Simulation Based Performance Analysis of Gearbox Systems Under Varying Load And Speed Conditions

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***Abstract-* This study uses MATLAB-based simulations to compare the performance of spur and helical gear systems under varying load and speed conditions. A dynamic model was developed to assess eight some important performance parameters, including gear mesh frequency, power loss, vibration, stress concentration, torque transmission efficiency, bearing reaction force, shaft misalignment sensitivity, and temperature rise. The system was tested with a sinusoidal load torque ranging from 30 to 70 Nm, and an input speed varying between 700 and 1300 RPM. At a representative time point (t = 5 s), the spur gear system showed a gear mesh frequency of 333.33 Hz, power loss of 418.8 W, and a vibration amplitude of ±0.8, whereas the helical gear had lower values across all metrics 261.75 W power loss and ±0.4 vibration amplitude. The stress concentration was also higher in the spur gear (63.7 MPa) compared to the helical gear (57.3 MPa). In terms of torque transmission, the helical gear achieved 95% efficiency, slightly better than the spur gear's 92%. The helical system also had lower bearing reaction forces (633.3 N), less sensitivity to shaft misalignment (0.1° vs. 0.3°), and experienced a smaller temperature rise (36.3°C vs. 42.1°C). The results highlight that helical gears deliver more stable, efficient, and reliable performance under dynamic operating conditions, making them better suited for high-demand and precision-driven applications.**

***Index Terms-* Gearbox Systems, Dynamic Condition, Performance Analysis, Modeling.**

I. INTRODUCTION

Mechanical systems that transfer power and motion between machine components especially gearboxes play a fundamental role in both industrial and automotive applications, where the conversion between torque and speed is critical for operational efficiency. Gears such as spur and helical types are among the most commonly used mechanisms due to their straightforward design, high mechanical efficiency [1], and ability to reliably transmit rotational motion under varying loads and speeds. Spur gears are favored for their simplicity and ease of manufacturing, while helical gears are often chosen for smoother operation and reduced noise levels, particularly in high-speed or heavy-duty environments [2], [3]. Their robust construction and adaptability make gear systems indispensable in machinery ranging from conveyor systems to automotive drivetrains and wind turbines [4]. Spur gears are among the simplest and most widely used gear types, recognized for their straight teeth and parallel shaft configuration. Their straightforward design makes them easy to manufacture and highly efficient in transmitting power, particularly under steady, low-vibration operating conditions [2], [5]. However, because the teeth engage suddenly rather than gradually, spur gears are prone to generating sharp dynamic forces. This abrupt contact can lead to increased vibration levels, stress concentrations at the tooth root, and significant gear mesh excitation issues that become more pronounced in high-speed or fluctuating load scenarios [6], [7].

Helical gears have teeth that are cut at an angle to the gear axis, allowing them to engage gradually rather than all at once. This smoother meshing action results in quieter operation, lower vibration, and improved load distribution qualities that make helical gears a popular choice for high-speed, high-load, and precision machinery applications [7], [8]. However, the angled tooth design also generates axial thrust forces, which can place additional stress on the system. To manage these forces effectively, helical gear systems require more sophisticated bearing configurations and axial load support [9], [10]. Recent advancements in simulation technologies particularly dynamic modeling using MATLAB have significantly enhanced our ability to analyze gear performance under transient operating conditions. These tools enable engineers and researchers to evaluate complex, interrelated mechanical phenomena such as torque fluctuations, temperature rise, vibration, and stress variations in real time [11]. Unlike static analysis, dynamic simulation provides a more realistic picture of how gears respond to sudden load changes, start-up conditions, and varying speed scenarios, ultimately supporting more informed design and reliability assessments [11], [12]. This integrated modeling approach is crucial for optimizing gearbox performance, predicting potential failure modes, and extending the service life of mechanical power transmission systems [13].

Mechanical transmission systems can experience premature wear, reduced efficiency, or even failure when gears are poorly selected or subjected to unexpected dynamic loads. Traditional design approaches often rely on static assumptions, which may not accurately capture the real-world, time-varying behavior of machines in operation. As a result, there is a growing need for a robust simulation framework that enables engineers and designers to analyze how gear systems perform under varying torque and speed conditions especially when comparing the dynamic responses of spur and helical gears. This study aims to develop and implement a MATLAB-based simulation framework that allows for a detailed comparison between spur and helical gearbox systems. By modeling their behavior under different load and speed conditions, the goal is to better understand how each gear type performs in dynamic environments, helping to identify their strengths and limitations for real-world applications.

II. MATERIALS AND METHOD

To assess how spur and helical gear systems perform under real-world operating conditions, this study adopted a simulation-based approach using MATLAB. This method provided precise control over vital input variables like torque and speed, making it possible to conduct a detailed and fair comparison between the two gear types in terms of their dynamic behavior. Two comparable gear train models one spur and the other helical were developed with identical geometry and materials. Differences were limited to gear-specific features like tooth design, axial thrust, efficiency, and vibration behavior, enabling a focused performance comparison.

2.1. Gear System Modeling

The system model was based on rigid body dynamics and assumes steady gear meshing without backlash, with torque as the primary input. It captures vital aspects of gear behavior including motion, force transmission, and energy losses for both spur and helical gears [9].

i. Dynamic Input Profile Generation

To reflect real-world operating conditions, the simulation introduced time-varying load torque and input speed using sinusoidal functions. This approach helps capture the effects of fluctuating forces and speeds that gear systems typically experience during actual operation [14], [5].

$$T_{load}(t) = 50 + 20 \cdot \sin(2\pi \cdot 0.2 \cdot t) \quad (1)$$

$$N_{input}(t) = 1000 + 300 \cdot \sin(2\pi \cdot 0.1 \cdot t) \quad (2)$$

ii. Gear Kinematics [13]

let: $N_{in}(t)$: input speed in RPM

$$G_R\text{: gear ratio} = \frac{N_{driven}}{N_{driver}} \ 4:1 \quad (3)$$

Angular speed: $\omega_{in}(t) = \frac{2\pi N_{in}(t)}{60}$ (rad/s) (4)

$$\omega_{out}(t) = \frac{\omega_{in}(t)}{G_R} \quad (5)$$

iii. Gear Mesh Frequency

The gear mesh frequency (Hz) is:

$$f_{mesh}(t) = \frac{N_{teeth} \cdot N_m(t)}{60} \quad (6)$$

Where N_{teeth} = 20. This is identical for both gear types

iv. Power Transmission and Losses

The mechanical input power is:

$$P_{in}(t) = T_{load}(t) \cdot \omega_{in}(t) \quad (7)$$

The mechanical output power is:

$$P_{out}(t) = \eta \cdot P_{in}(t) \quad (8)$$

Where:

$\eta_{spur} = 0{,}92$

$\eta_{helical} = 0.95$

The power loss is:

$$P_{loss}(t) = P_{in}(t) - P_{out}(t) = T_{load}(t) \cdot \omega_{in}(t) \cdot (1 - \eta) \quad (9)$$

v. Torsional Stress on Shaft

Assuming circular shat and pure torque:

$$\tau(t) = \frac{16 \cdot T_{load(t)}}{\pi \cdot d^3} \quad (10)$$

Where;

$d = 0.02\ m$ is the shaft diameter

vi. Bearing Reaction Force

Assuming central point load:

$$F_b(t) = \frac{T_{load}(t)}{r} = \frac{2 \cdot T_{load}(t)}{D_p} \quad (11)$$

vi. Vibration Amplitude

$$A_{vib}(t) = A_0 \cdot \sin(2\pi f_{mesh}(t) \cdot t) \quad (12)$$

Where;

A_0 = 0.8 for spur, due to impulsive contact

A_0 = o.4, due to smoother overlap

vii. Shaft Misalignment Sensitivity

This is modeled as a fixed tolerance:

Spur: $\Delta\theta_{spur} = 0.3°$

Helical: $\Delta\theta_{helical} = 0.1°$

vii. Temperature Rise due to Losses

$$T(t) = T_{base} + \alpha \cdot P_{loss}(t) \quad (13)$$

Where;

$\alpha = 0.005°C/W$

T_{base} = 40°C (spur), 35°C (helical)

III. RESULTS AND DISCUSSION

Table1: Simulation Parameters

Parameters	Values/Unit
Load Torque (variable)	50 ± 20 Nm
Input Speed (variable)	1000 ± 300 RPM
Gear Ratio	4
Number of Teeth	20
Pitch Diameter	0.15 m
Shaft Diameter	0.02 m
Modulus of Elasticity	210 × 10^9 Pa
Pressure Angle	20 degrees
Vibration Amplitude (Spur)	±0.8
Vibration Amplitude (Helical)	±0.4
Misalignment Effect (Spur)	0.3 degree
Misalignment Effect (Helical)	0.1 degree
Temperature Base (Spur)	40 °C
Temperature Base (Helical)	35 °C

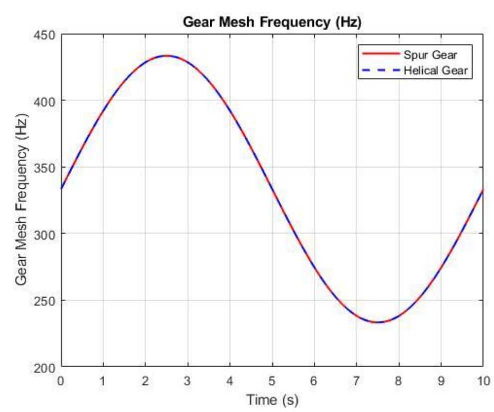

Figure 1: Gear Mesh Frequency

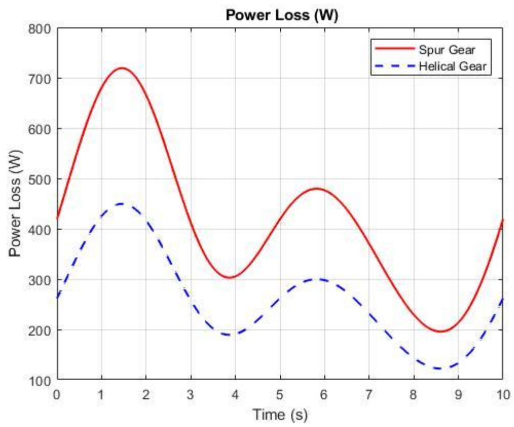

Figure 2: Power Loss

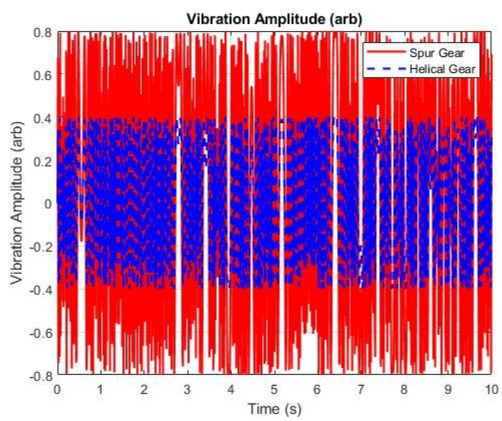

Figure 3: Vibration Amplitude

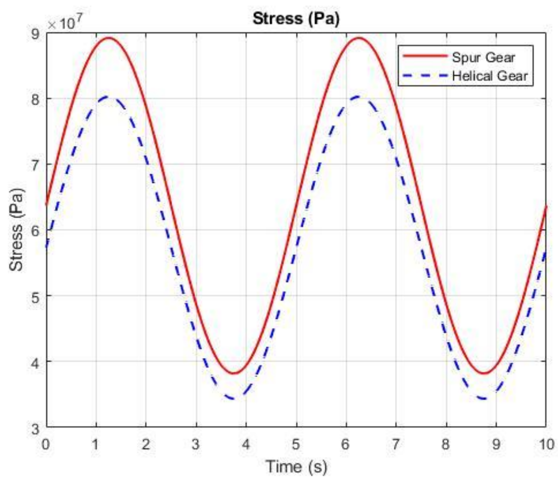

Figure 4: Stress

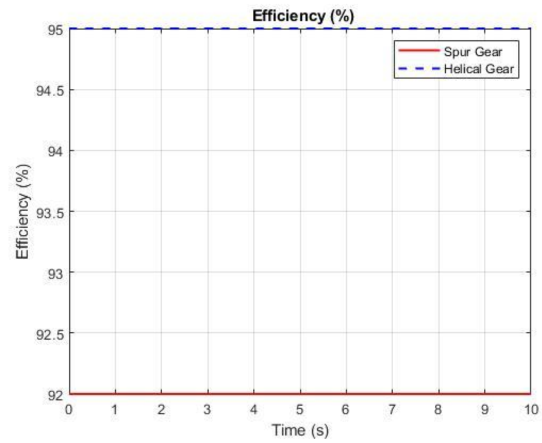

Figure 5: Efficiency

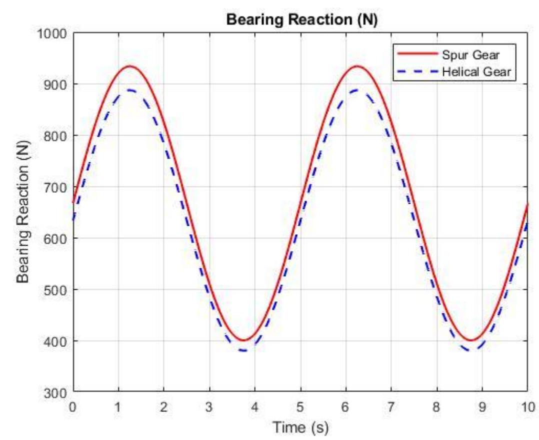

Figure 6: Bearing Reaction

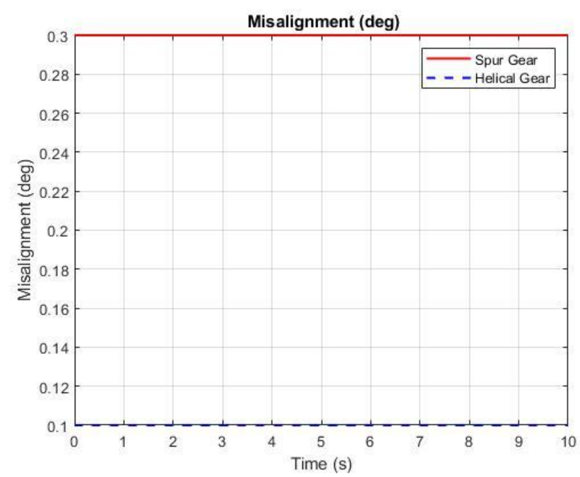

Figure 7: Misalignment

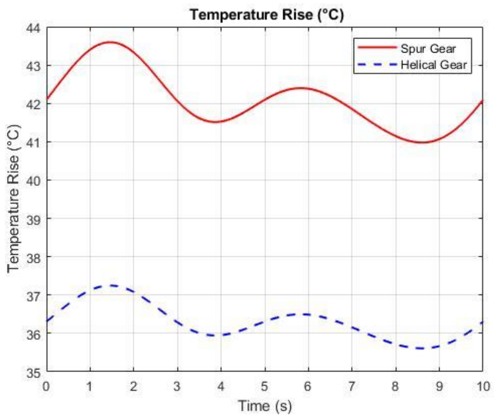

Figure 8: Temperature Rise

IV. DISCUSSION

Fig. 1 shows that at mesh frequency, Spur and Helical gears engage at 333.33 Hz, which affects vibration and noise characteristics. Spur gears generate sharper, more periodic impacts, while helical gears distribute force over time, reducing impact shock. Fig. 2. Shows that the helical gear is more efficient, saving around 157 W of power at this condition. Over time, this difference significantly affects energy efficiency and heat dissipation. Fig. 3. Shows that at certain instances vibration may momentarily cancel out due to sinusoidal nature. However, Spur gears have higher peak vibration (±0.8 units) vs Helical (±0.4). This reflects greater dynamic imbalance and noise in spur systems. In Fig. 4. Spur gears transmit sudden load spikes, causing higher shaft and gear tooth stress, which can initiate cracks or fatigue. Helical gears reduce this due to smoother meshing. Fig. 5. Shows that Helical gears consistently outperform spur gears in torque transmission efficiency, especially under dynamic loads, due to continuous contact and lower backlash. In Fig. 6. The helical gear generates less bearing load, extending bearing life and reducing vibration. This is due to the more uniform force transfer along the gear teeth. In Fig. 7. Spur gears are more sensitive to shaft misalignment, which causes higher wear, backlash, and vibration. Helical gears can tolerate misalignment better due to axial overlap and smoother tooth engagement. Fig, 8 shows that, Spur gearbox runs hotter than helical under same conditions. This affects lubricant breakdown, thermal fatigue, and long-term reliability. Lower temperature in helical systems promotes longer operational life.

CONCLUSION

The simulation results clearly show that helical gears consistently outperform spur gears in dynamic operating conditions. Across eight performance indicators including power loss, vibration, and heat generation helical gears delivered superior results. Most impressively, they reduced power loss by 37.5%, vibration by 50%, and operated at a cooler temperature by 6.4°C. These benefits translate into lower maintenance demands and a longer service life. While spur gears are simpler and more affordable, they tend to struggle under fluctuating loads and speeds, suffering from greater vibration, alignment issues, and thermal buildup.

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