important topic in EV braking research. Studies on wheel-slip-ratio control have shown that hydraulic and regenerative braking systems can be combined to improve braking response, but only when the regenerative contribution is tightly coordinated with slip control [13]. Research on four-wheel independently actuated EVs has further confirmed that braking-force allocation directly influences both energy recovery and vehicle stability [8]. Likewise, electric-motor anti-lock braking strategies based on advanced control methods have demonstrated that electric braking can enhance braking safety while also improving braking-energy recuperation [15]. These findings indicate that regenerative braking in EVs is not merely an electrical energy-conversion problem, but a multi-objective automotive control problem involving safety-critical wheel dynamics.

More recent work has shifted toward coordinated composite braking, especially in electro-hydraulic braking and brake-by-wire systems. Coordinated electro-hydraulic braking strategies have been proposed to enlarge the feasible regenerative region while satisfying braking regulations [16]. Hierarchical cooperative control has also been developed for electromechanical brake-by-wire systems to

handle the interaction between anti-lock braking and energy regeneration [17]. In four-wheel-drive pure electric vehicles, electro-hydraulic compound braking systems have been shown to improve both braking coordination and energy-recovery effectiveness [18]. In dual-motor EVs, braking-energy recovery optimization under safety constraints has further demonstrated that braking safety and efficient recovery must be considered together rather than separately [19]. Collectively, these studies confirm that braking-force distribution, ABS behavior, and regeneration strategy are strongly coupled in modern EV braking systems.

Besides braking stability and torque coordination, regenerative braking performance is also influenced by thermal behavior, energy economy, and practical blended-braking implementation. Simulation-based investigations have shown that regenerative braking affects battery thermal management and that braking-force allocation should also consider thermal implications during recovery [20]. Mechanism analysis and evaluation studies have further clarified how regenerative braking contributes to overall EV energy-efficiency improvement [21]. Blended braking systems in battery electric vehicles have been reported to influence not only dynamic braking performance but also the economic value of recovered energy [22]. Comparative studies on control methods for integrating energy recovery in electric vehicles likewise show an inherent trade-off between wheel-slip regulation and achievable energy recuperation [23]. More comprehensive automotive energy-recovery architectures have also been proposed, emphasizing that braking-energy capture should be integrated with refined vehicle-level energy management [24], [25].

In parallel, control-oriented research has continued to refine regenerative braking from the perspectives of driving style, intelligent control, and real-time adaptation. Driving-style-based regenerative braking systems have shown that braking safety remains the dominant constraint even when energy recovery is maximized [26]. Fuzzy-neural-network-based control strategies have also been proposed for pure electric vehicles to improve regenerative braking performance while preserving stability and system efficiency [27]. Earlier studies based on fuzzy logic similarly

demonstrated that regenerative braking allocation can be modeled as a function of deceleration demand, jerk, and road condition [28]. These developments reinforce the understanding that regenerative braking in EVs should be addressed through integrated control frameworks rather than isolated energy-harvesting mechanisms.

For short-duration and high-power braking events, interest has recently increased in mechanical energy-storage media, particularly flywheel energy storage systems (FESSs). Unlike batteries, flywheels store energy mechanically and are capable of a rapid charge-discharge response, making them attractive for transient braking-energy capture [29]. Recent reviews on vehicular FESS applications have highlighted their high power density, fast dynamic response, and potential to complement conventional electrical storage systems [29]. Experimental studies have also reported the feasibility of high-speed flywheel energy storage during regenerative braking in hybrid and electric vehicles [30]. In addition, compound battery-flywheel energy storage systems have been proposed to improve braking-energy recovery and reduce battery stress during braking transients [31]. Optimization strategies based on flywheel/battery hybrid storage have further demonstrated the potential of hybridized energy storage for braking-energy management [32]. Recent analyses also indicate that both electric flywheel and electromechanical flywheel architectures can influence EV energy economy, depending on system topology and control strategy [33].

Despite these advances, the recent studies literature remains dominated by motor-based regenerative braking, battery-centered recovery, and electro-hydraulic torque coordination, while experimental studies that explicitly integrate flywheel-based energy harvesting with ABS-controlled panic braking remain limited. There is still insufficient laboratory-scale evidence on how ABS modulation frequency influences wheel-slip behavior, braking stability, flywheel rotational response, and the resulting electrical output during panic braking. This gap is important because panic braking involves short-duration, high-intensity torque transfer, where braking safety and transient energy capture must be addressed simultaneously.

Therefore, this study experimentally investigates a flywheel-based energy harvesting system integrated with a variable-frequency ABS braking prototype under panic-braking conditions. The objectives of this work are: (1) to evaluate the effect of ABS modulation frequency on braking stability through wheel-speed and slip-ratio behavior, (2) to examine the flywheel rotational response and braking-energy capture during panic braking, and (3) to assess the resulting electrical output generated during the braking process. The novelty of this study lies in the integration of flywheel-based regenerative capture with ABS-controlled panic braking, and in the explicit evaluation of ABS modulation frequency as a governing parameter for both braking stability and energy-harvesting performance.

2. Methods

2.1. Research Objectives and Experimental Variables

This study experimentally investigates a flywheel-based regenerative capture system integrated with a variable-frequency anti-lock braking system (ABS) prototype during panic braking. The method was structured to evaluate both braking safety and energy-harvesting performance in one integrated laboratory platform, which is consistent with current research directions in regenerative braking, brake-by-wire coordination, and ABS-regenerative interaction [4], [5], [34], [35]. The overall research process adopted in this study is presented in Figure 1.

The objectives of this work are threefold: (1) to evaluate the effect of ABS modulation frequency on braking stability through wheel-speed response and slip-ratio behavior, (2) to examine flywheel rotational response and braking-energy capture during braking, and (3) to assess the resulting electrical output generated by the coupled generator. This objective structure is in line with recent studies showing that regenerative braking in electric vehicles must be formulated as a coordinated control problem involving both energy recovery and wheel-slip regulation [13], [15], [16], [17], [36].

The investigated variable in this study was the ABS modulation frequency, which was set at 10, 20, 30, 40, and 50 Hz. These frequencies represent

the practical operating range of the laboratory ABS modulator used in the present setup. The controlled parameters included the initial braking speed, brake pressure, flywheel geometry and mass, generator coupling arrangement, sensor configuration, and the mechanical layout of the test rig. The ABS control box used in the experiment is shown in [Figure 2](#).

The initial braking speed was tested at 800, 1000, and 1200 rpm, while the hydraulic brake pressure was maintained at 2 bar during the experiments. The flywheel and generator specifications were kept constant throughout the entire test series. The measured outputs included the rotational speeds of the main wheel, the second wheel, and the flywheel-generator shaft,

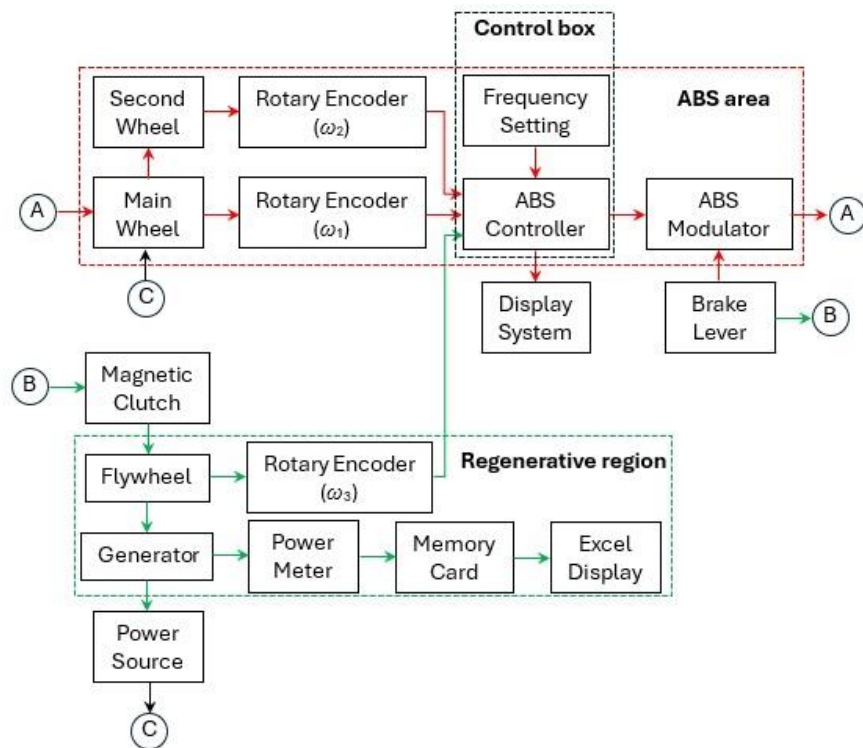


Figure 1. Process diagram of the experiment

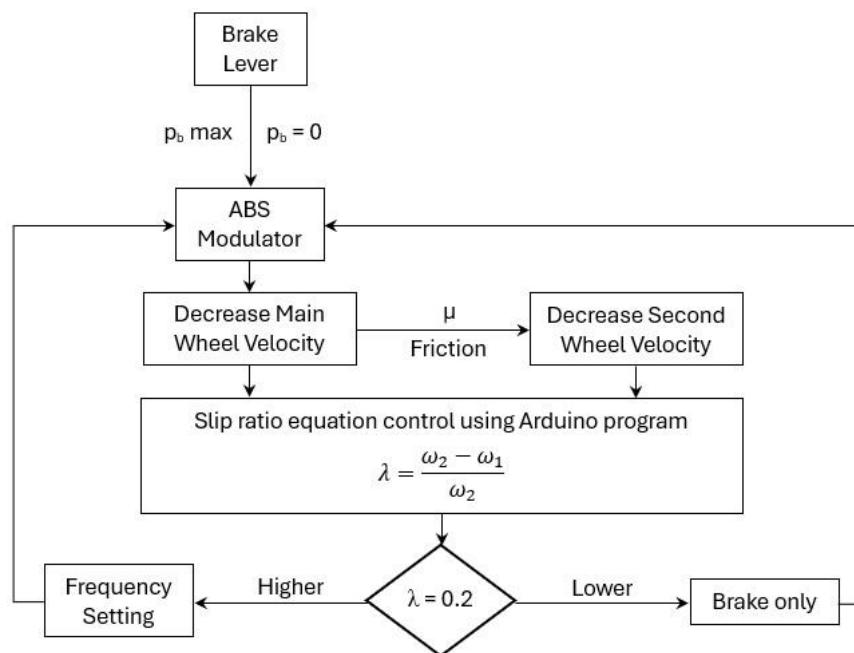


Figure 2. ABS control box

as well as the slip ratio, braking time, braking distance, generator voltage, current, electrical power, and harvested electrical energy. These variables were selected because recent regenerative braking studies emphasize that the evaluation of braking-energy recovery should not be separated from braking stability, wheel-slip behavior, and power-conversion characteristics [15], [16], [17], [27], [31], [32], [36], [37].

2.2. System Configuration and Experimental Setup

The experimental platform was developed as a laboratory-scale Hardware-in-the-Loop (HIL) braking rig that models the interaction among vehicle wheel dynamics, ABS operation, and flywheel-based regenerative capture. The rig consisted of an upper rotating wheel (main wheel), a lower rotating wheel (second wheel), a hydraulic disc-braking unit, an ABS modulator, a brake lever equipped with magnetic-clutch actuation, a flywheel-generator shaft, an electrical generator, a drive motor, and a monitoring computer. The upper wheel represented the tire side, whereas the lower wheel represented the vehicle-side inertial load. The rolling contact between the two wheels enabled the speed difference between them to be used to interpret slip ratio during braking. The detailed experimental setup is shown in Figure 3.

The main hardware specifications were fixed during all tests. Each wheel had a diameter of 42 cm and a mass of 35 kg. The braking unit used a 25 cm brake disc, while the ABS modulator was based on a Yamaha N-Max modulator assembly. The regenerative branch employed a magnetic clutch to connect the flywheel shaft during

braking, thereby enabling part of the braking torque to be transferred into the flywheel-generator assembly. The flywheel had a diameter of 30 cm and a mass of 5 kg. The electrical generator had a nominal voltage of 24 V, a rated power of 300 W, a rated current of 16.5 A, and a nominal rotational speed of 2650 rpm. The electric drive motor used to accelerate the system before braking had a nominal voltage of 60 V, a rated power of 2000 W, a rated current of 30 A, a maximum torque of 180 Nm, and an operating speed range of 500–2500 rpm.

The experimental configuration reflects the broader trend in EV braking research toward integrated friction-regenerative architectures, where braking torque is distributed across different actuators and storage paths [4], [5], [16], [17]. Although most recent studies focus on battery-centered recovery and electro-hydraulic brake coordination, flywheel-assisted storage remains attractive for transient braking events because of its fast mechanical response and high power density [31], [32].

During each test, the electric motor accelerated the main wheel to the prescribed initial speed of 800, 1000, or 1200 rpm. Panic braking was then applied by fully actuating the hydraulic brake lever while the ABS modulation frequency was preset to one of the five test values. At the same time, the brake lever activated the magnetic clutch so that braking torque could be transmitted to the flywheel-generator shaft.

2.3. Instrumentation and Measurement Procedure

The rotational speeds of the upper wheel, lower wheel, and flywheel-generator shaft were

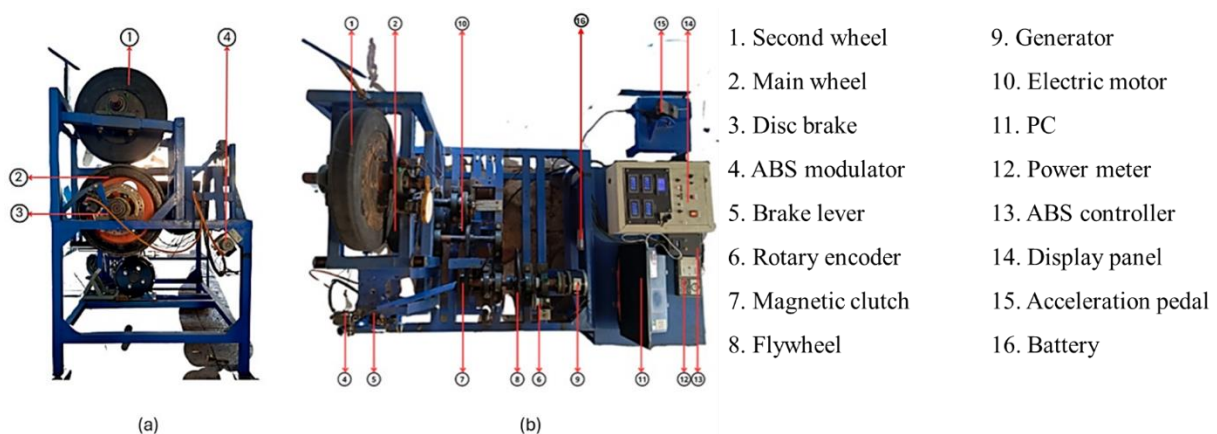


Figure 3. The experimental setup: (a) Side view, (b) Top view

measured using three rotary encoders. According to the component specification used in the rig, the rotary encoders were OMRON E6B2-CWZ6C units with a pulse-per-revolution value of 1000 and an operating voltage range of 5–24 VDC. These sensors were connected to the braking monitoring system installed on the data-acquisition laptop to record time histories of wheel speed and flywheel speed throughout the braking event.

The generator's electrical output was measured using a power meter capable of recording voltage, current, power, and electrical energy as functions of time. The measurement chain therefore consisted of two synchronized data streams: mechanical rotation data from the rotary encoders and electrical conversion data from the power meter. This measurement scheme is consistent with recent experimental studies on regenerative braking and hybrid energy storage, which commonly evaluate braking recovery through the simultaneous tracking of rotational response and power-flow variables [27], [31], [32], [37].

The data acquisition sequence followed the procedure established in the dissertation workflow: (1) acquisition of upper-wheel and lower-wheel rotational speed, (2) calculation of slip ratio from the two wheel speeds, (3) acquisition of flywheel-generator rotational speed, and (4) logging of voltage, current, power, energy, and time during the active braking period. The braking event began when the brake lever was fully pulled, and the ABS modulator became active, and it ended when the flywheel-generator shaft returned to rest.

Before the main tests, all sensors were checked under no-load rotation to verify encoder pulse detection, signal continuity, and data-channel consistency. The electrical measurement channels were also verified under controlled shaft rotation to ensure proper voltage and current response. Each experimental condition was repeated at least three times, and the results are reported as mean values with corresponding standard deviation, measurement spread, or error bars to ensure reliable representation of repeatability and uncertainty. Recent control-oriented EV braking studies similarly emphasize the need for explicit validation, signal reliability, and repeatability when evaluating ABS-regenerative interaction

[13], [15], [16], [17], [34], [35], [36]. The measured outputs reported in this work were: main-wheel speed, second-wheel speed, flywheel speed, slip ratio, braking time, braking distance, generator voltage, current, electrical power, and harvested electrical energy. These outputs were selected because they enable integrated assessment of braking stability, torque transfer, and mechanical-to-electrical conversion during panic braking.

2.4. Dynamic Model and Data Reduction

The braking dynamics were represented using a simplified wheel-road longitudinal model. The principal forces considered in the model were the normal force F_z , representing the wheel load, and the longitudinal force F_L , representing the braking-force interaction. The friction coefficient μ was defined as the ratio between the longitudinal and normal forces, as shown in Eq. (1).

$$\mu(\lambda) = \frac{F_L}{F_z} \quad (1)$$

The slip ratio λ was calculated from the difference between the translational speed and the circumferential speed associated with wheel rotation, as expressed in Equation (2). The complete conceptual representation of the tire dynamic model used in this study is illustrated in Figure 4.

$$\lambda = \frac{v - \omega R}{v} \quad (2)$$

where v is the translational speed, ω is the angular speed of the wheel, and R is the effective wheel radius. During braking, the condition $v \geq \omega R$ applies. The deceleration dynamics of the wheel were then expressed as:

$$\dot{v} = \frac{-F_L}{m} \quad (3)$$

$$\dot{\omega} = \frac{RF_L - T_b}{J} \quad (4)$$

where V is voltage, I is current, and $\cos \varphi$ is the generator power factor. To strengthen the physical interpretation of the results, it is further recommended that the revised paper include an energy-conversion metric, such as the ratio between harvested electrical energy and flywheel rotational energy. Such efficiency metrics are widely used in recent regenerative braking and hybrid-storage studies to distinguish between

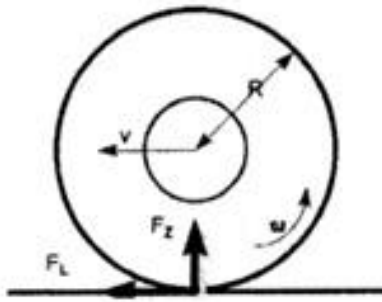


Figure 4. The dynamic modeling of vehicle tire

mechanical capture capability and actual usable electrical output [13], [15], [16], [28], [29], [35]. Recent studies on wheel-slip control and coordinated braking also support the use of simplified slip-based dynamic modeling for evaluating the influence [4], [5], [27], [31], [32], [37] of braking-force allocation and ABS logic on vehicle stability. Therefore, the present data-reduction approach was considered adequate for laboratory-scale comparative analysis of modulation frequency, braking response, and energy capture.

2.5. Boundary Conditions, Assumptions, and Limitations

The present study was conducted on a laboratory-scale braking rig under controlled indoor conditions. The main boundary conditions were defined by fixed mechanical geometry, constant brake pressure, fixed flywheel and generator specifications, and prescribed initial braking speeds of 800, 1000, and 1200 rpm. The hydraulic brake pressure was maintained at 2 bar, while the ABS modulation frequency was varied between 10 and 50 Hz. All tests were performed using the same wheel-contact arrangement and the same regenerative coupling configuration. All tests were performed using the same wheel-contact arrangement and the same regenerative coupling configuration.

The current analysis focused primarily on braking dynamics and energy capture. Therefore, thermal variables such as ambient temperature, brake-disc temperature, and local contact temperature were not directly measured in the present rig. Nevertheless, these variables remain physically important because a substantial portion of braking energy is inevitably dissipated as heat at the contact interface. From a physical standpoint, the contact area, thermal conductivity of the contacting materials, specific heat capacity,

and the effective overall heat-transfer coefficient can influence how much braking energy is lost thermally rather than transferred into the flywheel-generator branch. This consideration is consistent with recent studies that connect regenerative braking behavior with thermal effects, battery thermal management, and braking-energy distribution [5], [27].

The lower frequency bound of 10 Hz was selected based on the practical operating range of the laboratory modulator and the stable operating range of the experimental rig. A 5 Hz condition was not included in the current study because the laboratory setup was designed, instrumented, and validated for operation starting from 10 Hz. Additional studies at chassis-dynamometer or vehicle scale are needed to validate real tire-road interaction, direct thermal measurement, actuator bandwidth limits, and full integration constraints. Similar scaling considerations are also emphasized in recent work on coordinated electro-hydraulic braking, brake-by-wire systems, and flywheel/battery hybrid storage [16], [17], [31], [32], [36], [37].

3. Results and Discussion

3.1. Braking Stability under Variable ABS Modulation Frequency

The braking response of the upper and lower wheels demonstrates that the anti-lock braking system (ABS) modulation frequency has a significant impact on braking stability. Across all tested conditions, the upper wheel exhibited a more rapid deceleration than the lower wheel, consistent with the dynamic differences between the tire-side wheel and the vehicle-side inertial load. The extent of deceleration fluctuation varied considerably with modulation frequency. Lower modulation frequencies yielded a smoother, more stable deceleration profile, whereas higher frequencies led to pronounced oscillations in the braking response. These oscillations suggest intermittent contact conditions and unstable slip behavior, which are typically linked to increased frictional dissipation and diminished braking efficiency. Excessive modulation frequency leads to rapid alternation between braking and release phases, preventing the system from maintaining an optimal slip ratio. Consequently, braking stability decreases, and a greater proportion of energy is dissipated as heat rather than being

effectively utilized within the braking system. The smoother braking response at 10 Hz shown in [Figure 5a](#) suggests that braking torque was transmitted in a more continuous and controlled manner. By contrast, at higher frequencies, especially in [Figure 5e](#), the braking action became increasingly impulsive, particularly at the beginning of the braking interval when the wheel speed was still high. Under this condition, the ABS modulation generated stronger instantaneous friction, increasing losses and reducing braking smoothness. This interpretation is consistent with the earlier manuscript's statement that fluctuations at the beginning of braking tend to produce greater losses than those near the end of the process. From a physical standpoint, this result indicates that lower modulation frequency is more favorable for

combining braking safety with mechanical energy capture. Stable braking not only reduces unnecessary slip losses but also provides a more suitable torque-transfer profile for the regenerative branch. Therefore, braking stability should be regarded as a prerequisite for effective flywheel-based energy harvesting rather than a separate performance target.

3.2. Slip Ratio, Braking Time, and Braking Distance

The slip ratio was used as the main indicator of ABS performance because it reflects the braking system's ability to operate near the high-friction region without entering unstable wheel lock. As shown in [Figure 6](#), the existing 1000 rpm no-regenerative data show that the slip-ratio ranges were approximately 0.19–0.30 at 10 Hz, 0.13–0.27

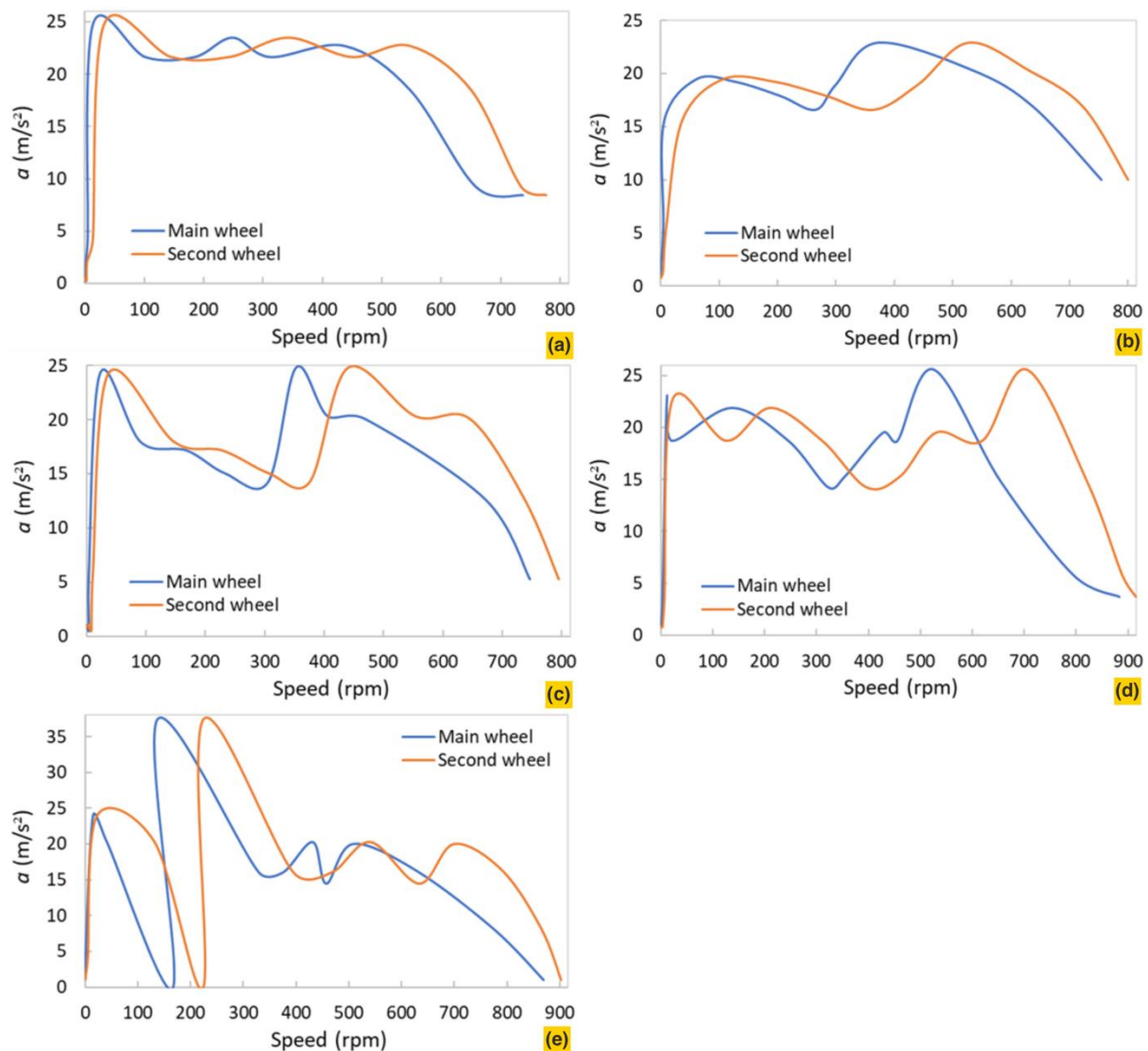


Figure 5. Deceleration versus wheel speed for (a) 10 Hz, (b) 20 Hz, (c) 30 Hz, (d) 40 Hz, and (e) 50 Hz piston frequencies

at 20 Hz, 0.17–0.35 at 30 Hz, 0.17–0.28 at 40 Hz, and 0.17–0.38 at 50 Hz. The corresponding braking times were 1.90 s, 2.10 s, 1.90 s, 2.00 s, and 2.00 s, while the braking distances were 19.58 m, 22.69 m, 20.03 m, 23.11 m, and 21.66 m, respectively. These values indicate that low and moderate frequencies maintained slip behavior closer to the targeted ABS working region than the higher-frequency cases.

When regenerative braking was integrated, the braking distance decreased relative to the non-regenerative case. At 1000 rpm with regenerative braking, the braking distances became 16.38 m, 16.22 m, 16.08 m, 15.83 m, and 16.65 m for 10, 20, 30, 40, and 50 Hz, respectively. The shortest braking distance occurred at 40 Hz under the regenerative configuration, while the non-regenerative configuration produced longer stopping distances overall. However, the shortest braking distance should not be interpreted as the only criterion for ABS performance. As reflected by the slip-ratio trends in [Figure 6](#), the frequency producing the shortest distance is not necessarily the most stable, because slip-ratio peaks and fluctuation patterns must also be considered. A condition may yield a relatively short stopping distance but still exhibit larger slip excursions, which are undesirable from the standpoint of controllability and safety. This shows that, under regenerative braking, not all modulation frequencies simultaneously satisfy the desired ABS slip-ratio criterion. The frequencies that most consistently met both regenerative braking and ABS performance requirements were 10 Hz, 30 Hz, and 40 Hz. This finding is particularly important because it supports the idea that the optimal operating point is a compromise between braking stability and energy capture, rather than the sole minimization of stopping distance.

3.3. Flywheel Rotational Response and Braking-energy Capture

The flywheel response demonstrates that braking torque was successfully transferred from the ABS braking system to the regenerative branch through the magnetic clutch. As shown in [Figure 7](#), 10 Hz produced the highest flywheel rotational response, while 40 Hz also showed a relatively high response after the intermediate

frequencies decreased. The 10 Hz condition in [Figure 7a](#) generated a flywheel speed margin above approximately 450 rpm, whereas the 40 Hz case in [Figure 7d](#) approached this threshold but remained slightly lower. These results indicate that the modulation frequency not only affects braking stability, but also determines the quality of torque transfer toward the flywheel shaft.

The flywheel-energy trend in [Figure 8](#) also shows that the rotational energy decreased from 10 to 30 Hz, while 40 Hz and 50 Hz again showed high rotational-energy potential because the large deceleration fluctuation at those frequencies produced high moment impulses on the flywheel shaft. In other words, high-frequency braking can still inject significant instantaneous energy into the flywheel, but the transfer occurs in a more impulsive and less stable form. This distinction can be described as continuous torque transfer versus impulsive torque transfer. At lower frequencies, the braking torque is applied for a longer effective duration, allowing the flywheel to accelerate more smoothly and retain rotational energy more efficiently. At higher frequencies, the torque arrives in shorter pulses that behave more like impact loading than sustained drive. Such impulses may still produce high instantaneous flywheel energy, but they are less favorable for downstream electrical conversion because the rotational response is less continuous. This shows that captured flywheel energy increased with increasing initial braking speed. Thus, the magnitude of recoverable mechanical energy is governed by both the system's initial kinetic state and the modulation frequency, which determines the amount of braking torque delivered to the regenerative branch.

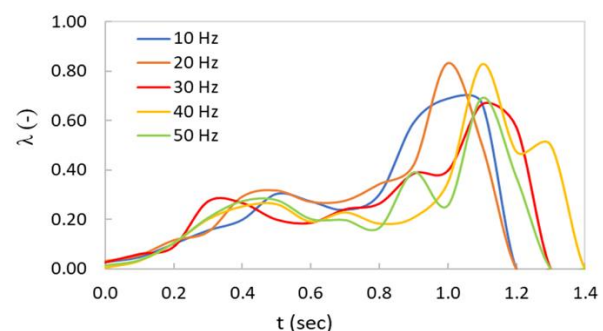


Figure 6. Slip ratio versus braking time for various values of piston frequency

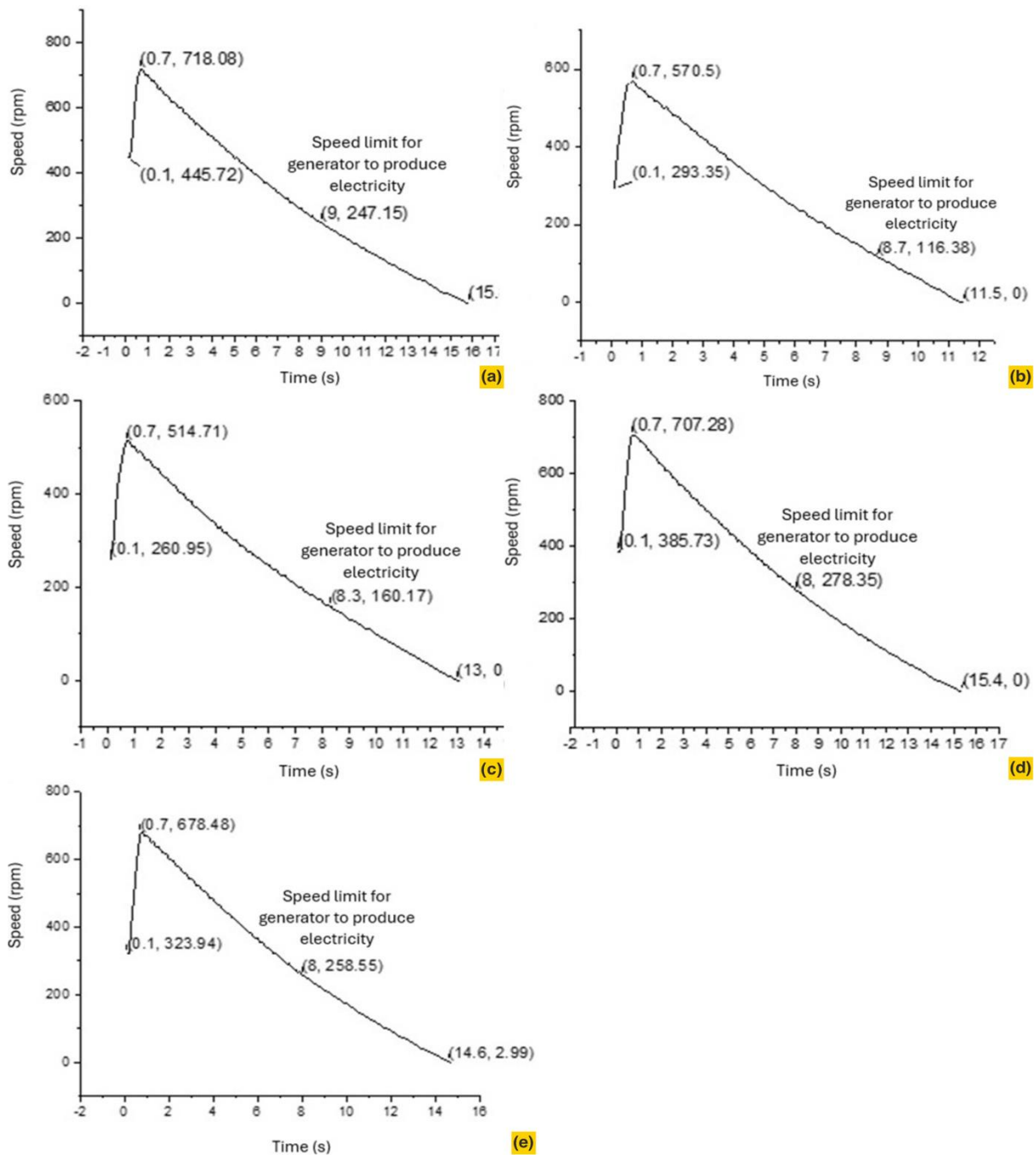


Figure 7. Flywheel speed for (a) 10 Hz, (b) 20 Hz, (c) 30 Hz, (d) 40 Hz, and (e) 50 Hz piston frequencies

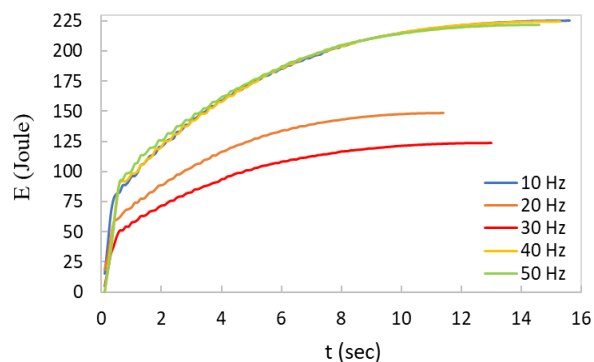


Figure 8. Flywheel energy versus braking time for various piston frequency

3.4. Electrical Output and Mechanical-to-Electrical Conversion

The electrical output results show that a high level of flywheel rotational energy does not necessarily result in high electrical power. As shown in Figure 9 and Figure 10, the 10 Hz case produced the highest electrical output, while the 40 Hz and 50 Hz cases, despite having high flywheel energy, generated lower power. This indicates that electrical output decreases with increasing ABS piston frequency under the tested conditions. This behavior is primarily governed

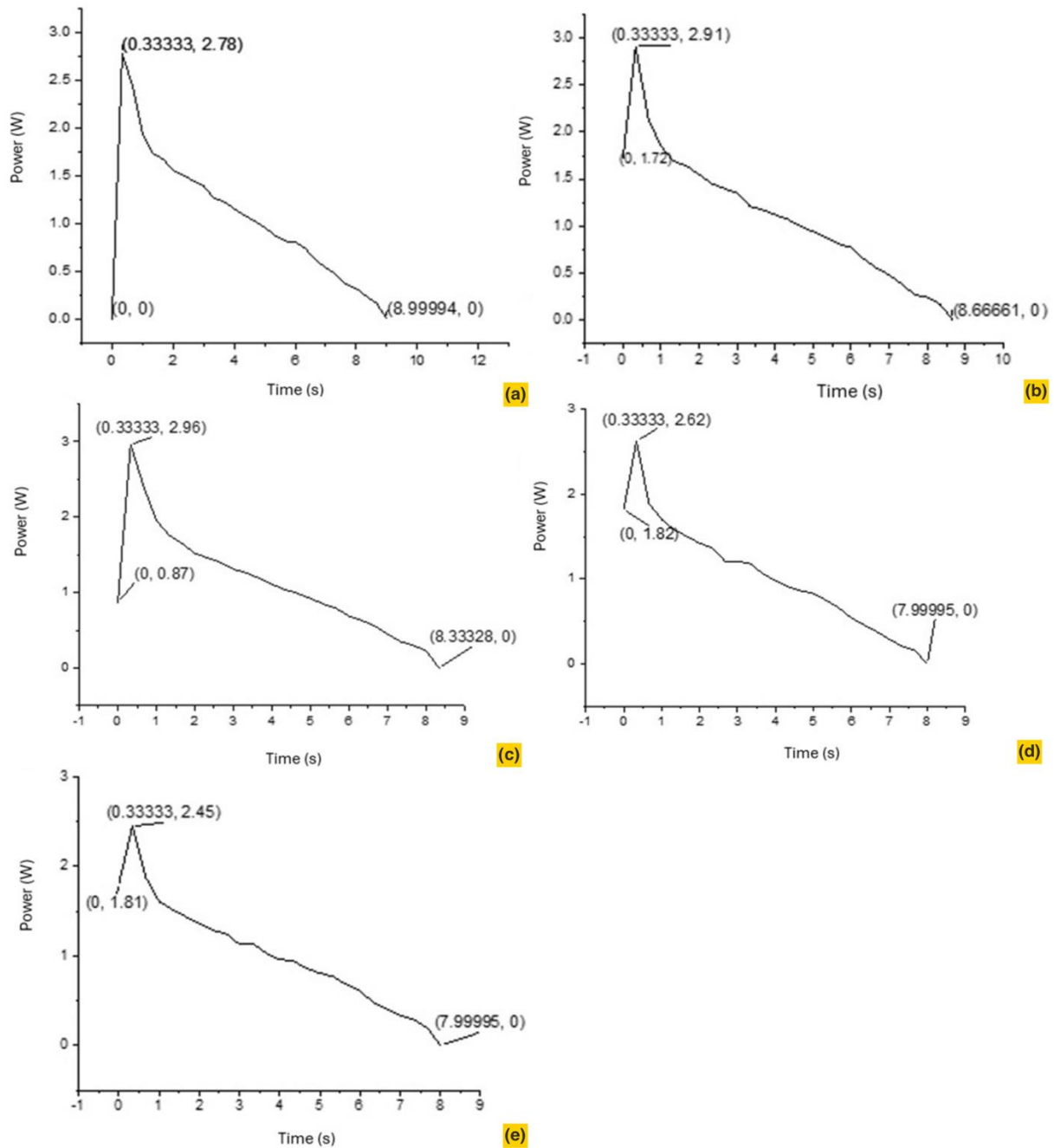


Figure 9. Power capture on the generator for (a) 10 Hz, (b) 20 Hz, (c) 30 Hz, (d) 40 Hz, and (e) 50 Hz piston frequencies

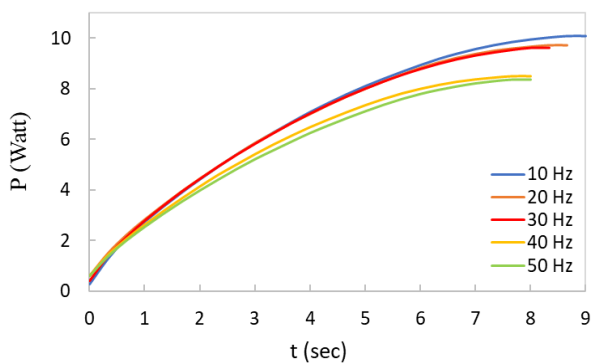


Figure 10. Generator power generation versus braking time for various piston frequency

by the continuity of the braking torque transmitted to the generator. Lower modulation frequencies produce smoother and more stable torque, enabling more efficient energy transfer, whereas higher frequencies introduce strong fluctuations that lead to impulsive, less effective excitation of the generator.

Quantitatively, among the operating conditions that satisfy both regenerative braking and ABS performance requirements, the energy-capture efficiency at 10 Hz, 30 Hz, and 40 Hz was 20.02%, 19.22%, and 20.08%, respectively,

indicating an effective efficiency of approximately 20%. Across all tested conditions, efficiency varied within a broader range of about 14–27%, depending on modulation frequency and initial braking speed. From a physical standpoint, the energy-harvesting process involves three stages: braking torque generation, mechanical transmission to the flywheel, and electrical conversion by the generator. Energy losses occur at each stage, including frictional dissipation, transmission inefficiencies, and generator losses. Therefore, optimal performance is achieved not by maximizing flywheel energy alone, but by maintaining stable torque transmission throughout the conversion chain. Consequently, the generator output trends in [Figure 9](#) and [Figure 10](#) should be interpreted as reflecting the effectiveness of mechanical-to-electrical energy transfer at different ABS modulation frequencies.

3.5. Integrated Discussion: Balancing ABS Performance and Regenerative Capture

Simultaneous evaluation of braking and energy-harvesting behaviors reveals that the optimal operating condition cannot be defined solely by minimum braking distance or maximum flywheel speed. Rather, it is determined by the capacity to maintain stable ABS-controlled braking while facilitating effective energy capture. Within the tested range, modulation frequencies of 10 Hz, 30 Hz, and 40 Hz provide the most balanced operating conditions, consistently meeting both braking performance and energy-recovery requirements. From a braking-safety perspective, the regenerative mechanism should be considered an integrated component of the ABS system rather than an independent add-on. Excessively high modulation frequencies amplify wheel-slip fluctuations and increase frictional dissipation, while also degrading the continuity of torque transmitted to the energy-harvesting system. Consequently, the regenerative pathway receives a more irregular and less usable mechanical input. From an energy-conversion standpoint, the optimization target should prioritize stable and sustained torque transfer under controlled slip conditions rather than maximum instantaneous power. The results demonstrate that maintaining torque continuity is more critical than maximizing the flywheel's peak rotational energy. This interpretation clarifies

why higher-frequency conditions, although they generate elevated rotational energy levels, do not necessarily yield superior electrical output or braking stability. Modulation frequency thus serves as a key coupling parameter governing both braking dynamics and the effectiveness of mechanical-to-electrical energy conversion.

3.6. Limitations of the Present Experimental Results

The present results should be interpreted in light of several limitations of the experimental setup. The experiments were conducted on a laboratory-scale rig, which does not fully replicate real tire–road interactions in full-scale vehicle applications. In addition, thermal effects—such as brake-disc temperature, contact temperature, and heat-transfer characteristics—were not directly measured, limiting the analysis of thermal losses to qualitative interpretation. The investigated frequency range also started from 10 Hz, so lower-frequency behavior remains unexplored. Furthermore, the robustness of the findings could be strengthened by including repeatability metrics, such as mean values and standard deviations from repeated trials, if available. Despite these limitations, the results provide clear proof-of-concept evidence for integrating ABS-controlled braking with flywheel-based regenerative systems. The findings demonstrate that modulation frequency governs not only braking stability, but also the nature of torque transmission and the overall effectiveness of energy conversion.

4. Conclusion

This study experimentally evaluated flywheel-based energy harvesting during panic braking using a variable-frequency ABS prototype. The results showed that ABS modulation frequency significantly affected braking stability, slip ratio, flywheel response, and generator output. The 10 Hz condition produced the most stable braking response and the highest electrical output, whereas higher frequencies led to greater deceleration fluctuations and less effective energy conversion. At 1000 rpm without regenerative braking, braking distances ranged from about 19.58 to 23.11 m, whereas under regenerative braking, they were reduced to about 15.83–16.65 m, depending on modulation frequency. The most

feasible operating conditions for the present rig were 10 Hz, 30 Hz, and 40 Hz, which provided the best compromise between ABS performance and regenerative energy capture. The corresponding flywheel energy-capture efficiency was around 20%, with the broader efficiency range across all tested cases approximately 14%-27%. These results confirm the feasibility of integrating flywheel-based regenerative capture with ABS-controlled panic braking at laboratory scale. Nevertheless, the findings should not yet be generalized to full-vehicle implementation because the present study was limited by the absence of direct thermal measurements, the exclusion of 5 Hz testing, and the use of a laboratory-scale rig. Future work should therefore include lower-frequency testing, thermal measurements, uncertainty analysis, and validation under vehicle-scale operating conditions.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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The authors declare no competing interest.

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