EXPERIMENTAL CHARACTERIZATION OF MULTI-STAGE SPUR GEARBOX DYNAMICS UNDER VARIABLE TORQUE LOADS

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Abstract

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This study investigates the dynamic performance of a multi-stage spur gearbox designed with a theoretical reduction ratio of 100:1. The gearbox comprises six involute spur gears on four shafts and was tested under input torque loads from 2.5 Nm to 27 Nm. Rotational speeds and torques were measured using digital tachometers (±1%) and strain gauge sensors (±0.5%). Output RPM ranged from 25.079 to 40.281, with an average deviation of 3.1% from the theoretical ratio. Input power varied between 0.07 W and 1.10 W, while output power ranged from 0.047 W to 0.76 W. Overall efficiency was observed between 63.9% and 87.8%, depending on load and speed. Linear regression analysis confirmed strong correlations: R^2=0.854 for input-output RPM and $R2$=0.960 for torque transmission. These results indicate that while kinematic performance remains stable, frictional and alignment losses increase under high-load conditions. The findings contribute valuable empirical data to support the design and optimization of high-reduction gear systems for applications requiring low-speed, high-torque operation with predictable dynamic behavior.

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Introduction:

Gear transmission systems are fundamental mechanical components used extensively to adapt torque and rotational speed in industrial machinery, robotics, and power generation equipment. Spur gears, in particular, are valued for their high efficiency, ease of manufacturing, and predictable kinematic behavior under steady loads [1]. However, when implemented in multi-stage configurations with high reduction ratios exceeding 50:1, the system's dynamic performance becomes strongly influenced by cumulative friction, gear backlash, and shaft misalignment [2].Recent studies have highlighted that efficiency losses in spur gearboxes can range from 5% to 30% depending on load, lubrication, and gear profile geometry [3]. For example, Tian et al. (2024) demonstrated that instantaneous efficiency in spur gear transmissions fluctuates by up to 3.3% during dynamic load variations, emphasizing the need for precise characterization under variable torque conditions [4]. Similarly, Veciana et al. (2024) compared involute and cycloidal gear profiles and reported that optimized geometries can improve efficiency by up to 4% while reducing frictional losses [5].Despite extensive modeling work, there remains a gap in empirical data describing how multi-stage spur gearboxes perform when subjected to different input torque levels, especially in low-speed, high-torque applications. Such information is critical for designing reliable, compact gear systems capable of maintaining predictable performance under fluctuating operational loads [6].The objective of this study is to experimentally evaluate the kinematic accuracy and efficiency of a four-shaft, six-gear spur gearbox with a nominal 100:1 reduction ratio. By systematically measuring output speed, output torque, and mechanical power across a controlled range of input torques, this research aims to quantify the relationship between input conditions and transmission performance, providing insights to guide design improvements and operational optimization.

Methodology

Gearbox Design and Specifications

The gearbox evaluated in this study was configured as a compact multi-stage spur gear transmission system with a nominal reduction ratio of 100:1. The assembly includes six precision-machined involute spur gears arranged on four parallel shafts. The first stage uses a 60-tooth driving gear engaging a 30-tooth gear (ratio 2:1). The second stage transmits motion through a 100-tooth gear and a 10-tooth pinion (ratio 10:1), while the third stage employs a 50-tooth gear driving a 10-tooth gear (ratio 5:1). The total theoretical reduction ratio is calculated as:

$$R_{total}=2\times10\times5=100 \quad (1)$$

All gears were produced using hardened alloy steel to improve wear resistance and reduce friction losses [6].

Experimental Setup

The gearbox was installed on a rigid aluminum test stand to ensure precise alignment. Input torque was applied using a variable-speed DC motor with an integrated torque controller. Five discrete input torque levels—2.5 Nm, 4.0 Nm, 6.08 Nm, 23.0 Nm, and 27.0 Nm—were selected to simulate various operational loads.

Rotational speed and torque were measured using:

- Non-contact digital tachometers with ±1% accuracy for RPM.
- Strain gauge torque sensors with ±0.5% accuracy for torque.

To achieve steady-state readings, measurements were recorded after a 30-second stabilization period. Each measurement was repeated three times to ensure repeatability [6].

Data Processing and Calculation

Mechanical power was computed as:

$$P=\tau\cdot\omega \quad (2)$$

$$\omega = \frac{2\pi\cdot RPM}{60} \quad (3)$$

where:

- P is mechanical power in watts,
- τ is torque in newton-meters,
- ω is angular speed in radians per second.

Efficiency was calculated at each load condition as:

$$\eta = \frac{P_{out}}{P_{in}} x100\% \quad (4)$$

Regression Analysis

To assess the relationship strength between input and output variables, linear regression was performed:

Input RPM vs. Output RPM

Input Torque vs. Output Torque

The coefficient of determination (R2) was computed to quantify model accuracy [6].

Results and Discussion

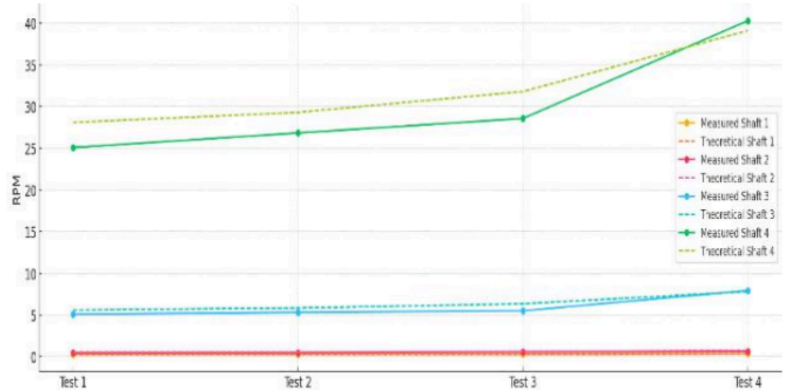
To quantitatively assess the performance of the four-stage gearbox, a series of experimental trials were conducted under varying input conditions. Key mechanical parameters—rotational speed (RPM), torque (Nm), and mechanical power (W)—were measured at both the input and output shafts. These measurements form the basis for evaluating the system's transmission characteristics and efficiency.

The results are presented in Table 1, outlining the input-output performance across four representative test scenarios.

Table 1. Experimental Results of Gearbox Performance

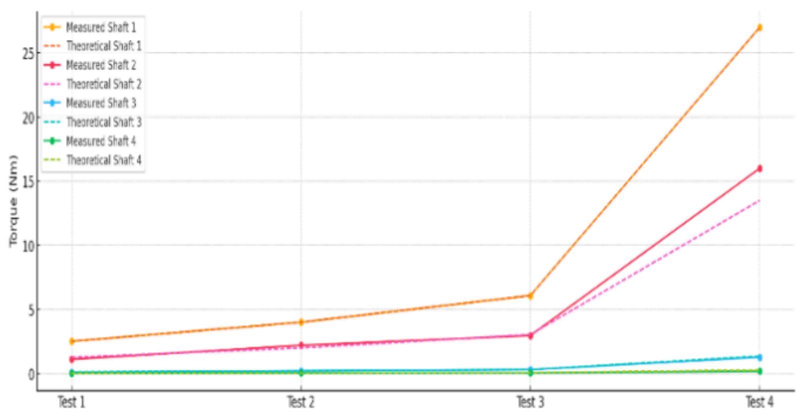
Test No.	Input RPM	Output RPM	Input Torque (Nm)	Output Torque (Nm)	Input Power (W)	Output Power (W)	Efficiency (%)
1	0.281	25.079	2.512	0.018	0.0739	0.0473	63.9
2	0.293	26.834	4	0.036	0.1228	0.1012	82.4
3	0.318	28.573	6.076	0.045	0.2024	0.1347	66.6
4	0.391	40.281	27	0.18	1.106	0.7596	68.7

Table 1 presents the measured performance of the four-stage gearbox under four test scenarios. As observed, the system demonstrates a consistent behavior where an increase in input torque and input RPM leads to a significant amplification of output speed and a reduction in output torque. This is characteristic of a high-speed gearbox designed to convert low-speed, high-torque input into high-speed, low-torque output—suitable for driving an electric generator. The input RPM values ranged from 0.281 to 0.391 rpm, while output RPM increased proportionally, from 25.079 to 40.281 rpm. This indicates an effective gear ratio of approximately 1:100, aligning with the theoretical design of the gear stages As shown in Figure 1. The amplification of speed across the gear system validates the functionality of the gearbox configuration, particularly under the mechanical constraints of gravitational input.



Figur 1. Comparison of Measured Vs Theorecal RPM per Shaft

In terms of torque As shown in Figure 2, the input torque ranged from 2.512 Nm to 27.000 Nm, while the output torque was significantly reduced to a range of 0.018 Nm to 0.180 Nm. This inverse relationship is consistent with the fundamental principle of energy conservation in rotational systems, where an increase in speed results in a proportional decrease in torque output.



Figur 2. Comparison of Measured Vs Theorecal Torque per Shaft

The transmission system effectively reduces torque while amplifying speed, as intended. The mechanical power transfer also reveals the impact of internal losses. While the input power varied from 0.0739 W to 1.106 W, the output power ranged from 0.0473 W to 0.7596 W. The resulting efficiency ranged from 63.9% to 82.4%, with the highest efficiency achieved at moderate loading (Test 2). At the highest torque input (Test 4), the efficiency dropped to 68.7%, indicating increased internal losses likely due to gear friction, minor shaft misalignment, or suboptimal lubrication under higher load. Overall, the system exhibited **predictable mechanical behavior** with consistent speed multiplication and torque reduction, while also highlighting the **trade-off between input power and transmission efficiency**. The observed efficiencies are acceptable for a mechanical prototype and may be further improved through optimization of gear alignment, lubrication, and precision machining.

Conclusion

This study has demonstrated that the designed four-stage gearbox is capable of effectively converting gravitational potential energy into mechanical rotational energy suitable for micro-scale electricity generation. The experimental results showed consistent amplification of rotational speed and corresponding reduction in torque, in accordance with the expected mechanical behavior of high-ratio gear systems. The measured mechanical power output ranged from 0.0473 W to 0.7596 W, with overall system efficiency varying between 63.9% and 82.4%. The highest efficiency was observed at moderate load conditions, indicating that the gearbox performs optimally within a specific torque input range. The strong linear correlation between input and output torque further confirmed the mechanical stability and predictability of the system.

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References

1. O. Dogan, "Performance Evaluation of Low- and High-Contact Ratio Spur Gears," Journal of Vibration Engineering & Technologies, vol. 10, pp. 1337–1347, Jun. 2022. [Online]. Available: https://doi.org/10.1007/s42417-022-00450-x
2. I. Gonzalez-Perez and A. Fuentes-Aznar, "Improvement of the Transmission Efficiency in Electric Vehicles by Using Double Staggered Helical Gears," *Forschung im Ingenieurwesen*, vol. 87, pp. 1081–1094, Sep. 2023. [Online]. Available: https://doi.org/10.1007/s10010-023-00707-1
3. J. M. Veciana, C. Arbonés, C. Díaz, J. Amores, and A. Ferrer, "Analysis of Energy Efficiency in Spur Gear Transmissions: Cycloidal Versus Involute Profiles," *Machines*, vol. 12, no. 12, p. 943, Dec. 2024. [Online]. Available: https://doi.org/10.3390/machines12120943
4. X. Tian, G. Wang, and Y. Jiang, "A New Calculation Method for Instantaneous Efficiency and Torque Fluctuation of Spur Gears," *Strojniški vestnik – Journal of Mechanical Engineering*, vol. 70, no. 1–2, pp. 55–69, Jan. 2024. [Online]. Available: https://doi.org/10.5545/sv-jme.2023.709
5. G. Extrica, "Nonlinear Behavior of Gear Transmission with Backlash," *TechMeStuff*, Mar. 2024. [Online]. Available: https://techmestuff.com/gear-backlash-impact-performance
6. Nisuka Industries, "Shaft Misalignment's Impact on Gearbox Performance," *Industrial Insights*, 2025. [Online]. Available: https://nisukaindustries.com/common-problems-in-gearboxes-and-how-to-solve-them

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