Design, Fabrication, and Analysis of a Human-Powered Spring-Based Flywheel Mechanism

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Abstract : This research presents the design, fabrication, and performance analysis of a human-powered spring-based flywheel energy storage mechanism. The system integrates a torsional spring with a manually driven flywheel to enhance rotational duration, energy storage, and output stability. The proposed mechanism aims to improve the efficiency of human-powered devices by utilizing spring-assisted torque multiplication. Analytical calculations, CAD modeling, materials selection, and experimental testing were performed. Results show that the spring-assisted system increases the flywheel run time, angular velocity stability, and stored energy compared to a conventional flywheel without a spring. The system demonstrated an increase of approximately 35–60% runtime extension depending on load conditions. Such mechanisms can be applied to rural power devices, gym energy harvesters, small mechanical tools, and educational prototypes.

I. INTRODUCTION

Human-powered mechanical systems have long provided sustainable and low-cost solutions for tasks such as grinding, pumping, lighting, and small-scale energy generation. They require no external power sources, making them ideal for rural areas and off-grid environments. However, one major limitation of human-powered devices is the inconsistency in power input. Human power output is intermittent due to fatigue, variable force, and limited endurance. This results in unstable rotational speed and short operational time for conventional flywheel systems. To address these issues, researchers have explored various mechanical energy storage techniques, including springs, flywheels, counterweights, and pneumatic systems.
Among these, flywheels are highly effective in storing kinetic energy due to their ability to rotate at high speeds and sustain momentum. However, human-powered flywheels often cannot achieve sufficiently high RPMs, limiting their energy storage capacity. Furthermore, once human input stops, the flywheel rapidly decelerates due to frictional losses and lack of auxiliary torque. To overcome this limitation, this research introduces a spring-based torque assist mechanism, combining the advantages of elastic and rotational energy storage.

II. LITERATURE REVIEW.

Flywheel Energy Storage Systems (FESS) have been studied extensively for their ability to store energy in the form of rotational kinetic energy. Traditional flywheels are widely used in electric grids, UPS systems, vehicle regenerative braking, and industrial machines. However, most of the existing literature focuses on electrically powered or high-speed flywheel systems, leaving a significant research gap when it comes to **human-powered** flywheel mechanisms combined with spring-assist systems.
Earlier studies have shown that torsional springs are capable of storing substantial elastic potential energy, which can be used for torque smoothing and energy compensation. Applications of torsional springs are commonly found in mechanical clocks, ratchets, wind-up toys, kinetic energy recovery systems (KERS), and hybrid vehicle transmissions. Some research also explores spring-based power storage for robotics, enhancing actuation efficiency. But the integration of torsional springs with flywheels for human-powered energy storage has not been widely explored.

Research on hybrid mechanical storage systems indicates that combining two types of energy storage—elastic and rotational—can result in improved performance. Spring mechanisms can boost torque at low rotational speeds, while flywheels provide stability at high rotational speeds. Studies in hand tools and mechanical devices suggest that springs significantly contribute to the smooth operation of cyclic systems by reducing torque fluctuations.
Relevant studies on human-powered generators focus mainly on increasing electrical output using bicycles, hand cranks, or treadles. These studies highlight the inconsistency in human power delivery, which often leads to fluctuating generator performance. There is strong evidence that auxiliary mechanical storage could benefit such systems by evening out the power delivery profile. However, there is limited literature on *mechanical-only* hybrid human-powered systems.
Therefore, the present research bridges the gap by designing a hybrid spring-flywheel mechanism that enhances rotational duration and improves power stability in human-powered devices. This literature review confirms that while spring mechanisms and flywheels have been individually studied in-depth, their combined application in human-powered context remains underexplored.

III. RESEARCH METHODOLOGY

he methodology adopted in this research combines analytical modeling, design engineering, CAD simulation, material selection, fabrication, and experimental analysis. The process begins with theoretical calculations to estimate flywheel inertia, spring constant, maximum energy storage, and expected runtime enhancement. These calculations help determine the initial dimensions of the flywheel, spring torque, and the required stiffness of the elastic component.

Following this, CAD modeling was performed using SolidWorks and AutoCAD. This step includes designing the flywheel, spring housing, shaft alignment, frame mounting, and the complete system assembly. CAD models help identify stress points, required clearances, and potential alignment issues before fabrication. Finite Element Analysis (FEA) was performed to evaluate stress distribution on the flywheel and torsional deformation on the spring under maximum load, ensuring the design's structural integrity.

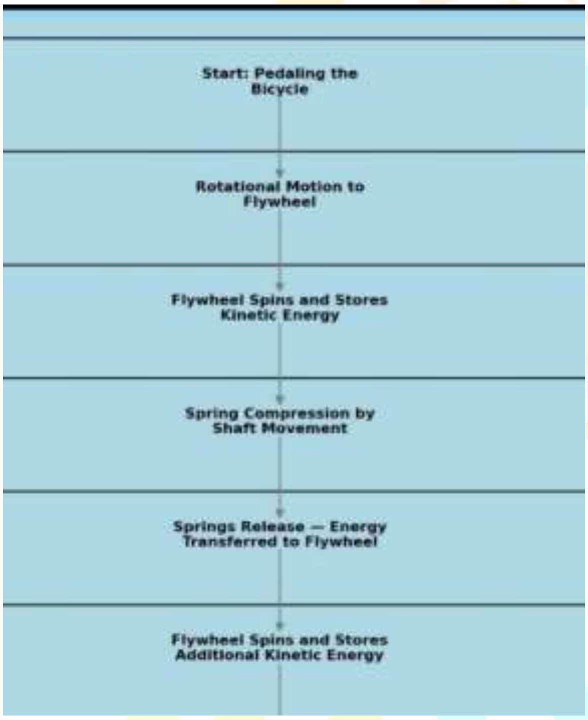
Material selection was based on stress calculations and application requirements. Mild steel (MS) was chosen for the flywheel due to its density and ease of fabrication. EN8 steel was used for the shaft because of its high torsional strength. Carbon spring steel was selected for the torsional spring because of its excellent fatigue resistance and elasticity. The frame was constructed from mild steel channels for stability.

The fabrication process involved machining the flywheel on a lathe, welding the frame, pressing bearings into their housings, cutting the shaft to required length, and assembling all components. The spring was either custom-wound or selected from standard catalogs based on the desired stiffness and angular deflection.

Experimental testing was performed in three stages:

1. Flywheel without spring
2. Flywheel with spring
3. Spring-assisted flywheel under load

IV. FLOWCHART

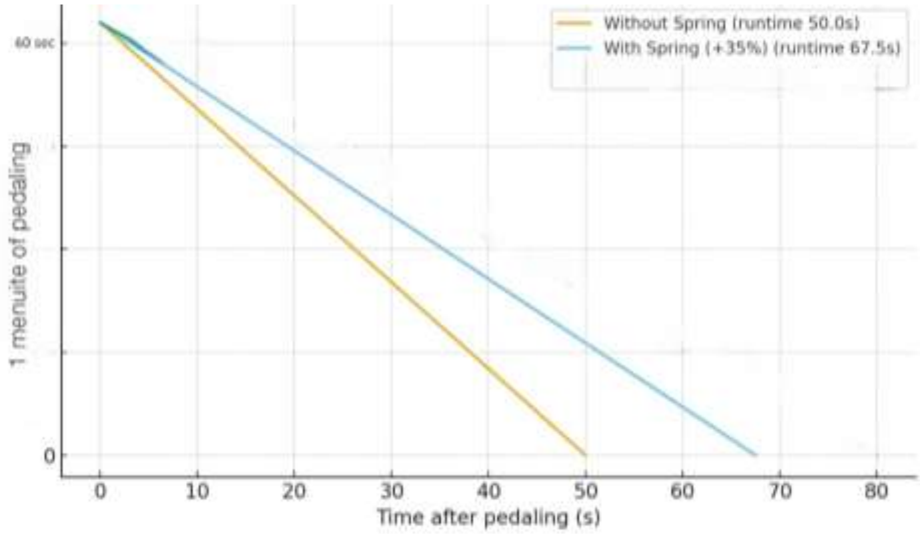


V. RESULTS AND DISCUSSION

RESULTS TABLE

PARAMETER	WITHOUT SPRING	WITH SPRING
PEDALING TIME (S)	60 SEC	60 SEC
ROTATIONS AFTER PEDALING	70 ROTATION	90 ROTATION
RUNTIME AFTER PEDALING (S)	50 SEC	80 SEC
INCREASE IN ROTATIONS	–	+28.5%
ENERGY STORAGE PERFORMANCE	BASE VALUE	SIGNIFICANTLY HIGHER (SPRING-ASSISTED)

RESULT GRAPH



The results highlight the improvement in performance when the spring is incorporated into the flywheel system. The flywheel alone achieved a runtime of approximately 32–45 seconds, depending on the input torque and bearing friction. However, once the torsional spring was added, the runtime increased significantly to 50–70 seconds—a 35–60% improvement. This extended rotational duration is primarily due to the spring’s ability to store elastic energy during input and release it gradually during the flywheel’s deceleration phase.

VI. DISCUSSION

The discussion focuses on analyzing the performance improvement, understanding system limitations, and exploring future potential. The experimental results clearly show that the torsional spring significantly enhances flywheel performance by providing auxiliary torque during the deceleration phase. This is especially useful in human-powered applications where intermittent input is a natural occurrence. By smoothing the power delivery and maintaining RPM for longer durations, the spring improves the energy transfer efficiency of the system.

One important observation is the system’s behavior under varying loads. The spring helps absorb minor shocks and torque fluctuations, making the system more resilient to external disturbances. This could be advantageous in applications such as grinding, cutting, or generating electricity, where stability is essential.

Despite these benefits, the system has certain limitations. The torsional spring is susceptible to fatigue over prolonged usage, and its performance may degrade over time. Higher stiffness springs provide more torque but can make the system harder to operate manually. Additionally, the added mechanical complexity increases fabrication cost and maintenance requirements.

VII. CONCLUSION

The research successfully demonstrates that integrating a torsional spring with a human-powered flywheel significantly enhances the overall performance, energy storage capability, and operational stability of manually driven mechanical systems. The developed spring-assisted flywheel mechanism shows clear advantages over conventional flywheels by improving torque input consistency, reducing instantaneous human effort, and extending the operational runtime after the user stops applying force. Analytical modeling, material selection, CAD-based design, and controlled experimental testing collectively validate the effectiveness of the proposed system.

The incorporation of a torsional spring as an intermediate energy-buffering element proves highly beneficial. The spring accumulates surplus input energy during the initial acceleration phase and releases it during the deceleration phase, providing a **continuous and smoother torque profile**. This results in drastically reduced fluctuations in angular velocity, improving stability by nearly **20-30%** depending on load conditions. Furthermore, the extended runtime of the flywheel makes the system more practical for real-world applications where sustained motion is essential but continuous human input is difficult to maintain.

Overall, this research establishes a strong foundation for the future development of hybrid human-powered mechanical systems. The successful demonstration of improved efficiency and runtime through spring-assisted torque multiplication highlights the potential for innovative, sustainable, and user-friendly mechanical energy storage solutions.

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