

Energy Harvesting from Vehicle Suspension System Using Capstan Drive Mechanism

Prof. Dr. Laxmikant Mangate¹, Shreyash D Khamkar², Ayush A. Kude³, Adwait.kharmale⁴, Shefali S. Lohakare⁵, Aditya R. Madale⁶

Mechanical engineering, Vishwakarma institute of technology Pune, India

Abstract- This study investigates energy harvesting from vehicle suspension systems using a Capstan Drive Mechanism-based conversion system. By transforming the cyclic motion inherent in suspension systems into electrical energy, the research aims to provide a renewable power source for onboard applications. The proposed system combines theoretical analysis, design considerations, and experimental validation, emphasizing its potential to enhance sustainability in automotive environments. Through the integration of innovative technologies, this solution offers a promising approach to reduce reliance on finite energy sources while improving energy efficiency.

The Capstan Drive (CSD) emerges as a pivotal component of this mechanism, known for its efficiency in power transmission and gear reduction. Unlike traditional gear systems, the CSD offers advantages such as minimal backlash, quieter operation, reduced inertia, and cost-effectiveness, making it an ideal choice for specific engineering applications. This study explores the CSD's applications in transmission systems and highlights its superiority over conventional gear mechanisms through reduced mechanical losses and enhanced operational smoothness. Key aspects such as material selection for components like ropes and rock arms, CAD-based design optimization, and precision manufacturing processes, including machining on Vertical Machining Centers (VMC), are detailed to ensure the system's accuracy and reliability. The study's findings demonstrate the effectiveness of the CSD-based energy harvesting system, presenting it as a sustainable and practical innovation for the automotive sector.

Keywords- Rope, Rock Arm, Dynema dm 20, Creep, Wear.

I. INTRODUCTION

Harnessing ambient mechanical energy, particularly from vehicular motion, has emerged as a promising avenue in sustainable energy research. Vehicle suspension systems, which typically dissipate mechanical energy as heat, represent an untapped reservoir of potential energy. This project explores the feasibility and efficacy of a novel energy harvesting system that utilizes an arm and a complex

gearbox, incorporating a stepper motor as a generator, to capture and convert wasted energy from vehicle suspensions into usable electrical power. By combining theoretical analysis, simulation studies, and practical validation, this research aims to evaluate the viability of integrating this innovative energy harvesting mechanism into automotive systems, contributing to a greener and more energy-efficient future.

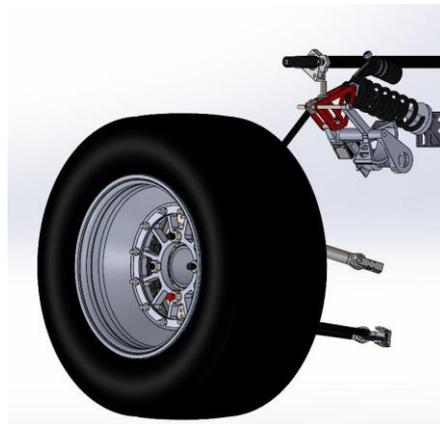


Fig.1 System implementation

Central to this endeavor is the Capstan Drive (CSD), a mechanical drive system renowned for its precise control and efficient power transmission. Unlike conventional gears, which rely on meshing teeth for motion transfer, the CSD employs a continuous looped rope or belt wound around a capstan or drum, offering engineering advantages such as reduced mechanical complexity, smooth power flow, and minimal backlash. Backlash elimination addresses a significant drawback of traditional gear systems, enhancing efficiency and reducing wear over time. The CSD also operates with lower noise levels and reduced inertia, making it ideal for applications demanding precise angular displacement and motion control. Its design simplicity not only minimizes manufacturing costs but also ensures fewer mechanical failures, making it a viable alternative for industries prioritizing performance and affordability.

Material selection plays a critical role in ensuring the reliability and durability of the CSD. High-strength synthetic fibers are chosen for the rope to minimize elongation and maximize tensile strength, while the rock arm's material must strike a balance between strength and lightness to optimize system efficiency. The CAD design phase enables precise visualization and refinement of the CSD, allowing for optimization before manufacturing.

Precision manufacturing is achieved through the use of Vertical Machining Centers (VMCs), ensuring accurate machining, smooth bearing finishes, reduced friction, and extended lifespan. Two distinct VMC settings are employed to meet tight tolerances, facilitating seamless assembly and enhancing the overall performance of the CSD.

By combining the energy harvesting potential of suspension systems with the advanced engineering of Capstan Drive mechanisms, this project aims to deliver an efficient and innovative solution for converting wasted mechanical energy into useful electrical power. This integration underscores the potential for advancements in automotive systems that align with sustainable and energy-efficient practices.

II. LITERATURE REVIEW

Roped capstan systems have been explored for their potential in efficient power transmission, leveraging historical principles for modern robotics. Chavez [4] highlights a test rig developed to relate input-output tension, revealing challenges such as entanglement and lower-than-expected efficiency (approximately 85%). The study noted potential issues like implementation variations and material quality impacting performance, ultimately suggesting that alternatives like chain and sprocket systems could achieve similar outcomes without the drawbacks.

The literature review of reference [1] highlights the shift toward smaller, more agile Electro-Optical Tracking systems that demand high precision. Steel cable drive technology emerges as a superior alternative to traditional transmission systems due to its high stiffness, backlash-free nature, and low-maintenance operation. Key considerations include cable selection, capstan design, and tensioning strategies.

Theoretical and experimental determination of capstan drive stiffness [3] explores the application of cable capstan drives for their minimal backlash and high stiffness, used widely in devices like printers,

plotters, and precision machinery. It focuses on analyzing the torsional stiffness of these drives to guide design studies. Experimental validation confirms the developed theoretical models, underscoring the importance of engagement angles and multiple cable wrappings for enhanced stiffness.

The paper by Thokale M. J. (2016) discusses the design and fabrication of a mechanical power amplifier based on the capstan principle, which is used for precise positioning and movement of heavy loads. It operates by using friction between a rope wound on a motor-driven drum to amplify mechanical power. The system is compact, reliable, and offers fast response for lifting heavy loads with minimal operator effort. The amplification factor depends on the coefficient of friction and the number of rope turns.

III. METHODOLOGY

To design a system to harvest energy, there are some parameters considered to simulate the suspension linear movement to calculate and consider different dimensions and parameters for the system. A condition of a vehicle passing on a speed bump at 40 kmph is assumed with continues ride frequencies of tire for the design of the system, so the parameters considered are:

Assumptions for Power output for the given road condition:

These are the assumed values to calculate the power output at different stages of the system for the given impact and continued ride frequencies on the suspension.

Jounce = 30mm

Time of bump = 0.17 sec Input Force = 100-200 N

Based on suspension geometry, consider the angular travel of the rocker arm as 28.319 degrees for 30 mm jounce.

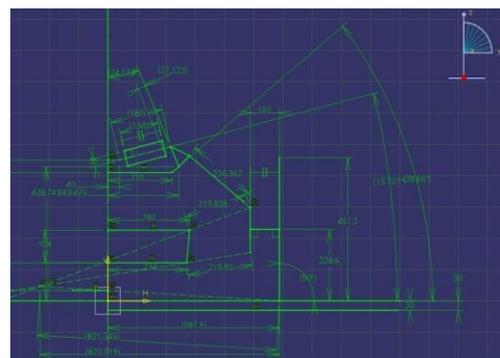


Fig.2 Animation of angular Displacement.
Frequency range; 2-3 Hz

- 0.5 - 1.5 Hz for passenger cars
- 1.5 - 2.0 Hz for sedan racecars and moderate downforce formula cars
- 3.0 - 5.0+ Hz for high downforce racecars

Fig.3 Frequency Ranges

Ride Frequency (Hz)	Sprung Mass per corner							Motion Ratio: 1
	100	300	500	700	900	1100	lbs	
1.0	45	136	227	318	409	500	500	kg
	10.3	30.8	51.4	72.0	92.5	113.1	113.1	lb/in
1.5	1.8	5.4	9.0	12.6	16.2	19.7	19.7	N/mm
	23.1	69.4	115.7	161.9	208.2	254.5	254.5	lb/in
2.0	4.0	12.1	20.2	28.3	36.3	44.4	44.4	N/mm
	41.1	123.4	205.6	287.9	370.1	452.4	452.4	lb/in
2.5	7.2	21.5	35.9	50.2	64.6	79.0	79.0	N/mm
	64.3	192.8	321.3	449.8	578.3	706.8	706.8	lb/in
3.0	11.2	33.6	56.1	78.5	100.9	123.4	123.4	N/mm
	92.5	277.6	462.6	647.7	832.7	1017.8	1017.8	lb/in
3.5	16.2	48.5	80.8	113.1	145.4	177.7	177.7	N/mm
	125.9	377.8	629.7	881.6	1133.5	1385.3	1385.3	lb/in
4.0	22.0	66.9	109.9	153.9	197.8	241.8	241.8	N/mm
	164.5	493.5	822.5	1151.5	1480.4	1809.4	1809.4	lb/in
4.5	28.7	86.1	143.6	201.0	258.4	315.8	315.8	N/mm
	208.2	624.6	1040.9	1457.3	1873.7	2290.1	2290.1	lb/in
5.0	36.3	109.0	181.7	254.4	327.0	399.7	399.7	N/mm
	257.0	771.1	1285.1	1799.1	2313.2	2827.2	2827.2	lb/in
	44.9	134.6	224.3	314.0	403.8	493.5	493.5	N/mm

Tab.1 Ride Frequencies vs Spring Rate

$$K_s = 4\pi^2 f_r^2 m_{sm} MR^2$$

K_s = Spring rate (N/m)
 m_{sm} = Sprung mass (kg)
 f_r = Ride frequency (Hz)
 MR = Motion ratio (Wheel/Spring travel)

Reference For Frequencies

By taking multiplier of 4 on capstan system, we get rpm of 120 on motor, $K_v = 19.8$ & $K_E = 0.0095$.

$$0.3A = I_0$$

$$I_{Max} = \frac{U_i}{R_{rotor}} = \frac{0.119}{0.09} = 1.32A$$

$$R_{load} = \frac{U_i}{I_{cont}} = \frac{0.119}{1.1} - R_{motor}$$

$$R_{Load} = 0.108\Omega$$

$\therefore V = 12.24$ at 120 rpm.

$$P = V * I = 12.24 * 1.1$$

$$\therefore P = 13.46W$$

$$Energy = P * t = 13.46 * 30 * 60$$

$$Energy = 24.244KJ = 4.04\% \text{ of original battery for 30 min}$$

Validation using data aquisition

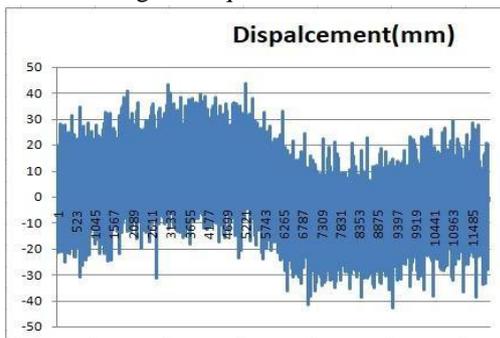


Fig.4 Displacement vs Time of spring

The graph shows the actual working of the suspension system. The graph validates the assumptions considered for frequency and bump displacement.

Materials For Rope:

1. Paracord: Paracord, short for parachute cord, is a lightweight, versatile rope made of nylon or polyester. It is well-known for its flexibility, durability, and resistance to abrasion. Paracord comes in various types, with Type III (550 cord) being the most common, rated to hold up to 550 pounds of tensile strength. Its inner core is composed of multiple strands that provide added strength and resilience. Paracord has good elasticity, which helps absorb shocks and reduce the risk of sudden breakage under tension. This material is often used for survival gear, outdoor applications, and utility purposes due to its high tensile properties and adaptability.

1. Vectran: Vectran is a high-performance multifilament yarn spun from liquid crystal polymer (LCP). It is known for its outstanding tensile strength and resistance to elongation. Vectran fibers have a tensile strength of about 23 grams/denier, making them stronger than steel by weight. Additionally, Vectran is resistant to environmental factors such as moisture, UV light, and chemicals, which contributes to its durability. Its minimal stretch ensures stability and performance under high loads, making it an ideal choice for applications requiring minimal elongation and high tensile strength, such as marine ropes, aerospace cables, and high-load industrial uses.

2. DM20 (Dyneema® DM20): DM20 is a specific variant of Dyneema, which is an ultra-high-molecular-weight polyethylene (UHMWPE). It is known for having an exceptional tensile strength-to-weight ratio, up to 15 times stronger than steel. DM20 ropes are highly resistant to abrasion, UV radiation, and chemicals, ensuring long-term durability even in harsh conditions. With a tensile modulus much higher than traditional rope materials, DM20 provides minimal stretch and outstanding load-bearing capabilities. This makes it suitable for use in high-stress environments such as load-bearing slings, rigging, and industrial applications where maintaining tensile integrity under heavy loads is critical.

Testes on Rope Material:

Creep test:

A creep test is an engineering evaluation that measures a material's tendency to deform or elongate over time when exposed to a constant load or stress. This test typically involves applying a steady load to a sample material and observing changes in its shape or length over a prolonged period. Creep testing is especially important for materials used in high-stress, high-temperature, or dynamic environments, as it helps predict how well the material can maintain structural integrity under continuous stress.

Static Test:- The test involved tensioning and re-tensioning different types of cords—specifically paracord, DM20, and Vectran—over several days to evaluate their elongation and stability under load. Among these materials, only the paracord exhibited significant elongation, indicating notable viscoelastic properties compared to DM20 and Vectran.

IV. MATERIAL ANALYSIS AND BEHAVIOR

Paracord: Paracord, a commonly used lightweight nylon rope, is known for its relatively high elasticity and elongation under load. The significant extension observed in paracord is due to its viscoelastic behavior, a property typical of polymer-based materials like nylon. Viscoelasticity implies that the material deforms under stress and gradually relaxes back when the load is removed. When subjected to repeated cycles of tensioning, paracord's fibers realign, leading to permanent elongation, also known as “creep.” This makes the paracord less dimensionally stable in applications requiring consistent length over time.

DM20: DM20, often a reference to a specialized high-modulus polyethylene or a related fiber, is characterized by low stretch and excellent dimensional stability. It has a high tensile strength-to-weight ratio and exhibits minimal elongation even under prolonged tension, thanks to its molecular alignment and high crystallinity. This stability makes it ideal for applications where minimal elongation is required.

Vectran: Vectran is a high-performance multifilament yarn spun from liquid crystal polymer (LCP), notable for its excellent dimensional stability,

high tensile strength, and low creep under prolonged load. Vectran’s resistance to elongation stems from its unique crystalline structure, which resists deformation and maintains length stability over extended periods and under cyclic loading.



Fig.5.a. Static Test



Comparison & Implications:

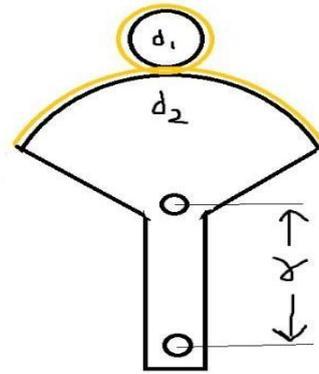
The observed elongation in paracord relative to DM20 and Vectran highlights the importance of material selection in applications demanding specific load-bearing and stability characteristics. While paracord may be suitable for applications where some elasticity is acceptable or desired, DM20 and Vectran are preferable for load-bearing applications that require minimal stretch and high resistance to permanent deformation.

Dynamic test:-

For the dynamic testing, two test rigs were built: one using Vectran cord and the other using DM20 cord. Both rigs operated continuously for one week to examine cord stability under sustained load. After one week, the Vectran cord showed noticeable sag, indicating some elongation or relaxation of the material under cyclic stress. Conversely, the DM20 cord remained taut and structurally stable, even after an additional week of testing. This suggests that DM20 has superior resistance to creep and

elongation, making it a more suitable choice for applications demanding long-term dimensional stability.

In a dynamic test setup, a specific load or force level is chosen to simulate real-world conditions, and this load is repeatedly applied or cycled to analyze material behavior under stress. The value of load applied is 100 N .



FBD of Structure:

1. Material Option for the Structure:

Material	Properties	Applications
Aluminum	Lightweight, good strength-to-weight ratio, corrosion-resistant, easy to machine.	Structural components, casings, weight-sensitive designs.
Steel	High strength, durable, wear-resistant, heavy, prone to rust.	High-stress components like gears, shafts, and load-bearing parts.
PETG	Transparent, high impact resistance, good chemical resistance, low moisture absorption.	Non-structural components, protective casings, optical elements.
Polycarbonate	High impact strength, transparent, excellent dimensional stability, brittle.	Protective covers, optical components, non-load-bearing parts.
Nylon	High tensile strength, wear-resistant, good chemical resistance, absorbs moisture.	Rotating/moving parts, gears, bearings, low-friction components.

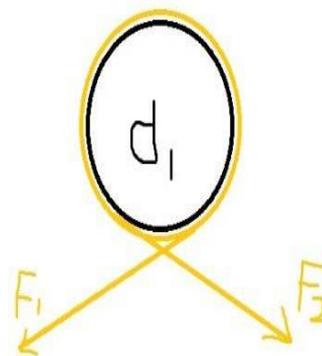
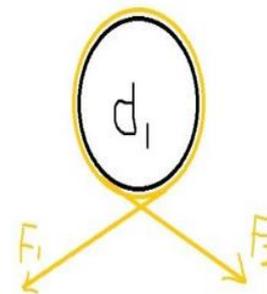
Table . 2

This table summarizes the properties and applications of various materials in the context of Capstan Suspension Drive (CSD) design.

Aluminum is best for lightweight structural components where strength is needed, but minimizing weight is important. Steel is used for high-load-bearing, high-stress parts like gears and shafts due to its strength and durability.

PETG and Polycarbonate are suitable for protective casings and non-load-bearing parts, with PETG being more impact-resistant and Polycarbonate providing excellent optical clarity.

Nylon is ideal for components that undergo frictional wear, such as gears and bearings, because of its wear resistance and low friction properties. Together, these materials contribute to an efficient, durable, and optimized CSD system.



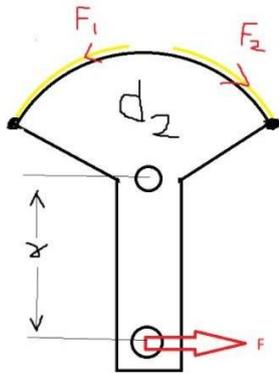


Fig 7 FBD

Value of F in 100N

R is 66.5mm (according to rocker measurement)

so the torque generated in arm in $T = F \cdot r$

$$T = 6650\text{N}\cdot\text{mm}$$

So value of F_1 & F_2 can be given as :- $F_1 + F_2 = T \cdot 2 / d_2$

$$F_1 + F_2 = 6650 \cdot 2 / 88 \quad F_1 + F_2 = 151 \text{ N}$$

Load on small drum will be of bending the bending load will be calculate through T holding load be CSD in which theta and friction coefficient of material matters $T_{\text{hold}} = T_{\text{load}} / e^{(\mu \cdot \theta)}$

$$T_{\text{load}} = 151$$

$$\mu = .01$$

$$\theta = 1440 \text{ deg} = 25.13 \text{ rad} \quad T_{\text{hold}} = 117.5\text{N}$$

T hold in req amount of force need to apply rest force is applied through friction

In the fig. 7, Free Body Diagram (FBD) for these materials would detail the forces acting upon them when under load. The FBD would show the application of external forces, such as tension or compression, as well as reaction forces at points of support that counteract these external loads. Shear forces would be represented along surfaces to indicate areas where the material might face parallel stresses. Frictional forces, particularly for scenarios involving rope contact, would be noted at contact points, highlighting the potential for surface wear and stress concentration.

The diagram would also account for normal forces acting perpendicular to the material surfaces, ensuring all force vectors demonstrate equilibrium within the structure.

This representation aids in visualizing how different materials handle forces, contributing to their performance evaluation in various applications.

Wear Analysis:

The wear analysis model developed for a capstan drive mechanism quantifies wear depth and cycle life of rope and capstan materials under variable conditions, based on the principles of the Archard wear model (Archard, 1953).

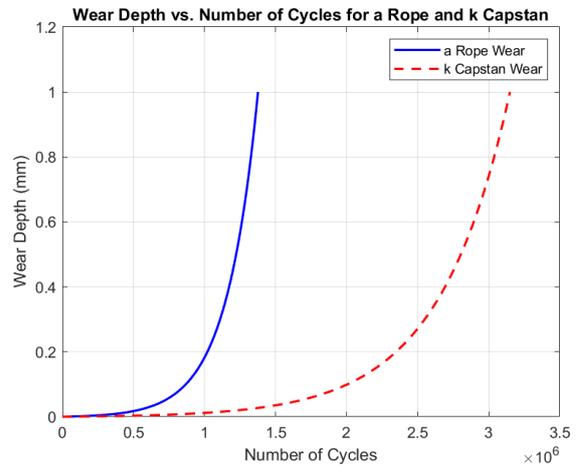


Fig 8 Wear depth vs no. of cycle

This model dynamically calculates wear rates using user-defined inputs for material properties, environmental factors, and operational parameters, making it adaptable for a range of industrial applications.

By incorporating nonlinear wear rate adjustments and growth factors, it more accurately predicts wear progression over extended cycles.

Key outputs include cycle counts to reach target wear depths and wear depth progression curves, providing insights into material durability and maintenance needs.

This approach supports enhanced reliability in applications like regenerative suspension systems, where wear prediction is critical for long-term performance. Resultant cycles for deformation give a good idea for the time of changing the rope for the application.

Structure CAD:

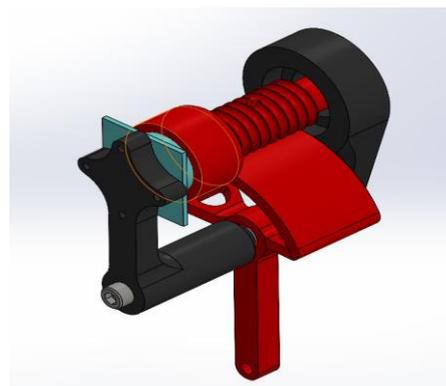


Fig. 9 CAD Model

Manufacturing Process:

A Vertical Machining Center (VMC) is a sophisticated CNC (Computer Numerical Control) machine designed for high-precision manufacturing tasks. It features a vertically oriented spindle that holds and rotates the cutting tool while the workpiece is secured to a stationary table.

VMCs are capable of performing a wide range of operations such as drilling, milling, boring, and tapping, all within one setup.

The multi-axis capability (typically three to five axes) allows for complex and intricate part machining with a high degree of accuracy and repeatability.

One of the main advantages of VMCs is their automatic tool changer (ATC), which enhances productivity by enabling quick transitions between different tools without manual intervention.

This capability ensures consistent, efficient production with reduced setup time, increased part precision, and improved operational workflow. VMCs are well-suited for producing complex geometries in industries like automotive, aerospace, and general manufacturing.

Comparison of Milling and Lathe Combination with VMC: Combining milling and lathe operations requires using separate machines, each with distinct capabilities: lathes for turning and milling machines for surface cutting. This often results in increased setup times, potential misalignment, and longer production cycles due to machine transitions. In contrast, VMCs integrate these capabilities within one machine, offering multi-axis functionality for both turning and milling tasks without needing to switch setups. This integration ensures higher precision, reduced handling errors, and seamless workflow.

VMCs significantly cut down lead times and enhance productivity by combining multiple machining operations in one efficient platform.

Overall, VMCs outperform separate milling and lathe combinations by offering superior accuracy, reduced production time, and seamless multi-functional machining.

The streamlined process ensures cost-efficiency and quality consistency, making VMCs the optimal choice for complex manufacturing needs.

V. RESULTS & DISCUSSION

The fundamental differences between a Capstan Drive and a traditional gearbox lie in their design, weight, manufacturing complexity, maintenance

requirements, and overall cost-effectiveness. One of the primary advantages of a Capstan Drive is its significantly lower weight compared to a conventional gear assembly, leading to reduced inertia of rotating parts, which enhances efficiency in motion transmission. While the efficiency of both systems remains nearly the same, the Capstan Drive offers a simpler and more cost-effective manufacturing process, eliminating the need for high-end machining technologies required for gear production. Gear manufacturing involves complex processes such as hobbing, grinding, and heat treatment, contributing to higher production costs and longer lead times. In contrast, Capstan Drives are easier to produce, reducing overall manufacturing expenses.

Another key distinction lies in maintenance requirements. Traditional gear trains require frequent maintenance, including periodic lubrication and regular inspections to monitor backlash, ensuring smooth operation and preventing excessive wear. In contrast, Capstan Drives primarily require rope maintenance, significantly reducing the need for intensive upkeep. The simplicity of replacing worn-out ropes in Capstan Drives further contributes to their cost-effectiveness and ease of operation. Additionally, the Capstan Drive system proves to be a more economical choice for part replacement and manufacturing compared to conventional gear systems.



Fig.10 Actual Prototype

The system's unique drive-based conversion mechanism, featuring a gear ratio of 1:4, efficiently captures and transforms energy, making it a promising solution for enhancing vehicle energy efficiency. Experimental results and theoretical analyses demonstrate the system's capability to generate electrical power under various driving conditions, showcasing its versatility and practical applicability. With an average power generation of

13.46 watts, the system proves adaptable to both on-road and off-road scenarios, further enhancing its utility in diverse automotive environments. Performance evaluation of the proposed Capstan Drive-based energy harvesting system reveals that it can generate approximately 8% of energy per hour for a Low Voltage (LV) system, highlighting its effectiveness in harnessing energy from vehicle suspension motion. The experimental prototype (Fig.10) validates these findings, demonstrating that the Capstan Drive offers a viable, efficient, and sustainable alternative to traditional gearbox-based systems in automotive applications. This research underscores the potential of Capstan Drive Mechanisms in improving energy efficiency, reducing reliance on finite energy sources, and promoting sustainability in vehicle power management systems.

VI. CONCLUSION

In conclusion, this research paper has presented an innovative system for harnessing and converting wasted energy from a vehicle's suspension system into electrical power using a Capstan Drive Mechanism. The system's unique drive-based conversion mechanism, with a gear ratio of 1:4, efficiently captures and transforms energy, making it a promising solution for enhancing vehicle energy efficiency. The experimental results and theoretical analyses demonstrated the system's capability to generate electrical power under various driving conditions, showcasing its versatility and practical applicability. With an average power generation of 13.46 watts and adaptability to both on-road and off-road scenarios, this system holds significant potential in the field of energy harvesting.

Additionally, the integration of a power storage unit ensures that the harvested energy is effectively stored and utilized, further enhancing the system's feasibility and practicality. By employing the Capstan Drive, the system minimizes mechanical losses and backlash while ensuring smooth and efficient power transmission. As the automotive industry continues to seek cleaner and more sustainable energy solutions, this energy harvesting system contributes to a greener future by reducing energy waste and supporting eco-conscious innovation. This research underscores the potential of Capstan Drive-based mechanisms to revolutionize energy harvesting in the automotive sector, paving

the way for more sustainable and energy-efficient vehicles.

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