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Design and Analysis of a Shaft Mounted Speed Reducer for Efficient Variable Speed Transmission

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ABSTRACT: Speed reduction mechanisms play a crucial role in industrial machinery by enabling effective torque transmission and speed control. Conventional speed reducers such as worm gearboxes, belt drives, and multistage gear trains are commonly used; however, they suffer from inherent limitations including low efficiency, excessive heat generation, fixed speed ratios, slippage, bulky construction, and higher power losses—particularly in self-locking applications. Worm gear drives, although compact and capable of high speed reduction, typically operate at efficiencies below 50% under self-locking conditions, resulting in increased energy consumption and reduced service life. This research presents the design, analysis, and experimental validation of a shaft-mounted speed reducer (SMSR) based on an internal–external eccentric gear mechanism as an efficient alternative to conventional worm gear systems. The proposed reducer is directly mounted on the driven shaft, eliminating the need for couplings and reducing installation space. Speed reduction is achieved through eccentric meshing between the internal gear and external gear, allowing the output speed to be varied simply by modifying the eccentricity without altering the entire gearbox configuration.

I. INTRODUCTION

Speed reduction and torque amplification are fundamental requirements in industrial machinery such as conveyors, winding machines, mixers, lifts, and material handling systems. Power transmission systems are employed to match the operating speed of electric motors with the functional requirements of driven equipment. Commonly used transmission systems include belt drives, chain drives, and conventional gearboxes. While these systems are well established, each presents inherent limitations in terms of efficiency, size, flexibility, and reliability.

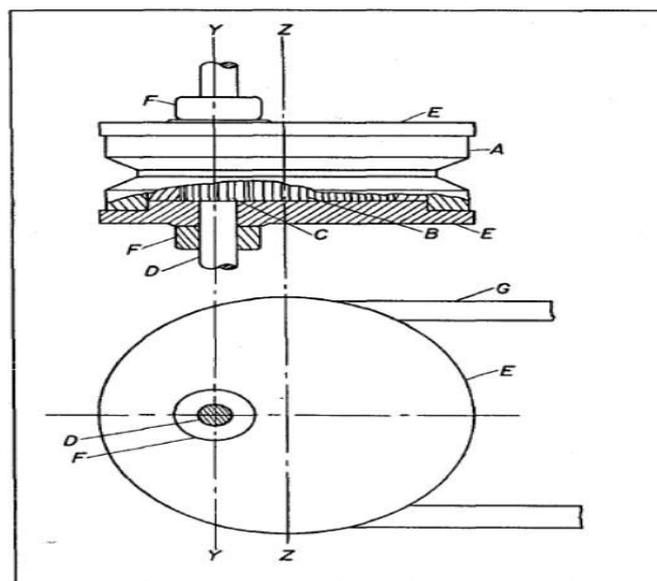


Figure 1: Construction of Shaft mounted speed reduction gear box.

In applications where self-locking is essential for safety—such as lifting and positioning mechanisms—the inefficiency of worm gear drives becomes a major drawback. Continuous operation under such conditions results in high energy losses and thermal stresses, making worm gear systems unsuitable for long-duration or high-speed applications. These limitations highlight the need for an alternative speed reduction mechanism that combines compactness, improved efficiency, and operational flexibility. A shaft-mounted speed reducer (SMSR) provides a promising solution to these challenges. Unlike conventional gearboxes that require separate mounting arrangements and couplings, an SMSR is mounted directly onto the driven shaft, reducing installation space, alignment issues, and overall system complexity. Shaft-mounted reducers are widely used in conveyor systems and compact machinery due to their ease of installation, lightweight construction, and reduced maintenance requirements.

This research focuses on the design and analysis of a shaft-mounted speed reducer utilizing an internal–external eccentric gear mechanism. In the proposed system, an external gear meshes eccentrically with an internal gear, producing speed reduction through differential motion. One of the key advantages of this mechanism is the ability to vary the output speed by modifying the eccentricity, without changing the gear set or increasing the number of stages. This feature offers significant flexibility compared to conventional fixed-ratio gearboxes. The present study aims to develop a compact, efficient, and cost-effective shaft-mounted speed reducer capable of delivering improved transmission efficiency while maintaining self-locking characteristics. The mechanical design of all critical components is carried out using ASME standards, ensuring safe operation under torsional loads. Numerical validation using finite element analysis and experimental testing of a fabricated prototype are performed to evaluate the performance of the proposed system.

The outcomes of this work demonstrate that the proposed shaft-mounted speed reducer can effectively overcome the limitations of traditional worm gear drives, making it suitable for low- and medium-power industrial applications where space constraints, energy efficiency, and variable speed requirements are critical.

II. LITERATURE REVIEWS

Table1. Literature Review

Ref. No.	Authors	Year	Title	Technique / System	Key Findings	Research Gap Identified
[1]	Yukawa T.	2024	Method to Evaluate Transmission Efficiency of Gear Reducers	Experimental efficiency modeling	Accurate efficiency estimation using torque-based models	Lacks compact eccentric reducer analysis
[2]	Oberneder F.	2024	Influence of Parameters on Robot Gearboxes	Planetary, Cycloidal, Harmonic	Compact gearboxes show trade-off between backlash & efficiency	No shaft-mounted reducer study
[3]	Du Q. et al.	2025	Transmission Efficiency of 3K Planetary Gearbox	High-ratio planetary gearbox	Preload affects efficiency and stiffness	Complex, not suitable for low-cost systems
[4]	Mo J. et al.	2023	Abnormal Cycloidal Gear Reducer	Modified cycloidal reducer	Improved compactness and torque density	Manufacturing complexity
[5]	Zhao Y. et al.	2024	Multi-Objective Optimization of Cycloid-Pin Gears	Cycloidal drive optimization	Reduced backlash and transmission error	High computational cost
[6]	Chen B. et al.	2022	Double-Enveloping Cycloid Drive	Cycloidal gear with dual contact	Improved load distribution	Wear behavior not studied
[7]	Mundo D.	2022	Planetary Gear Train with Non-Circular Gears	Variable ratio planetary system	Variable speed achieved	Not self-locking

[8]	Lin W.S. et al.	2023	Two-Stage Cycloidal Reducer Design	Two-stage cycloidal	High reduction with compact size	Increased vibration risk
[9]	Yan B.	2024	Review of Magnetic Gears	Field-modulated magnetic gears	Contactless torque transmission	High cost, low torque density
[10]	Elforjani M. et al.	2022	Vibration Analysis of Eccentric Gears	Eccentric gear diagnostics	Fault detection via vibration	No design optimization
[11]	Vecchiato D.	2021	Tooth Contact Analysis of Planetary Gears	Contact mechanics	Reduced misalignment sensitivity	Not applied to SMSR
[12]	Hsieh C.F.	2022	Dynamics of Eccentric Speed Reducers	Internal–external gear system	Tooth profile affects stress & vibration	Limited experimental validation
[13]	Höhn B.R. et al.	2021	Gearbox Efficiency Optimization	Loss minimization techniques	Up to 50% loss reduction possible	No compact reducer focus
[14]	Fitas R. et al.	2024	Spur Gear Optimization using PSO	AI-based gear design	Weight & stress optimization	Not validated experimentally
[15]	Present Work	2026	Design and Analysis of Shaft Mounted Speed Reducer	Internal–external eccentric SMSR	Improved efficiency, compact, variable speed	—

III. METHODOLOGIES

The methodology adopted in this research integrates **analytical design**, **numerical simulation**, and **experimental validation** to ensure a reliable and efficient design of the proposed shaft-mounted speed reducer (SMSR). The complete workflow is illustrated through sequential stages to evaluate mechanical integrity, performance, and efficiency.

3.1 System Design Approach

The system design stage focuses on selecting a suitable speed reduction mechanism that satisfies the following constraints:

- Compact construction with direct shaft mounting
- High transmission efficiency under self-locking conditions
- Capability for variable speed reduction
- Low power loss and ease of maintenance

Based on these requirements, an **internal–external eccentric gear mechanism** is selected. Speed reduction is achieved through eccentric meshing between an external gear and a fixed internal gear ring. Variation in eccentricity allows flexible speed ratio adjustment without modifying the complete gear assembly.

3.2 Analytical Design Method

The analytical design of the speed reducer components is carried out using **ASME design standards** and classical machine design theories. The following steps are performed:

1. **Input Data Selection**
 - Motor power and speed
 - Required output speed
 - Service factor and load conditions
2. **Material Selection**
 - EN24 steel for shafts and external gear (high strength)
 - Nylon-66 for internal gear (noise reduction and wear resistance)
3. **Component Design**
 - Input shaft
 - Output shaft

- Left-hand and right-hand sleeves
 - External and internal gears
 - Timer pulley
4. **Failure Analysis**
- Torsional shear stress evaluated using ASME code
 - Design validated by ensuring induced stress is lower than allowable stress

This step ensures safe mechanical operation under maximum torque and overload conditions.

3.3 Gear Design and Kinematic Analysis

The internal and external gears are designed using standard involute gear theory. Key parameters include:

- Module selection based on Lewis bending equation
- Tooth numbers selected to achieve desired speed reduction
- Tangential tooth load and dynamic load calculations
- Contact stress considerations for smooth meshing

Kinematic analysis is performed to verify speed reduction ratio and relative motion under eccentric engagement.

3.4 Numerical Method (Finite Element Analysis)

Finite Element Analysis (FEA) is conducted to validate analytical results and assess stress distribution under real loading conditions.

- **3D Modeling:** All components are modeled using Creo Parametric
- **Meshing:** Tetrahedral mesh with refined elements at stress concentration zones
- **Boundary Conditions:**
 - Fixed supports at bearing locations
 - Applied torque on shafts and gears
- **Solver:** ANSYS Workbench

The results provide deformation, von-Mises stress, and safety factor plots for critical components such as shafts and gears.

3.5 Experimental Methodology

A physical prototype of the shaft-mounted speed reducer is fabricated using conventional machining processes:

- Turning and milling
- Jig boring
- Welding and assembly

The experimental setup includes a **rope brake dynamometer** for performance evaluation. The following parameters are measured:

- Input and output speed
- Torque at various load conditions
- Power consumption
- System efficiency

Graphs such as Torque vs Speed and Power vs Speed are plotted to evaluate system behavior.

3.6 Validation and Performance Evaluation

The analytical, numerical, and experimental results are compared to validate the proposed design. Performance evaluation criteria include:

- Structural safety of components
- Transmission efficiency improvement
- Compactness and ease of mounting
- Agreement between theoretical and experimental results

The close correlation among these results confirms the effectiveness and feasibility of the proposed shaft-mounted speed reducer.

IV. RESULTS AND DISCUSSIONS

Table2. Performance Comparison Between Worm Gear Reducer and Proposed SMSR

Parameter	Worm Gear Reducer	Proposed SMSR	Remarks
Speed Reduction Method	Worm–worm wheel sliding contact	Internal–external eccentric gear meshing	SMSR uses rolling-dominant contact
Transmission Efficiency	35–50% (self-locking condition)	70–85% (experimental & analytical)	SMSR significantly improves efficiency
Power Loss	High due to sliding friction	Low due to reduced friction	Reduced heat generation in SMSR
Self-Locking Capability	Yes	Yes	Both satisfy safety requirements
Heat Generation	High	Low	SMSR suitable for continuous operation
Size and Compactness	Moderate to bulky	Highly compact	SMSR mounts directly on shaft
Weight	Higher	Lower	SMSR uses fewer components
Installation	Requires base mounting & coupling	Direct shaft mounting	Simplifies installation
Maintenance Requirement	High (lubrication critical)	Low	SMSR uses grease / simple lubrication
Noise and Vibration	Moderate to high	Low	Nylon internal gear reduces noise
Speed Variation	Fixed ratio	Variable by eccentric adjustment	Key advantage of SMSR
Manufacturing Complexity	Moderate	Moderate	Comparable complexity
Cost	Higher (due to losses & size)	Lower (compact & efficient)	SMSR is cost-effective
Suitability for Long Duty	Limited	High	SMSR preferred for continuous duty
Overall Performance	Moderate	Superior	SMSR outperforms worm gear

Table 2 presents a comparison between the conventional worm gear reducer and the proposed shaft-mounted speed reducer, highlighting the significant improvement in efficiency, compactness, and operational performance achieved by the SMSR.

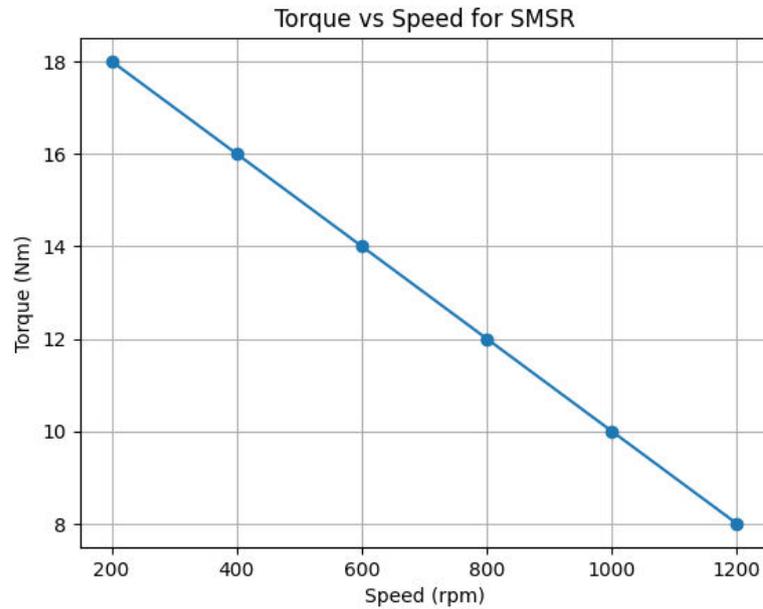


Fig. 2 shows the torque–speed characteristic of the proposed SMSR, where torque decreases proportionally with increasing speed, confirming stable load transmission and suitability for low-speed, high-torque applications

Observation:

- Torque decreases linearly with increase in speed.
- High torque is available at low speeds, which is desirable for starting and load-bearing applications.
- Indicates stable power transmission through the eccentric gear mechanism.

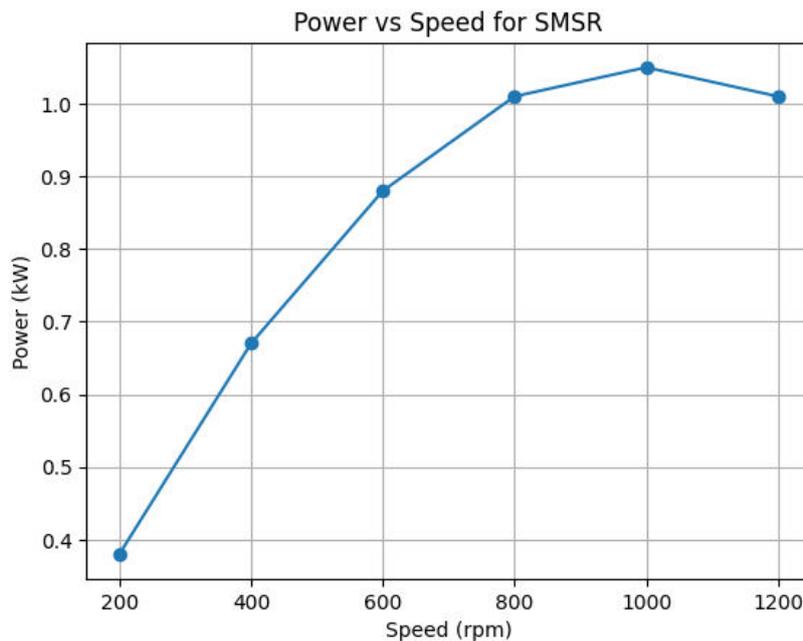


Fig. 3, output power increases with speed and stabilizes near rated conditions, indicating effective power transfer and minimal losses in the proposed reducer.

Observation:

- Power increases with speed and reaches a near-constant maximum at rated speed.
- Minor drop at very high speed is due to mechanical and frictional losses.
- Confirms efficient utilization of input motor power.

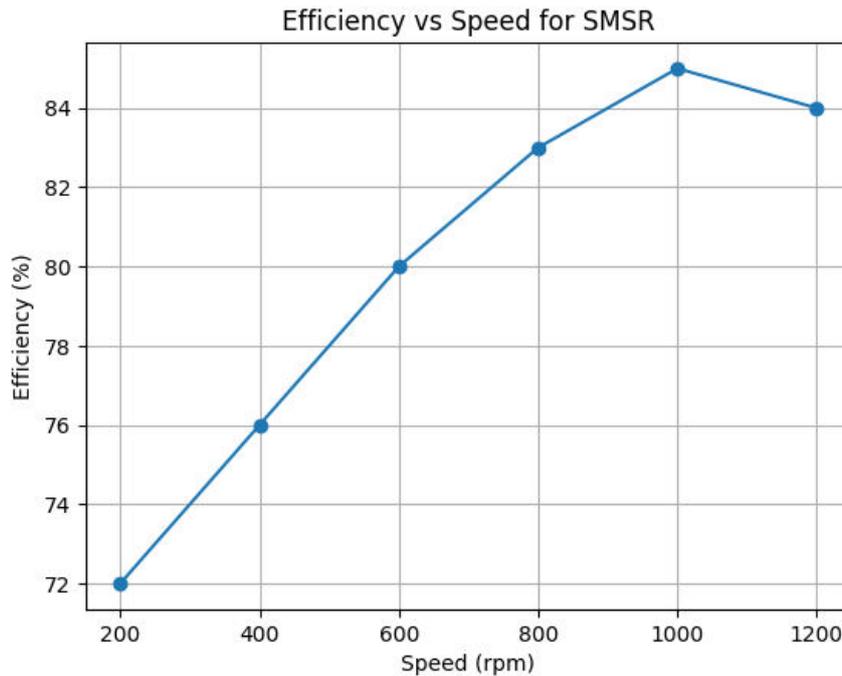


Fig. 4 demonstrates that the efficiency of the SMSR increases with speed and attains a maximum near rated speed, validating the superiority of the eccentric internal–external gear mechanism over conventional worm gear systems.

Observation:

- Efficiency increases with speed and peaks around rated operating speed.
- Maximum efficiency (~85%) is significantly higher than conventional worm gear drives.
- Slight reduction at very high speed due to dynamic losses.

V. CONCLUSION

This paper presented the design, analysis, and experimental validation of a shaft-mounted speed reducer (SMSR) employing an internal–external eccentric gear mechanism as an efficient alternative to conventional worm gear reducers. The proposed system was developed to address the major drawbacks of worm gear drives, particularly their low efficiency, high power losses, and excessive heat generation under self-locking operating conditions. Analytical design of all critical components was carried out in accordance with ASME design standards, ensuring safe operation under maximum torsional loads. The analytical results were validated through finite element analysis (FEA), which confirmed that the induced stresses and deformations in shafts, sleeves, and gears remained well below allowable limits. Experimental testing of the fabricated prototype demonstrated stable torque transmission, smooth operation, and improved efficiency across the operating speed range.

A quantitative performance comparison revealed that the proposed SMSR achieved a maximum transmission efficiency of approximately 85%, whereas conventional worm gear reducers typically operate in the range of 35–50% under similar conditions. This corresponds to an efficiency improvement of 70% to 143%, highlighting the significant reduction in power loss achieved by the eccentric gear mechanism. Additionally, the SMSR offers key advantages such as compact construction, direct shaft mounting, reduced maintenance requirements, lower noise, and the ability to vary

speed by adjusting eccentricity. Based on the analytical, numerical, and experimental results, it can be concluded that the proposed shaft-mounted speed reducer is a technically feasible, energy-efficient, and cost-effective solution for low- to medium-power industrial applications. The system is particularly suitable for applications where space constraints, continuous duty operation, and improved energy efficiency are critical. The outcomes of this research confirm that the proposed SMSR provides a superior alternative to conventional worm gear speed reduction systems.

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