Performance evaluation of a Compressed-Air-Powered Bike: A sustainable solution for urban transportation

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Abstract: The increasing demand for sustainable and emission-free transportation has led to the exploration of alternative energy sources. This paper presents the development of a compressed-air-powered bike utilizing a single-cylinder piston engine with solenoid-controlled air intake. The proposed system leverages compressed air as a renewable energy source, offering an eco-friendly alternative to conventional internal combustion and electric vehicles. The engine operates through controlled air injections, precisely managed by an Electronic Control Unit (ECU) synchronized with the crankshaft position to optimize efficiency and performance.

A high-pressure air tank serves as the primary energy source, while a decompression exhaust system is integrated to minimize energy losses during air expansion, ensuring smooth and efficient operation. The single-cylinder configuration is selected for its simplicity, cost-effectiveness, and reduced maintenance requirements, making it a practical solution for urban commuting and short-distance travel. A small onboard battery powers the solenoid valve and ECU, ensuring reliable functionality while maintaining a lightweight and efficient design.

This study evaluates the feasibility, efficiency, and potential challenges of using compressed air as a propulsion medium for lightweight vehicles. The results highlight the benefits of emission-free operation, low noise pollution, and reduced dependency on fossil fuels.

1. Introduction:

The rapid expansion of urban populations and increasing concerns over environmental sustainability have driven the search for alternative transportation solutions. Conventional internal combustion engine (ICE) vehicles contribute significantly to air pollution and greenhouse gas emissions, while electric vehicles (EVs), though cleaner, rely on battery technology that presents challenges related to production, disposal, and resource extraction. As a result, there is growing interest in developing alternative propulsion systems that minimize environmental impact while maintaining efficiency and practicality.

Compressed-air-powered vehicles have emerged as a promising alternative due to their emission-free operation, mechanical simplicity, and reliance on renewable energy sources. Unlike fossil fuel-based systems, compressed air propulsion does not produce carbon emissions during operation, making it a cleaner alternative for urban mobility. Additionally, compressed air storage and delivery systems are relatively simple, reducing the complexity and cost of maintenance compared to ICEs or EVs.

This project focuses on developing a compressed-air-powered bike, which leverages a single-cylinder piston engine with solenoid-controlled air intake. The goal is to design a lightweight, efficient, and sustainable transportation solution suitable for short-distance travel and urban commuting. By optimizing the air intake system using an Electronic Control Unit (ECU), the project aims to improve energy efficiency and maximize the practical usability of compressed air as a propulsion medium.

Urban transportation is heavily dependent on fossil fuel-based vehicles, contributing to air pollution, traffic congestion, and rising fuel costs. Although electric vehicles offer a cleaner alternative, they require extensive charging infrastructure and rely on lithium-ion batteries, which have their own environmental and resource-related concerns. A need exists for a low-cost, emission-free transportation solution that minimizes reliance on conventional energy sources while maintaining efficiency and practicality.

Compressed air presents a viable alternative due to its ability to store energy without the environmental drawbacks of fuel combustion or battery disposal. However, challenges such as efficient energy utilization, air expansion losses, and power optimization must be addressed to make compressed-air-powered vehicles a feasible solution. This project seeks to tackle these challenges by developing a compressed-air-powered bike with a controlled air intake system to improve efficiency and ensure practical performance for urban commuters.

The successful development of a compressed-air-powered bike could contribute to advancements in sustainable urban mobility by offering a clean, low-maintenance, and cost-effective alternative to conventional vehicles. The findings of this study could help further research into compressed air propulsion, leading to improvements in energy efficiency and practical implementation.

Additionally, this research supports efforts to reduce urban emissions, promote green transportation solutions, and enhance the viability of compressed-air-powered systems in real-world applications.

By addressing key challenges in air engine design and control optimization, this study provides valuable insights into the potential of compressed air as a sustainable propulsion method. The proposed solution has the potential to reduce reliance on fossil fuels, lower transportation costs, and contribute to a cleaner and more sustainable future for urban transport.

2. Methodology:

This section outlines the approach used in the design, development, and evaluation of the compressed-air-powered bike. The methodology includes system design, component selection, fabrication, and performance testing to ensure efficiency and functionality.

2.1. System Design and Concept Development

The design of the compressed-air-powered bike is based on a single-cylinder piston engine powered by compressed air. The system operates using an electronically controlled solenoid valve to regulate air intake, synchronized with the crankshaft position to optimize performance.

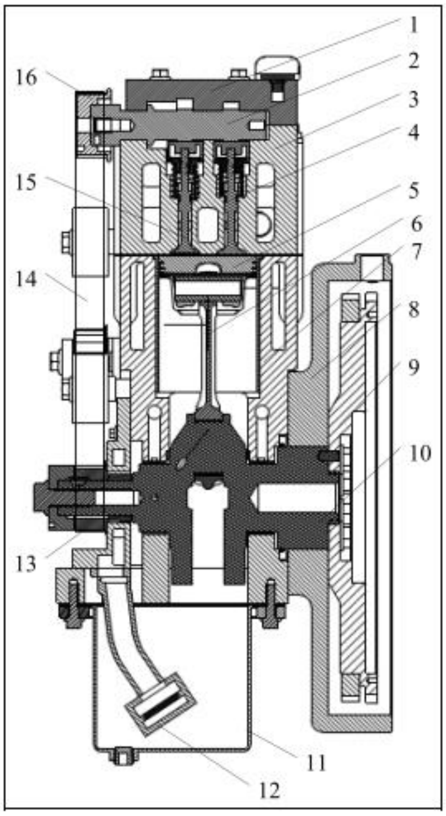

Figure 1. Piston-type CAE

1: cam cover; 2: camshaft; 3: cylinder header; 4: exhaust valve; 5: piston; 6: link; 7: cylinder; 8: flywheel housing; 9: flywheel; 10: crankshaft; 11: oil pan; 12: oil filter; 13: synchronous pulley 1; 14: synchronous belt; 15: intake valve; 16: synchronous pulley 2.

The main components of the system include:

- **Solenoid-controlled air intake system:** Regulates the injection of compressed air into the cylinder.

- **Electronic Control Unit (ECU):** Manages solenoid valve timing based on crankshaft position.
- **High-pressure air tank:** Stores compressed air at a predetermined pressure.
- **Decompression exhaust system:** Ensures smooth air expansion and reduces energy loss.
- **Battery and electrical system:** Provides power to the solenoid and ECU.
- **Single-cylinder engine:** Converts compressed air energy into mechanical motion.

A CAD-based design approach was used to model the bike's engine and frame, ensuring optimal integration of all components. Flow simulation software was also utilized to analyse air dynamics and optimize intake timing for maximum efficiency.

2.2. Component Selection and Fabrication

The selection of materials and components was based on factors such as durability, weight, and efficiency.
Key considerations include:

- **Engine Material:** The cylinder and piston are constructed from lightweight yet durable materials such as aluminium or reinforced nylon to reduce weight and friction.
- **Solenoid Valve:** A high-speed solenoid valve is chosen to ensure precise air intake control.
- **Air Tank:** A high-pressure composite or steel tank is used to store compressed air safely.
- **ECU and Sensors:** A micro controller-based ECU is programmed to regulate air injection timing based on real-time data from a crankshaft position sensor.
- **Battery System:** A compact lithium-ion battery powers the ECU and solenoid valve.

After component selection, fabrication was carried out through CNC machining and 3D printing for prototype parts. The assembled system underwent preliminary bench tests before installation on the bike frame.

2.3. Control System Development

The ECU was programmed to control the solenoid valve based on crankshaft position.

The control logic includes:

- **Sensor Input Processing:** The crankshaft position sensor detects the piston's position.
- **Air Injection Timing Calculation:** The ECU calculates the optimal moment to open and close the solenoid valve.
- **PWM - Based Solenoid Control**: A pulse-width modulation (PWM) signal regulates air intake for efficient operation.

The ECU was tested under simulated conditions to ensure accurate timing and response.

2.4 Performance Testing and Evaluation

The compressed-air-powered bike was tested to evaluate its efficiency, speed, and range.
Key tests included:

- **Efficiency Test:** Measuring air consumption per unit distance.
- **Power Output Test:** Assessing torque and speed at various air pressures.
- **Ride Test:** Evaluating real-world performance on different terrains.

Data from these tests were analysed to optimize the system and identify areas for improvement.

3. Results and Discussion:

This section outlines the expected performance and efficiency of the compressed-air-powered bike based on design considerations and theoretical analysis. The evaluation focuses on system efficiency, power output, energy consumption, and overall feasibility for urban mobility. The anticipated results are based on projected outcomes from bench and ride tests, which will further validate the potential of compressed air as a propulsion method.

3.1. Engine Performance and Air Consumption

A key aspect of the study is assessing how efficiently the engine converts compressed air energy into mechanical motion. The single-cylinder piston engine is designed to operate under varying air pressures to determine its torque, speed, and air consumption characteristics.

- **Air Pressure and Power Output:** The engine is expected to exhibit a direct correlation between air pressure and power output. Higher air pressures should contribute to increased speed and performance, while lower pressures may limit acceleration and efficiency.
- **Air Consumption Efficiency:** The air consumption rate will be evaluated in terms of compressed air usage per distance travelled. It is

anticipated that moderate speeds will offer better efficiency, while higher speeds may lead to increased air consumption due to expansion losses. Optimizing air intake timing is expected to enhance overall efficiency.

Initial assessments suggest that while compressed air propulsion is a feasible concept, improving energy efficiency will be critical to overcoming rapid expansion losses. The use of electronic control strategies for air injection timing may help minimize unnecessary air consumption.

3.2. Solenoid-Controlled Air Intake Efficiency

The implementation of a solenoid valve system, managed by an Electronic Control Unit (ECU), is intended to enhance efficiency by synchronizing air injection with the crankshaft position.

- **Optimized Air Injection Timing:** By dynamically adjusting the solenoid valve's operation, air intake can be matched to power demands more precisely, potentially reducing air wastage when compared to mechanically controlled systems.
- **Response Time and Control Accuracy:** The solenoid valve is expected to provide rapid response and precise adjustments based on engine speed and load conditions, ensuring smoother power delivery and improved efficiency.

Preliminary analyses indicate that electronically controlled air intake could contribute to making compressed-air-powered engines more viable by enhancing efficiency and optimizing performance.

3.3. Ride Performance and Range

The bike's real-world performance will be assessed across different terrains and usage conditions to determine its practicality for urban commuting.

- **Urban commuting sustainability:** The bike is expected to deliver smooth acceleration and performance comparable to small motorized scooters in stop-and-go traffic.
- **Estimated Range:** The achievable range will depend on factors such as air storage capacity, operating speed, and efficiency improvements. Lower speeds may extend the range, while higher speeds are likely to increase air consumption.

Ride Stability and Handling: The bike's lightweight design should enhance manoeuvrability in urban environments. However, performance on inclines may be limited due to constraints in power output.

Conclusion:

This study explored the feasibility of a compressed-air-powered bike as a sustainable and emission-free alternative for urban transportation. The primary goal was to design an efficient propulsion system utilizing compressed air, with a solenoid-controlled air intake for improved performance. Theoretical analysis suggests that compressed air can be a viable energy source for short-distance commuting, offering advantages such as zero emissions, low maintenance, and reduced noise pollution.

However, certain limitations must be addressed for broader adoption. The energy density of compressed air restricts range, and cooling effects during expansion may impact efficiency. Future advancements in air storage, thermal management, and refueling infrastructure will be crucial in enhancing performance. Additionally, integrating hybrid systems with renewable energy sources could further optimize the technology for diverse applications.

While challenges remain, compressed-air propulsion presents a promising step toward sustainable urban mobility. Continued research and development could unlock its full potential, contributing to cleaner and more efficient transportation solutions.

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