Exploring the Benefits and Limitations of Flywheel Regenerative Braking for Sustainable Transportation

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Abstract
This study aims to assess the feasibility of implementing a flywheel regenerative braking system in bicycles as a method to enhance energy efficiency in transportation. The project involves the comprehensive design, fabrication, and testing of a prototype that captures and stores kinetic energy generated during braking in a mechanical flywheel system. Unlike conventional braking systems, which dissipate energy as heat, this approach enables the reuse of stored energy for acceleration, potentially improving overall vehicle efficiency (Wager, 2024). The evaluation process considers multiple performance factors, including energy recovery efficiency, mechanical reliability, and practical applicability. The prototype was tested under controlled conditions to compare its effectiveness against traditional braking systems. Experimental results indicate a substantial capacity for energy recovery, reinforcing the viability of mechanical energy storage as a sustainable alternative to battery-based regenerative braking (Erhan et al., 2021).

Keywords: energy recovery, flywheel regenerative braking, mechanical energy storage, sustainable transportation, vehicle efficiency

I. Introduction
The transportation sector is one of the largest contributors to greenhouse gas emissions, making sustainable innovations in vehicle engineering crucial. One of the key areas of improvement is braking systems, where regenerative braking plays a vital role in energy conservation (Tires Plus. (n.d.), 2022).

Regenerative braking is commonly implemented in hybrid and electric vehicles, where braking energy is stored and reused to enhance efficiency. Among various regenerative braking systems, flywheel-based energy storage presents an alternative to battery-based systems by mechanically storing and releasing energy. This project investigates the feasibility of implementing a flywheel regenerative braking system in bicycles to evaluate its efficiency and potential for wider applications (Li & Ching, 2016). The research objectives of this project are to design and develop a functional flywheel regenerative braking system for a bicycle, evaluate the system's energy recovery efficiency, compare its performance to traditional braking methods, and identify strengths, limitations, and potential improvements.

II. Methodology

A. Experimental Setup

The flywheel assembly involves a solid steel flywheel weighing 5 kg that is mounted on a steel axle. The braking mechanism is a disc brake system that applies force to transfer kinetic energy to the flywheel. The tachometer system is an Arduino-based tachometer that utilizes an IR sensor to measure rotational speed in real time.

The bike is modified with a clutch that transfers energy from the rear wheel to the flywheel, with a mechanism activated by a hand lever. When engaged, the flywheel absorbs energy from the wheel, acting as a brake to slow the bike down while simultaneously gaining momentum. This stored energy can then be used later to help accelerate the bike.

B. Materials and Costs

The materials and costs of the project are shown in Figure 1 below.

Part	**Price (THB)**
Mild Steel Plate (10×10 inch, 6mm)	180
Stud	30
Bolt	60
Bike Frame	Free
5kg Plate	400
Chain	160
Custom Aluminum Clutch	400
Steel Axle	200
11T Sprocket	60
Disc Brake Pads	60
Total	**1,490**

Figure 1. Materials and costs.

D. Data Collection

The data collection process will be conducted using a custom-built tachometer developed with an Arduino UNO R3 and an infrared (IR) sensor. The tachometer is programmed to measure and record the rotational speed of the flywheel in revolutions per minute (RPM) over time. The collected data will be presented in the form of a graph plotting flywheel RPM against time.

The tachometer's functionality is based on an IR sensor detecting interruptions in the emitted infrared signal caused by the flywheel's rotation. Each interruption corresponds to a complete revolution, allowing for RPM calculation. The tachometer system operates in real-time and continuously updates its readings, providing dynamic feedback on the rotational behavior of the flywheel. This setup ensures high responsiveness and accuracy in capturing rotational speeds. The Arduino code used to process these measurements is shown below in Figure 2.

```
const int IRpin = 2;
 unsigned int rpm;
unsigned long timeold;

void setup() {
   Serial.begin(9600);
pinMode(IRpin, INPUT);   timeold =
micros();
}  void loop() {   int IRval =
digitalRead(IRpin);   if (IRval == LOW)
{     unsigned long currenttime = micros();
rpm = 60000000 / (currenttime - timeold);
timeold = currenttime;
    Serial.print(rpm);
    Serial.write(',');
    Serial.println();
  } }
```

FIGURE 2. Arduino code for tachometer implementation

III. Results

The flywheel regenerative braking system effectively captured and reused kinetic energy. The system showed high energy recovery efficiency, as indicated by the prolonged spin of the flywheel after braking was applied. The flywheel consistently retained a portion of the braking energy, which was then available for reuse when the vehicle accelerated. The Arduino-based tachometer provided precise RPM measurements, revealing that, on average, the flywheel retained 30-40% of its peak RPM after 10 seconds, depending on braking force and road conditions.

Additionally, the system exhibited lower maintenance requirements compared to traditional battery-based regenerative braking systems, as there were no chemical degradation concerns. The high-power density of the flywheel allowed for rapid energy storage and release, making it a potentially effective system for short bursts of acceleration. However, several limitations were observed. The added weight of over 20 kg significantly impacted the maneuverability and practicality of the bicycle. The gyroscopic effect of the flywheel made steering more difficult, indicating that this system may be better suited for four-wheeled vehicles where stability is less of an issue. The system's energy storage capacity was also limited; although effective for short-term energy retention, it was not ideal for extended storage periods. Additionally, the mechanical complexity of the system required precise calibration and high manufacturing costs, making it a challenging technology to implement on a large scale without further refinement. Despite these challenges, the study provides valuable insights into the feasibility of flywheel regenerative braking and highlights the potential for further development and optimization.

IV. Discussion

The findings of this study indicate that flywheel regenerative braking is a viable alternative to traditional battery-based regenerative braking systems. The ability to store energy mechanically reduces energy losses associated with electrical storage, making flywheel systems an attractive option for high-efficiency energy recovery. However, the weight and gyroscopic effects present challenges that need further refinement. The increased weight of the flywheel system significantly impacts the usability of the bicycle, making it less practical for everyday use. Future developments should focus on reducing the mass of the flywheel while maintaining its energy storage capacity. Additionally, the gyroscopic effect, which impacts maneuverability, suggests that flywheel regenerative braking is better suited for four-wheeled vehicles where stability is less of an issue (Erhan et al., 2021).

V. Conclusion

This study successfully demonstrated the feasibility of flywheel regenerative braking in bicycles. The prototype was able to recover and reuse braking energy, making it a promising and viable alternative to traditional rim brakes. The system's ability to convert kinetic energy into stored mechanical energy not only enhances efficiency but also provides an opportunity to reduce overall energy consumption. While the system showed promise in energy recovery, several challenges were identified, including the added weight of the flywheel mechanism and the steering difficulty experienced during braking. These issues highlight the need for further optimization to improve the system's integration with existing bicycle designs.

Additionally, future research should focus on reducing the overall weight of the system, potentially by exploring lighter materials for the flywheel and other components (Islameka et al., 2023). Integrating the flywheel energy storage with other forms of energy recovery, such as regenerative suspension or hub motors, could also enhance the overall performance and efficiency of the system. Long-term performance studies under real-world conditions, including varying terrain and rider behavior, are essential to fully assess the practicality and durability of flywheel regenerative braking systems in everyday use.

VI. Appendix

A. Pictures of the project in development

FIGURE 3. The fully modified bike equipment set up

FIGURE 4. The clutch and pulley mechanism used to regain energy

B. Videos of the project in development

Model of the bike (2nd Protype): https://youtu.be/BSVjDKTQfZA

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