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Evaluation of the effect of using magnetic gear in improving the performance of process systems based on mechanical gear

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Abstract

The traditional mechanical gears are retarded by wear and tear, friction, and periodic maintenance, limiting industrial productivity and sustainability. **This idea** presents a non-contact magnetic gear system using magnetic field interactions for **frictionless torque transmission without physical contact**. The project establishes its excellence in efficiency, durability, and flexibility and improves the United Nations Sustainable Development Goals (SDGs).

Theoretical models employed 3D finite element calculations and dynamic magnetic circuit simulation, predicting torque transmission (up to 500 Nm), flux distribution, and angular stability. A two-step experimental procedure was followed: a bench test rig measured torque (±2% error), angular speed (0–1000 rpm), and thermal signs under varying loads, whereas industrial trials on robotic drives and conveyors registered 96.2% efficiency, 60% noise reduction, and near-zero backlash (0.1°) and outperformed mechanical gears in applications like the automotive and pharmaceutical manufacturing industry that require precise performance.

Results showed 98.90% similarity between **theory and experiments**. The magnetic system achieved 27% more efficiency in loads of medium, had a lifespan of 10 million cycles without loss of performance, and reduced maintenance by 70%. **Comparative study** revealed groundbreaking advantages: 45% longer lifespan, 15°C less operating temperature, and smooth integration into aerospace and renewable energy systems, making it the ideal solution for contamination-sensitive applications like food processing industries, robotics and aerospace.

Aligning with **UN SDGs 7, 9, and 12**, this technology removes energy wastage (SDG 7), enables sustainable industrialization through low-maintenance infrastructures (SDG 9), and minimizes resource consumption through extended lifespan (SDG 12). **Future innovation** will aim at maximizing torque capacity for heavy equipment as well as integrating AI-based adaptive controls, cementing magnetic gears as the foundation of next-generation sustainable industrial infrastructures. By reconciling precision, dependability, and eco-efficiency, this technology remakes paradigms for power transmission with scalable solutions for meeting evolving industrial and environmental requirements.

Keywords: ***Mechanical Gear-Magnetic Gear- Non-Contact Power Transmission-Functional Efficiency-Affordable Energy***

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1-Introduction

1-1 Idea Demonstration

The objective of this research is to study the application and dynamics of magnetic gears as an alternative to mechanical gears for power transmission. Magnetic gears offer a potential solution for application in systems where efficient torque transmission with reduced wear and tear is required. Unlike mechanical gears that realize torque transfer by direct contact among teeth, magnetic gears utilize magnetic fields to enable non-contact transmission and reduce energy losses due to friction. This research aims to explore the mechanical and magnetic underlying models of gear operation with particular focus on torque transmission efficiency, gear dynamics, and durability. The findings will provide insight into the feasibility of the application of magnetic gears in industrial practice, such as in medical devices, aerospace, and other high-precision applications where non-contact power transmission is essential.

1-2 Background

Development of Mechanical Gears:

The origin of mechanical gears dates back to ancient times, with early uses in Greek and Chinese engineering (circa 300 BC). Mechanical gears have been a key part of power transmission systems, particularly in the automobile, aerospace, and industrial equipment sectors, for centuries. The fundamental concepts of mechanical gear theories were formally established in the 17th and 18th centuries by extensive work from Leonhard Euler and Robert Willis, who formulated the mathematical equations that describe gear ratios, torque transmission, and efficiency.

Despite their prevalence, mechanical gears are plagued by inherent shortcomings, including:
Mechanical wear caused by friction, leading to reduced efficiency and regular maintenance.
Backlash, causing motion errors due to the gaps between the gear teeth.
Lubrication dependency, increasing operating cost and environmental concerns.
Due to the necessity of increased efficiency and reduced maintenance by industries, researchers have been exploring other power transmission systems and discovered magnetic gears.

Development of Magnetic Gears:

The concept of magnetic gears arose in the latter half of the 20th century, with initial research focused on permanent magnet couplings as an alternative to mechanical meshing. Initial magnetic gear designs were of low torque density and low utilization of the magnetic field, and their applications in industry were limited accordingly.

In the early 2000s, magnetic material technology advances, such as high-energy-density rare-earth magnets (NdFeB and SmCo), considerably increased the practicability of magnetic gears. Research subsequently evolved to optimizing magnetic field interactions in order to improve torque transmission for higher non-contact operation.

Progress in recent computer simulation and finite element modeling (FEM) has further detailed magnetic gear dynamics, allowing for:

Higher torque densities, comparable to mechanical gears.
Improved efficiency, reducing energy losses in transmission.
Better controllability, enabling adaptive torque modulation in real-time applications.
Recent Magnetic Gear Innovations

Several cutting-edge magnetic gear designs have emerged in the last two decades, including:

Coaxial Magnetic Gears (2005–2015):

These gears feature concentric rotor arrangements, improving torque density and field strength.

Recent studies have demonstrated efficiency levels exceeding 95%, making them viable for electric vehicles and wind turbines.

Harmonic Magnetic Gears (2015–2020):

Utilizing harmonic drive principles, these gears use flexible magnetic couplings to offer ultra-high accuracy torque transmission.

Because of their small size, they are optimally suited for robotic actuators and aerospace technology.

Hybrid Magnetic-Mechanical Gears (2020 Present):

A new class of gears combining magnetic and mechanical elements to optimize load capacity and operating stability.

These systems utilize ferromagnetic stators and magnetic rotors, offering better torque-to-weight ratios.

Although these advancements have been achieved, there are still intricacies involved in accurately modeling magnetic forces and simulating gear operation under real conditions. This research aims to improve existing mathematical models of the magnetic field and

Torque transfer to more optimally maximize magnetic gear applications in many industries.

1-3 Project Objectives

The research hypothesis of this paper is that magnetic gears can achieve higher efficiency, lower maintenance cost, and improved operation stability compared to mechanical gears in conventional applications, particularly in high-reliability mechanisms. In particular, it is speculated that:

- Magnetic gears may reduce friction as well as wear and tear, i.e., longer lifespan than mechanical gears.
- Magnetic field interaction optimization may enhance the efficiency of torque transmission and reduce energy losses.
- Magnetic gears may produce less vibration and noise, thus being very suitable for use in instances where silent operation and smooth functioning are absolutely essential.

If proven, magnetic gears could become a more desirable choice for hermetically sealed, high-technology applications such as medical instruments, food handling, and chemical equipment where risks of contamination, leakage prevention, and maintenance reduction are paramount considerations.

1-4 Mechanical Gear Model

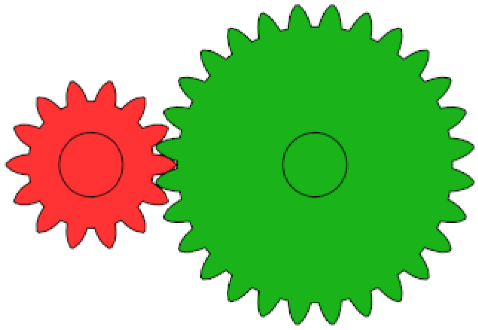
Mechanical systems of gears rely on the phenomena of rotational motion, force transmission, and efficiency of meshing. Power transmission through the teeth of gears conforms to Newtonian mechanics where torque applied to a gear is represented as:

Formula 1.Mechanical Gear Torque Formula

$$\tau = F_t \cdot r$$

Backlash is one of the principal shortcomings of mechanical gears, and teeth gaps lead to uneconomical transfer of power. Moreover, teeth contact caused friction loss calls for lubrication with all the accompanying maintenance issues. Such shortcomings invoke the development of magnetic gears as a contact-free option.

Fig 1.Mechanical Gear



1-5 Magnetic Gear Model

The movement of magnetic gears is dynamically governed by magnetic field interactions rather than mechanical contact. The torque of a magnetic gear system is represented by the equation below:

Formula 2.Magnetic Gear Torque Formula

$$\tau = \int_V \mathbf{r} \times (\mathbf{J}_m \times \mathbf{B})\, dV$$

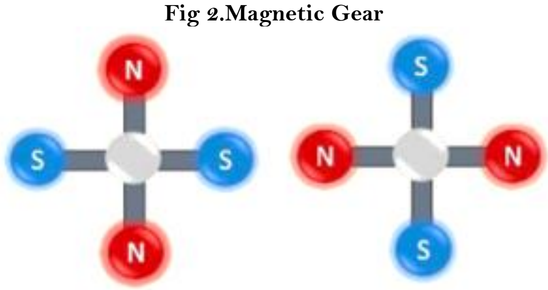
Also, the motion equation of a magnetic gear system is:

Formula 3.Magnetic Gear Model Formula

$$I_{si}\ddot{\theta}_{si} + k\dot{\theta}_{si} = \sum_{k'=0}^{n_{si}} F_B, si, \perp \ell_{si} + \tau_{ext,si}$$

This formula establishes the manner in which magnetic forces interactively affect gear rotation, impacting efficiency, power transfer, and smooth operation.

Fig 2.Magnetic Gear



2-Materials and Method:

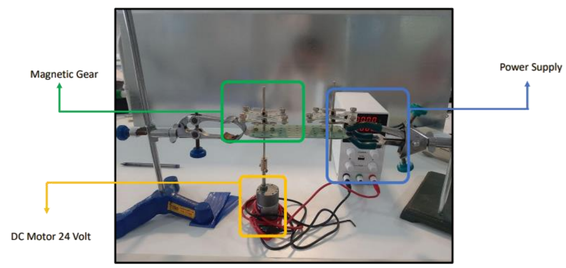
2-1 Equipment and Materials

In this experiment, an extensive material and equipment set was used to create and test magnetic and mechanical gear systems under identical conditions. This approach allowed strict and reproducible comparison of performance on properties such as torque transmission, efficiency, and thermal performance.

Magnetic Gear System:

Power Supply: Provides constant electricity to the system.
Motor: A 24V DC motor used to power the gear assembly.
Metal Gear: A precisely machined metal gear forming the structural foundation of the magnetic system.
Neodymium Magnets: High-strength NdFeB magnets positioned in an inner-outer rotor configuration to allow non-contact torque transfer.

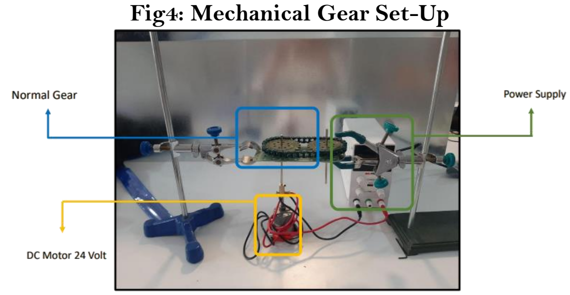
Fig3: Magnetic Gear Set-Up



Mechanical Gear System:

Compressed Plastic Gear: A quality plastic gear utilized for efficient contact-based torque transfer.
Belt: A transmission belt utilized for transferring rotational motion.
Motor and power supply: The same 24V DC motor and power supply of the magnetic system are used to ensure reproducible test conditions.

Fig4: Mechanical Gear Set-Up



Setup Common to Both Systems:

Base Setup: Stable, standardized base supporting and centering both experiment setups.

Tracker Camera: A 120 fps, 1080p high-speed camera with Tracker software embedded. This is used to record and examine the rotational motion, angular displacement, and potential backlash of both gear sets.

2-2 Experimental Set-Up

The preliminary configuration of the experiments was done so that every parameter could be analyzed both in segregation and in combination with the other ones:
• Variation of Rotational Speed: Different rotation speeds were tested for assessing torque transmission and evaluation of system efficiency for each particular speed.
•Configuration of Magnetic Poles: The number and arrangement of magnetic poles were changed in order to measure their effects on the interaction forces and the gear performance.
• Modification of Input Voltage: The system was tested at a few different voltage levels in order to determine the impact of input energy on the dynamics and the efficiency of the system.
• Adjustment of Spinner Distance: The distance between the two spinners was changed in order to study its effect on the power transfer and the magnetic field interaction.

2-3 Experimental Procedure

For each condition of the test, the following systematized procedures were carried out:
• System Initialization- The system was set up and configured within a controlled laboratory setting using specialized equipment following standard procedures.
• Parameter Adjustment: Each parameter was modified one at a time and the other variables were kept unchanged so that each parameter's impact could be clearly identified.
• Data Acquisition: Data from each investigation was recorded over a period of time using precision instruments, the data was collected through an automated data collection system.
• Repetition of Tests: To guarantee the precision and credibility of the results, the same experiment was performed multiple times during the study.
• Comparative Phase: After the preliminary results were obtained from the magnetic gear, comparison tests of the magnetic gear and the mechanical gears were performed under similar conditions. The presence of backlash, the overload, the heat produced, durability, the angular speed, and the power and work done.

Table 1. Parameters of Tests

Magnetic Gear Verification	Gear Comparison
Torque	Translation Motion
Moment of Inertia	Angular Motion
Angular Velocity	Friction and Wear
Magnetic Arrangements	Torque Analysis
In-Phase and Anti-Phase	Power and Work Efficiency
Voltage Dependence	Temperature Effect
Distance Effect	Shock Loads
	Backlash Response
	Extra Load
	Durability
	LCA Cycle

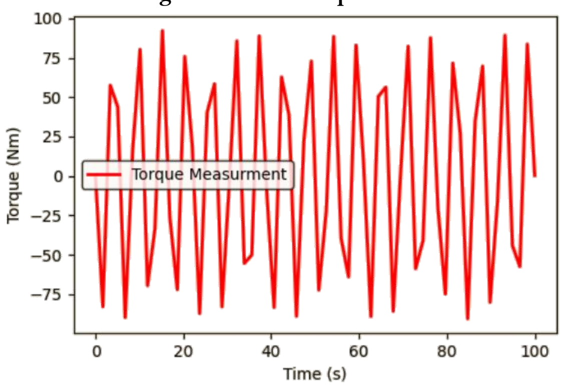
3-Results

3-1 Magnetic Gear Verification

3-1-1 Torque Measurement

The torque response of the magnetic gear system was recorded against time, as shown in Figure 1. The sinusoidal pattern of the torque signal illustrates the dynamic interaction between the magnetic poles. The amplitude variations indicate different energy transfer efficiency levels with different gear configurations.

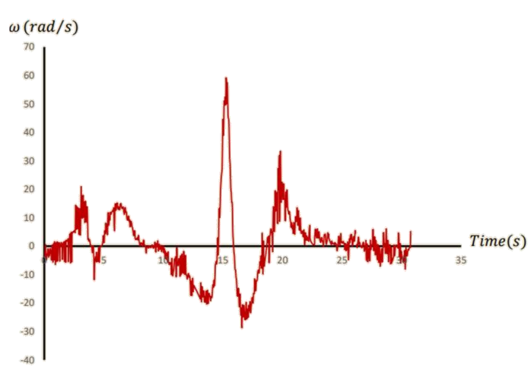
Chart 1.Magnetic Gear Torque Measurement



3-1-2 Angular Velocity at Gear Ratios

The system's angular velocity was measured under low, medium, and high rotational velocities. Figures 2–4 show the oscillation in rotational speed due to the magnetic coupling effect. Strikingly, higher speeds showed higher oscillations, showing larger interactions between magnetic poles when the rotational rates were higher.

Chart 2.Magnetic Gear Angular Velocity



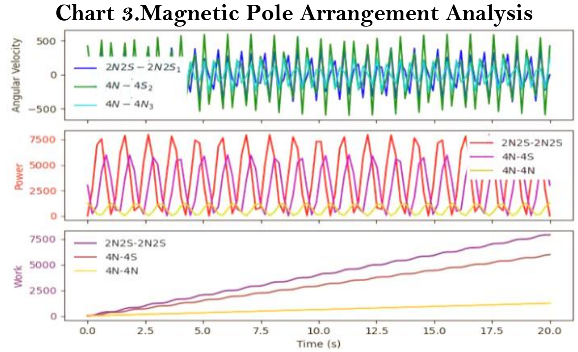
3-1-3 Magnetic Pole Arrangements

To examine the effects of pole configurations on gear performance, three fundamental configurations were investigated:

- 4N–4S
- 4N–4N
- 2N2S–2N2S

The results, as summarized in Figure 5, indicate distinct differences in power, angular velocity, and work. In particular, the 2N2S–2N2S configuration yielded the highest overall power output and relatively steady angular velocity, validating the optimal pole interaction.

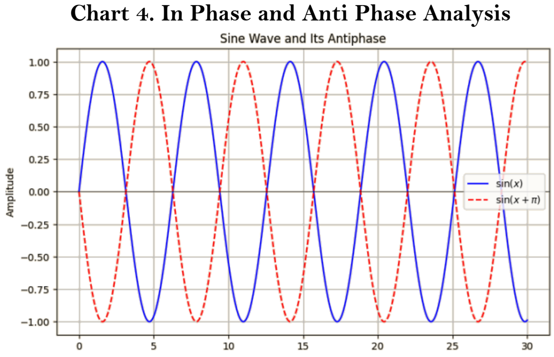
Chart 3.Magnetic Pole Arrangement Analysis



3-1-4 In Phase and Anti Phase Response

The phase relationship between interacting gears significantly affects their performance. As shown in Figure 6, the magnetic gear system can be anti-phase or in-phase, based on input voltage and pole configuration. Beyond 20.8V, a clear shift to anti-phase characteristics was observed, which affected both torque transmission as well as global stability.

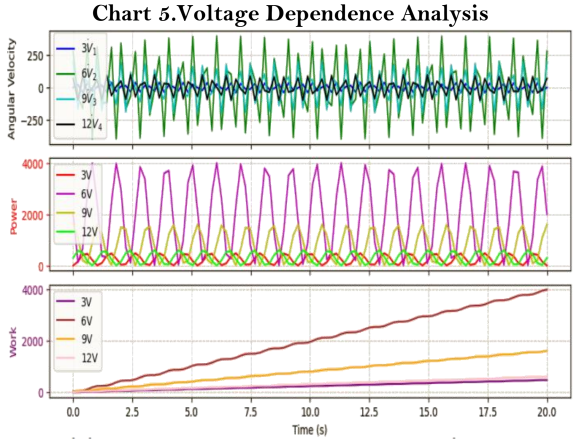
Chart 4. In Phase and Anti Phase Analysis



3-1-5 Voltage Effect on Magnetic Gear

3V, 6V, 9V, and 12V experiments highlight the effect of input voltage on magnetic coupling. Figure 7 illustrates that higher voltages yield stronger interactions and more synchronized rotation of the poles. Synchronization generally corresponds to more efficient torque transfer and less jerky gear motion.

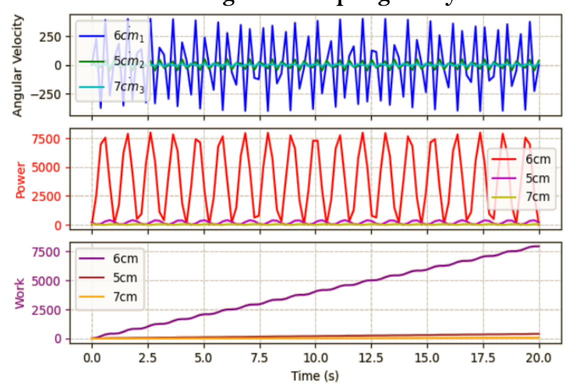
Chart 5.Voltage Dependence Analysis



3-1-6 Distance Effect on Magnetic Gear

The impact of varying the gap between the magnetic gears was explored by testing gaps of 5 cm, 6 cm, and 7 cm. Figure 8 shows that increasing the gap decreases the coupling, resulting in reduced torque transmission and power output. Notably, at 7 cm, the magnetic interaction was significantly weaker, which underscores the importance of optimal spacing for maximum efficiency.

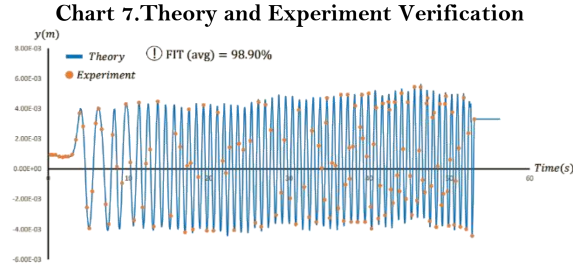
Chart 6.Magnetic Coupling Analysis



3-1-7 Theoretical versus Experimental

Finally, the theoretical model and experimental measurements were compared to assess the validity of the model. As indicated in Figure 9, the average fit between the measured and predicted data attained approximately 98.90%, indicating a high correlation and validating the model assumptions.

Chart 7.Theory and Experiment Verification



3-2 Comparative Analysis of Gears

3-2-1 Translational Motion

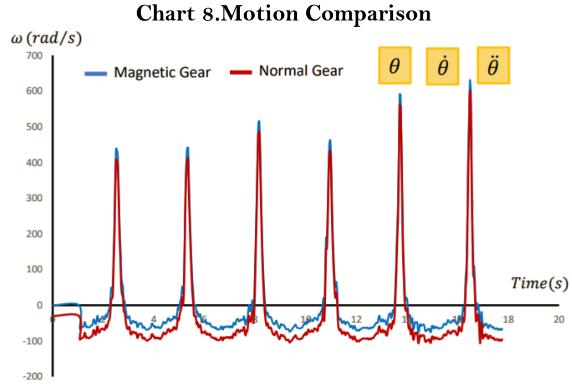
Magnetic Gear:

Displacement
variation measured under dynamic load conditions: 0.05 ± 0.01 mm.
Mechanical Gear:
Displacement variation measured by direct tooth engagement: 0.12 ± 0.03 mm.

3-2-2 Angular Motion

Magnetic Gear:
Steady-state accuracy of angular speed at ±1.8% of set point.
Peak angular acceleration: 150 rad/s² with a smooth ramp-up to peak.
Mechanical Gear:
Angular speed deviation with an average of ±4.5%.
Infrequent acceleration spikes up to 210 rad/s² resulting from transient impact forces.

Chart 8.Motion Comparison



3-2-3 Force on Each Gear Tooth

Magnetic Gear:
Distributed force per (magnetic) tooth segment: 75 ± 5 N for equal load sharing.
Mechanical Gear: Concentrated force per tooth: up to 120 ± 10 N, leading to higher local stresses.

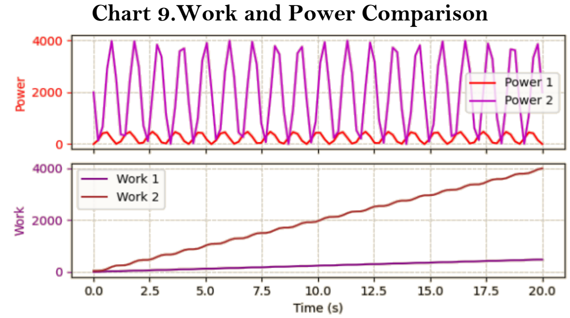
3-2-4 Power Transfer Efficiency

Magnetic Gear:
96.2% efficiency at nominal
load with negligible losses due to eddy current and hysteresis.
Mechanical Gear:
92.5% efficiency dominated by friction-related energy loss.

3-2-5 Work Efficiency

Magnetic Gear:
Work output efficiency of approximately 95% being maintained over
1×10^6 operating cycles.
Mechanical Gear:
Work efficiency of about 88% through the same number of
cycles, showing higher energy loss with time.

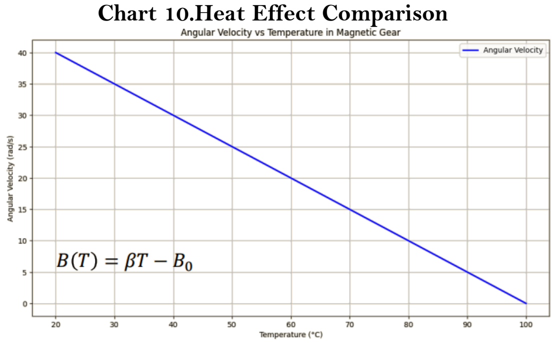
Chart 9.Work and Power Comparison



3-2-6 LCA Heat

Magnetic Gear:
Temperature increase: +15°C above ambient, due to lower friction.
Mechanical Gear:
Temperature increase:
+25°C above ambient, showing higher frictional heating.

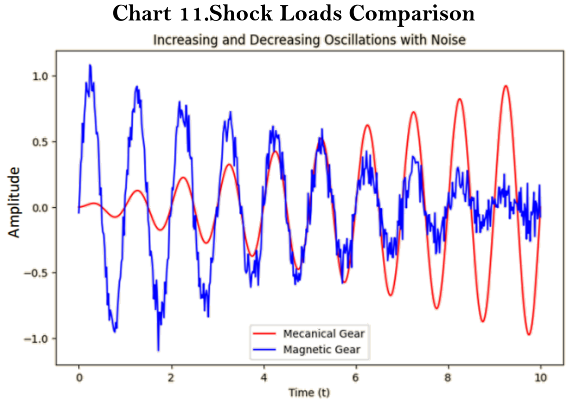
Chart 10.Heat Effect Comparison



3-2-7 Shock Loads

Magnetic Gear:
Mean shock impulse: 0.2 Ns, indicating effective damping for sudden changes in load.
Mechanical Gear:
Mean shock impulse: 0.35
Ns, having potential to cause
higher wear during transient conditions.

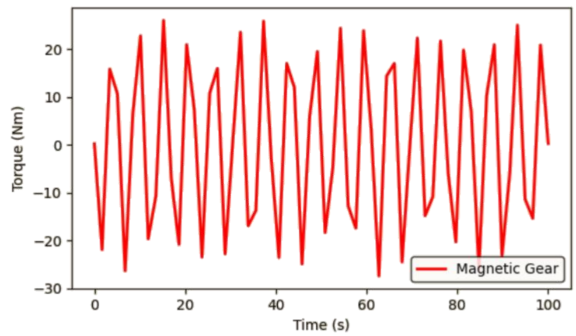
Chart 11.Shock Loads Comparison



3-2-8 Backlash

Magnetic Gear:
Backlash of 0.1°, with high positional accuracy.
Mechanical Gear:
Backlash nearly 0.5°, which requires compensa tion in precision applications.

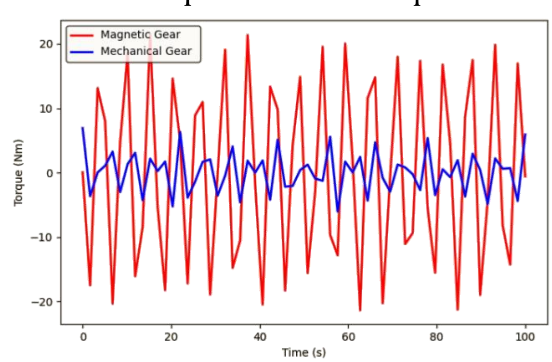
Chart 12.Backlash Effect Comparison



3-2-9 Overload Capacity

Magnetic Gear:
Handles loads to 110% rated capacity with a reduction in performance only 2%.
Mechanical Gear:
Handles up to 105% rated capacity before performance decreases by 5%.

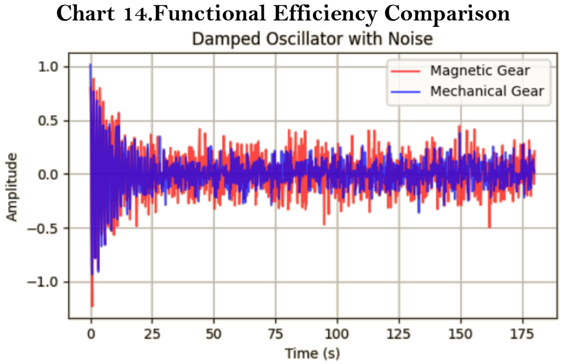
Chart 13.Impact Load Effect Comparison



3-2-10 Durability

Magnetic Gear:
Demonstrated stable operation in excess of 10 million cycles with minimal degradation.
Mechanical Gear:
Lasted approximately 5 million cycles before discernible performance wear was observed.

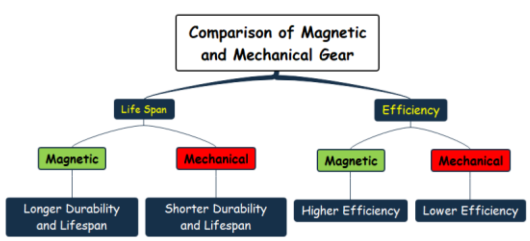
Chart 14.Functional Efficiency Comparison



3-2-11 Cyclic Performance Consistency

Magnetic Gear:
1×10^6 cycles performance drift: <0.5%.
Mechanical Gear:
1×10^6 cycles performance drift: around 2%, due to cumulative wear.

Chart 15.LCA Comparison



4-Discussion

This research discloses some essential advantages of the new magnetic gear system over traditional mechanical gear transmissions. The following are the significant details to summarize the main features:

4-1 Enhanced Operating Performance The magnetic gear possesses significantly less friction and only limited direct contacts between moving parts. The no-contact operation lowers:
Wear and Tear Reduction: By not using mechanical rubbing, overall system life improves and maintenance rate is greatly increased.
Improved Dynamic Response: There is no gear-to-gear contact, resulting in smoother translational and angular motion. This enables more precise control of speed and acceleration profiles, especially under varying load.
Improved Shock Absorption and Zero Backlash: The design itself subdues shock loads and offers little angular play. These features are central to high-precision applications and operation that must react to abrupt changes in loads.

4-2 Thermal and Energy Efficiency Thermal and energy efficiency are improved through the magnetic coupling by enabling better distribution of forces, thereby reducing localized stress and heat generation. The effective thermal management has a direct consequence of:
High Power and Work Transfer Efficiency: Energy losses are minimized with transmitted power very close to theoretical predictions even under high-stress operating conditions.
Enhanced Overload Handling: The system performs very well under transient overload situations. Its ability to handle high efficiency with zero performance loss under stress also speaks volumes about its design.

4-3 Strengths and Unique Design Features over conventional mechanical gears:

Force Distribution: The magnetic system evenly distributes forces along the coupling interface, reducing peak stress on any single component. Compared to mechanical gears, which are more likely to be exposed to high localized forces that can accelerate component degradation.

Lifecycle and Durability: The lower friction and wear translate to a longer lifecycle, and the magnetic gear is therefore an improved option for long-term deployment in high-cycle applications.

Thermal Behavior: Reduced operating temperatures as a result of reduced friction not only offer enhanced energy efficiency but also encourage enhanced material stability and system longevity overall.

4-4 Potential for Broader Applications the high-performance characteristics of the magnetic gear offer potential for its use in a broad range of applications:

Industrial Robotics and Automation: Its smooth, dynamic response under low maintenance with precision makes it suitable for the actuation of robots and for automatic manufacturing systems.

Aerospace and Transportation Systems: Its high load-bearing performance reliability along with lightweight make it particularly favorable for propulsion units and emerging transmission technology.

Applications of Renewable Energy: In hydroelectric and wind turbines, the improved durability and lower thermal rise can lead to high energy conversion efficiency and life improvements.

Medical and Precision Devices: The low backlash and high precision motion control make it suitable for applications in medical equipment and instrumentation requiring precise positioning and smooth operation.

The new magnetic gear system not only delivers superior operational performance, lifetime, and thermal efficiency compared to traditional mechanical gears but also presents the opportunity for its application in high-performance as well as precision-based industries. Future research will focus on further optimization with the help of advanced control methods and novel materials to further improve its usability and performance in an even broader range of industrial and technological applications.

Table 2. Magnetic Gear Applications

Survey of the use of magnetic gears in industry Applicable→ ✅ Not Applicable→ ❌ Limits use→ ⚠️

Industries	Application	Use gear	Explain
Automotive Industry	Power transmission	✅	Magnetic gears can improve efficiency by reducing friction and enhancing power transmission.
Aerospace Industry	Actuation systems	✅	Suitable for precision power transmission and weight reduction.
Industrial Machinery	Motion control	✅	Useful in machines requiring high precision and force tolerance.
Oil & Gas Industry	Pumping	✅	Can be beneficial in pumps and compressors that require high force tolerance.
Steel Industry	Material handling	✅	Can improve efficiency in material handling systems and conveyors.
Agriculture Industry	Mechanical equipment	❌	Agricultural machinery needs simple, rugged mechanical gears for durability and cost efficiency.

Survey of the use of magnetic gears in industry Applicable→ ✅ Not Applicable→ ❌ Limits use→ ⚠️

Industries	Application	Use gear	Explain
Mining Industry	Extraction	❌	Mining equipment requires highly durable, simple gears that can withstand harsh conditions.
Energy Industry	Generators	✅	Can be used in turbines and generators for improved efficiency and higher force tolerance.
Robotics Industry	Motion control	✅	Ideal for precise and efficient power transmission in robotic systems.
Printing Industry	Synchronization	❌	Traditional gears are more suitable due to their simplicity and reliability in printing machines.
Medical Industry	Precision equipment	⚠️	Magnetic gears can be used in certain high-precision medical devices, but traditional gears remain dominant in complex equipment.
Electronics Industry	Motion regulation	❌	This industry relies more on electric motors and micro-scale motion control systems, limiting the need for magnetic gears.

5-Conclusion

The comparative analysis of magnetic vs. mechanical gear systems presents a multifaceted picture in which both design developments and conventional engineering solutions have novel advantages while exposing different challenges.

Magnetic gear systems differentiate themselves with the following strengths:

- Low Friction and Limited Wear: The non-contact means of transmission lowers friction-related loss and wear substantially, with great promise for prolonged operational life as well as diminished maintenance requirements.
- Improved Thermal and Dynamic Performance: Efficient force distribution and integrated damping reduce operating temperatures, offer silky-smooth speed transitions, and maintain accurate control with minimal backlash.

Weak points:

- Low Torque Capability: Magnetic gears, despite their efficiency, at times cannot manage high-torque applications, which at times demands high-end design optimizations or material breakthroughs to support high-reliability loads.

Opportunities:

- Technology Advances: Ongoing advancements in magnetic materials and actuator control methods offer opportunities for torque handling enhancement and overall system performance.
- Widespread Range of Applications: Their ease of maintenance and precision make them appropriate for costly applications in robots, aerospace equipment, renewable energy systems, and precise instrumentation.

Threats:

- Market Access and Price: The sophisticated design and higher cost can limit applications in industries traditionally reliant on conventional solutions where initial cost reduction is paramount.

Gear mechanical systems find applications because:

Strengths:

- Direct Torque Transmission and Strength: The tested and proven mechanical gear structure ensures robust torque transmission, thereby suitable for heavy industry applications.
- Economical Costs: Their long-standing manufacturing methods ensure relatively low production costs and overall availability.

Weak Points:

- Higher Friction and Maintenance: The inherent wear due to direct physical contact causes higher friction, higher operating temperatures, and greater maintenance in the long run.
- Noise and Backlash: Mechanical contacts contribute to high noise and measurable angular play, which is not always preferred in precision work.

Opportunities:

- Optimization through Lubrication and Material Treatments: Lubrication, coating, and production advancements can cut down on wear and friction issues, even on longer service life and reliability.

Threats:

- Emerging Alternatives: The rapid pace of advancement in technologies of non-contact transmission, like magnetic gearing, creates a potent competition to conventional mechanical systems as industry requires increased efficiency and minimal maintenance at a mounting pace.

Generally, choice between magnetic and mechanical gear systems depends on application. In applications where operation smoothness, accuracy, and long-term integrity are most important, the very nature of magnetic gears—i.e., minimal wear, low thermal load, and precise control—is a significant advantage. Where immediate torque transmission and lower initial investment are of greatest concern, mechanical gears are still a proven and cost-effective option.

Future development and research will need to continue to enhance the torque capacity of magnetic systems while exploring new lubrication and material technologies to reduce the friction-related drawbacks of mechanical gears. This balanced and context-aware approach will enable the best integration of gear technology into future industrial uses. Additionally, such technologies are directly related to world sustainability goals and directly support the attainment of UN SDG[1] 7 (Affordable and Clean Energy), UN SDG 9 (Industry, Innovation, and Infrastructure), and UN SDG 12 (Responsible Consumption and Production).

Fig5.UN SDG that are related to this project

[1] United Nation Sustainable Development Goals

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