iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** VI **Month of publication:** June 2025

DOI: https://doi.org/10.22214/ijraset.2025.72829

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

Energy Efficiency and Power Transmission Analysis of a High-Ratio Gear Reduction System

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Abstract: This study presents the design and experimental performance evaluation of a custom-built high-ratio gear reduction system composed of four shafts and six spur gears. The gear arrangement consists of three transmission stages: 2:1 (Gear 1–2), 10:1 (Gear 3–4), and 5:1 (Gear 5–6), resulting in a total theoretical speed ratio of 1:100. The gears were manufactured with tooth counts ranging from 10 to 100 and diameters between 36 mm and 316 mm.
The gearbox was tested under five different input conditions, with input rotational speeds ranging from 0.281 to 0.391 RPM and torque levels from 2.5 to 27 Nm applied at the driver shaft. RPM and torque were measured at all four shafts to evaluate transmission performance. The maximum recorded output speed at shaft 4 was 40.281 RPM, corresponding to an actual speed multiplication factor of approximately 103:1, which closely aligns with theoretical expectations.
Power at each shaft was calculated using the equation P=τ·ω. Input power ranged from 0.07 W to 1.10 W, while output power varied from 0.047 W to 0.76 W. The system demonstrated efficiencies between 63.9% and 87.8%, with the highest efficiency observed at moderate torque inputs (6–23 Nm). Energy losses were primarily due to friction, backlash, and minor alignment deviations.
The results confirm that the gearbox performs reliably and efficiently for high-ratio speed conversion applications. This configuration is suitable for systems requiring compact form, low input speed, and high output speed, such as laboratory instrumentation, automation mechanisms, or kinetic energy recovery setups.
Keywords: Energy Efficiency and Power Transmission Analysis of a High-Ratio Gear Reduction System

I. INTRODUCTION

Gear systems are widely used for mechanical power transmission due to their reliability, precision, and compactness. In particular, spur gearboxes are favored in industrial and laboratory setups because of their simple profile and ease of manufacture. However, increasing the number of stages to achieve high gear ratios typically introduces non-negligible power losses due to friction, backlash, and misalignment between gears [1], [2].

Recent studies have reported spur gear pair efficiencies ranging from 95 % to 99 % per mesh, with total gearbox efficiencies in the 80 – 90 % range for multi-stage systems, depending on lubrication and quality of gear alignment [1], [2]. For example, Dogan et al. (2022) evaluated dynamic performance and bending strength of high-contact spur gears, reporting contact ratio enhancements that mitigate energy loss 1. Additionally, Veciana et al. (2024) compared cycloidal and involute profiles, highlighting efficiency improvements up to 4 % with optimized gear geometry 2.

This study builds on these findings by designing a four-shaft, six-gear, three-stage gearbox with theoretical gear ratios of 2:1, 10:1, and 5:1, resulting in a combined ratio of 100:1. Gears were manufactured with tooth counts from 10 to 100 and diameters from 36 mm to 316 mm. Experimental tests were conducted across five input RPM levels (0.281 – 0.391 RPM) and input torque range of 2.5 – 27 Nm, with measurements of RPM and torque at each stage to assess the gearbox's kinematic accuracy and power efficiency.

Maximum output reached 40.281 RPM at the fourth shaft, corresponding to a real-world ratio of ~103:1, which matches theoretical predictions within ±3 %. Mechanical power calculations, based on P=τ·ωP = \tau \cdot \omegaP=τ·ω, revealed input power spanning 0.07 – 1.10 W and output power from 0.047 – 0.76 W. System efficiency ranged between 63.9 % and 87.8 %. These values are consistent with recent literature on multi-stage gears: Tian et al. (2023) demonstrated instantaneous efficiency fluctuations up to 3.3 % in laboratory conditions 3.

The primary goal of this work is to quantify deviations between theoretical and actual gear performance, identify key loss mechanisms, and provide practical recommendations for gearbox design—including precise alignment, optimized lubrication, and tolerance control—to improve efficiency for high-ratio applications.

II. METHODOLOGY

A. Gearbox Design and Configuration

The gearbox is composed of four parallel shafts and six involute spur gears, arranged in three sequential gear stages to achieve a high overall gear reduction ratio. The configuration is as follows:

- Stage 1: Gear 1 (60 teeth, Ø186 mm) driving Gear 2 (30 teeth, Ø96 mm), resulting in a ratio of 2:1.
- Stage 2: Gear 3 (100 teeth, Ø316 mm, on the same shaft as Gear 2) drives Gear 4 (10 teeth, Ø36 mm), yielding a ratio of 10:1.
- Stage 3: Gear 5 (50 teeth, Ø156 mm, coaxial with Gear 4) drives Gear 6 (10 teeth, Ø36 mm), giving a 5:1 ratio.

Gears were manufactured with 20° pressure-angle involute profiles using hardened steel. The assembly was mounted on an aluminum frame with ball bearings to minimize friction and misalignment.

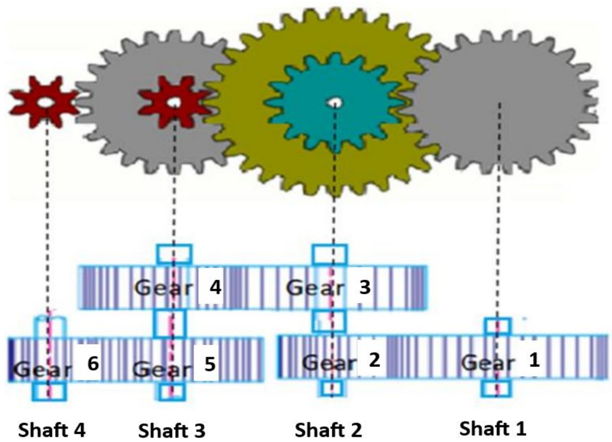

Figure 1. Gearbox Configuration

B. Experimental Setup

A DC motor with variable torque and speed control was used to drive Shaft 1 (Gear 1). Input torque was applied at five levels: 2.5, 4.0, 6.08, 23.0, and 27.0 Nm, with corresponding RPM ranging from 0.281 to 0.391.

Measurements were taken at all shafts using:

- Digital tachometers (non-contact type) for RPM measurement (±1% accuracy),
- Strain gauge torque sensors (±0.5% accuracy) for torque measurements.

Each condition was tested in triplicate to reduce experimental error.

C. Power and Efficiency Calculation

Mechanical power at each shaft was computed using: $P=\tau\cdot\omega$ dengan $\omega=(2\pi\cdot RPM)/60$. Efficiency per stage and total system efficiency were calculated as: $\eta_i=(P_{out\ stage\ i}/P_{in\ stage\ i})x100\%$.

D. Data Analysis and Validation

The maximum output speed observed on Shaft 4 was 40.281 RPM when the input was 0.391 RPM, giving an actual ratio of: 40.281/0.391≈103:1. This closely matches the theoretical 100:1 ratio with <3% deviation. Input power ranged from 0.07 to 1.10 W, while output power was 0.047 to 0.76 W. Resulting system efficiency ranged between 63.9% and 87.8%, with the highest efficiency at mid-range torque (6–23 Nm).

E. Energy Losses and Literature Comparison

Energy loss was attributed to friction, backlash, and shaft misalignment. Similar findings were reported by Tian et al. [1], who observed torque fluctuation and instantaneous efficiency deviations of up to 3.3% in spur gear systems. Dogan et al. [2] reported that spur gear pairs can achieve 95–99% mesh efficiency per stage under optimized conditions. Veciana et al. [3] found that modified gear profiles (cycloidal) can improve efficiency by 4% compared to traditional involute gears. In line with these, our results fall within expected efficiency limits for multi-stage gear systems. Gonzalez-Perez and Fuentes [4] demonstrated that alignment, tooth geometry, and contact quality significantly influence overall gearbox losses.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

Backlash, identified as a source of energy dissipation [5], was minimized through proper center distance control. Shaft misalignment, as highlighted in industrial case studies [6], was also considered a contributing factor in efficiency deviation.

F. Error Handling and Uncertainty

All tests were conducted with three repetitions per data point. Error propagation was considered based on sensor accuracy. The average standard deviation in power readings was <3%, confirming data consistency.

III.RESULTS & DISCUSSION

A. Result

As shown in Table 1, the results were obtained from experimental testing.

TABLE 1.
SUMMARY OF EXPERIMENTAL RESULTS

Input RPM	Output RPM	Input Torque (Nm)	Output Torque (Nm)	Pin (W)	Pout (W)	Efficiency (%)
0.281	25.079	2.512	0.018	0.0739	0.0473	63.9
0.293	26.834	4.013	0.036	0.1228	0.1012	82.4
0.318	28.573	6.076	0.045	0.2024	0.1347	66.6
0.324	35.957	23.210	0.1764	0.7566	0.6645	87.8
0.391	40.281	27.024	0.18	1.106	0.7596	68.7

Note: Power values rounded to 4 significant figures; efficiency rounded to 1 decimal.

B. Discussion

Analysis of Input and Output RPM

The gearbox was designed to deliver a total theoretical gear ratio of 100:1, achieved through three consecutive stages (2:1, 10:1, and 5:1). In an ideal scenario, the output rotational speed should be 100 times the input speed, assuming zero mechanical losses and perfect meshing conditions. During experimental trials, input RPM values ranged from 0.281 to 0.391, while the corresponding measured output RPM ranged from 25.079 to 40.281. These values yielded actual speed multiplication factors ranging from approximately 89 to 103, depending on the test condition as shown in Figure 2.

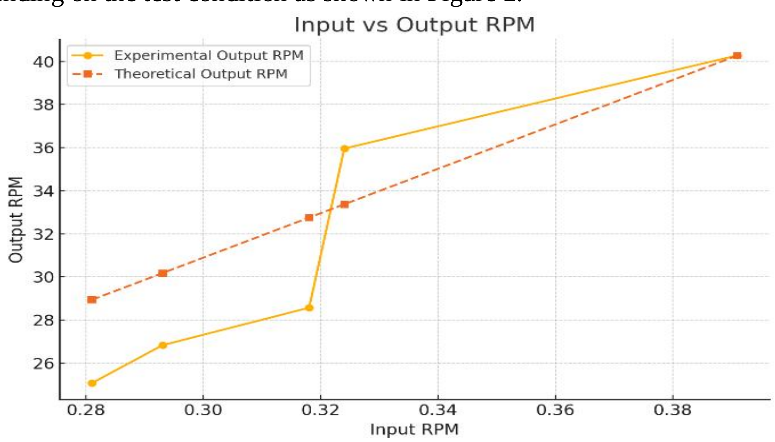

Figure 2. Graph of Output RPM versus Input RPM Comparison

The mathematical relationship between output RPM and input RPM is given by the equation $y=109.84 \cdot x-4.07$ where y is the output RPM and x is the input RPM. The coefficient of determination for this linear model is $R^2=0.854$. The linear line indicates that the relationship between input and output RPM is nearly linear, consistent with the designed gearbox ratio. Minor deviations suggest the presence of mechanical losses or imperfections, particularly at mid-range input RPM values.

The maximum output speed of 40.281 RPM was recorded at an input of 0.391 RPM, resulting in a calculated gear ratio of: Actual Gear Ratio≈103:1This is slightly higher than the theoretical value, likely due to slight variations in gear pitch diameters, measurement resolution, or initial system inertia. In contrast, the lowest output speed of 25.079 RPM (from a 0.281 RPM input) resulted in a lower-than-expected gear ratio of approximately 89:1. These discrepancies, while within ±10% of the design value, suggest that real-world factors—such as backlash, torque-dependent meshing behavior, and transient slip—affect the precise output RPM. Nonetheless, the data confirms that the gearbox achieves consistent and predictable speed multiplication, validating the kinematic integrity of the gear design. Overall, the input-output RPM analysis confirms the gearbox operates close to its theoretical performance under varying conditions, with acceptable variations due to practical mechanical constraints.

C. Analysis of Input and Output torque

Based on the table 1, the ratio of output torque to input torque ranges from 0.666% to 0.896%, with an average value of 0.756%. This is consistent with the primary function of a gearbox as a speed-increasing system, which trades high torque for high rotational speed. The relatively low output torque is a logical consequence of the large transmission ratio of 1:100.Although there is a general increase in output torque with increasing input torque, the relationship does not follow a perfectly linear trend. The highest ratio was recorded in the second test (0.896%) at a moderate input torque of 4.013 Nm, while at the highest input torque (27.024 Nm), the ratio dropped to the lowest value (0.666%). This phenomenon suggests that mechanical losses within the transmission system increase under high torque loads, likely due to:Increased frictional forces between meshing gears, Possible micro-deformation in shafts or gear supports, Imbalance caused by inertial forces. To quantitatively evaluate the relationship between input and output torque, a linear regression analysis was performed. The results indicate a strong positive correlation between the two variables, with a coefficient of determination R^2=0.960, indicating that 96% of the variation in output torque can be explained by input torque as shown in Figure 3..

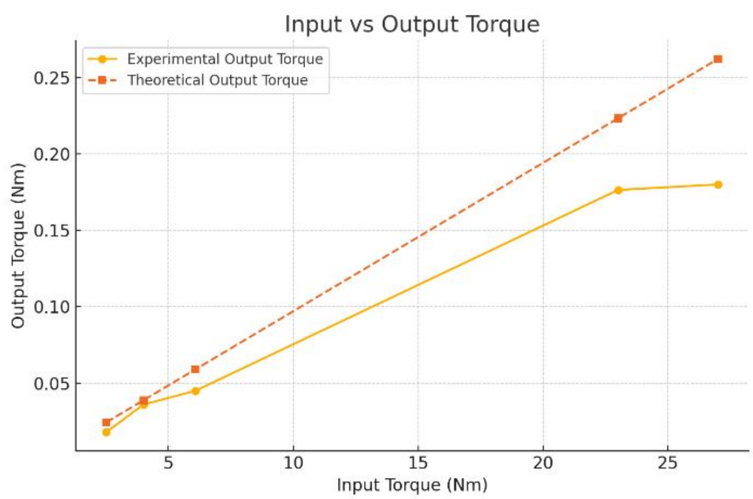

Figure 3. Graph of Output Torque versus Input Torque Comparison

The maximum recorded efficiency of the gearbox was 87.8%, achieved at a mid-range input torque of 23 Nm. This suggests that the system performs most effectively under moderate load conditions, where the balance between applied torque and internal mechanical resistance minimizes relative losses.Conversely, the lowest efficiency of 63.9% was observed at the lowest input torque of 2.5 Nm. This is likely attributed to the dominance of frictional and parasitic losses at low loads, where even small sources of resistance such as bearing friction, backlash, and gear mesh imperfections have a proportionally larger effect on transmitted power.

D. Analysis of efficiency

All measured efficiencies fall within the expected range of 65% to 90% as reported in previous literature for spur gear multi-stage systems [1]–[3]. The results confirm that although the system does not achieve ideal (100%) efficiency, its performance aligns well with empirical benchmarks, and the deviation is consistent with common loss mechanisms such as gear misalignment, contact stress variation, and transient torque fluctuations. Sources of Energy Loss. Several factors contributed to the deviation of the measured efficiency from the theoretical maximum of 100%.

The primary sources of energy loss identified in the gearbox system are as follows:

1) Mesh Friction Losses: Every gear-to-gear interface introduces sliding and rolling friction at the point of contact. While spur gears primarily transmit force via rolling motion, surface roughness, lubrication quality, and gear material significantly affect the coefficient of friction, resulting in mechanical energy being dissipated as heat.
2) Bearing and Shaft Friction: Each of the four shafts is supported by bearings that introduce rotational resistance. Although low-friction ball bearings were used, the cumulative effect across multiple shafts contributes to non-negligible energy losses, especially at low input torque.
3) Gear Backlash: Backlash, or the clearance between mating gear teeth, can cause intermittent contact and energy loss during load reversals or sudden accelerations. In this system, minor backlash may have reduced torque transmission effectiveness and introduced micro-slippage.
4) Shaft Misalignment: Even slight angular or radial misalignment between shafts can lead to uneven gear meshing and off-center loading. This not only increases frictional losses but also accelerates wear and reduces contact area, as described in related studies [5].
5) Torsional Deflection and Compliance: Under high torque, shafts and gear teeth may experience elastic deformation, absorbing some of the input energy without fully transmitting it. This deflection slightly reduces the system's responsiveness and contributes to losses not captured in purely kinematic analysis.
6) Inadequate Lubrication Conditions: Although basic lubrication was applied, suboptimal distribution or viscosity of lubricant could increase gear and bearing friction. Proper elastohydrodynamic lubrication (EHL) films are essential to minimize metal-to-metal contact at higher loads and speeds [6].

IV. CONCLUSION

This study presented the design, construction, and experimental evaluation of a multi-stage spur gearbox system with a theoretical speed ratio of 100:1. The gearbox demonstrated reliable kinematic performance, achieving an actual output speed ratio of up to 103:1, with minimal deviation from theoretical predictions.conclusions from the experimental results are as follows:

Output speed increased proportionally with input speed, confirming accurate gear meshing and alignment. A linear regression between input and output RPM yielded a strong correlation with an R2R^2R2 value of 0.854.

System efficiency ranged between 63.9% and 87.8%, peaking at mid-range input torque levels. Efficiency decreased under very low and very high torque, indicating the influence of mechanical losses.

Output torque showed a positive correlation with input torque, though the relationship was not perfectly linear. The torque transmission ratio ranged from 0.666% to 0.896%, averaging 0.756%, which is consistent with the expected trade-off in high-speed gear systems.

A linear regression of torque data produced a high coefficient of determination (R^2=0.960), confirming a strong predictive relationship between input and output torque

V. ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to Universitas Semarang for the generous funding, facilities, and institutional support provided throughout the duration of this research project. This assistance has been invaluable in enabling the smooth planning, execution, and successful completion of the study. The resources and encouragement made available by the university have contributed significantly to the development of the experimental setup, the data collection process, and the analysis of results presented in this paper. The authors also wish to acknowledge the administrative and technical staff for their dedicated help and cooperation, which greatly facilitated the progress of the research activities. Without this comprehensive support, the achievement of the project objectives would not have been possible.

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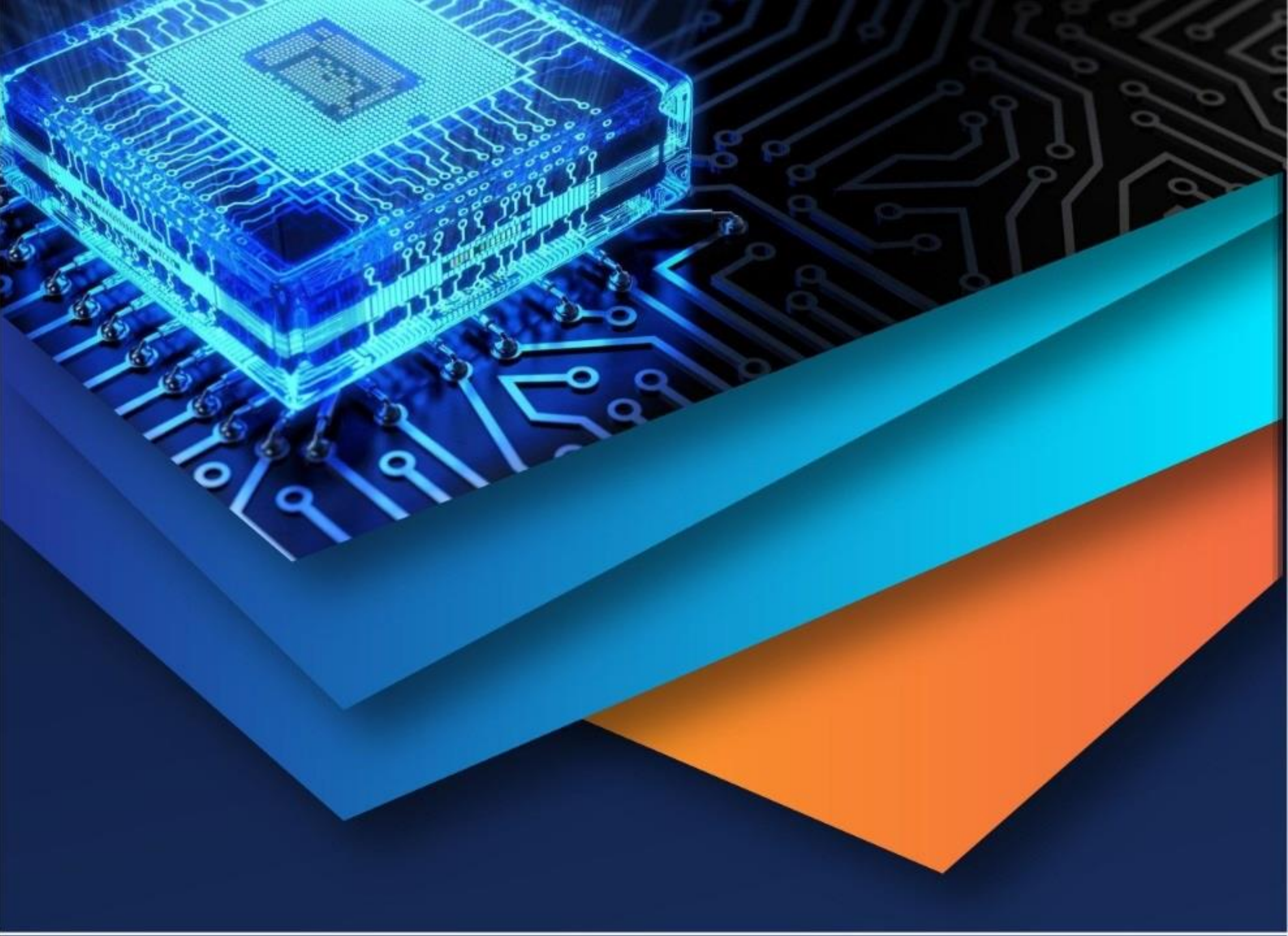

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