

# Exploring Manufacturing and Assembly Misalignment Errors on the Mechanical Behavior of a Planetary Gearbox

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## Abstract

Planetary gearboxes play a central role in many critical rotating machinery systems, where their manufacturing and assembly accuracy greatly influence their reliability and remaining useful life. Among common faults, gear misalignment stands out as a critical issue predominantly caused by manufacturing inaccuracies and assembly errors. Such misalignments increase operational stresses and accelerate failure mechanisms, adversely affecting gearbox lifespan. This study investigates the effects of various types of gear misalignments—including axial, parallel, and angular deviations—on the mechanical behavior and strength of planetary gearbox gears. Using the well-established KISSsoft software, a parametric analysis is conducted to assess how individual and combined misalignment types influence key performance metrics such as root stress, Hertzian contact stress, contact temperature, and transmission error. Results indicate that even small misalignment deviations considerably amplify fatigue damage, surface wear, noise, vibration, and thermal loads within the gearbox. These effects induce system instability, accelerating premature failure modes. The study further reveals the complex interactions between different misalignment types, demonstrating that combined deviations can have multiplicative negative effects compared to single-type misalignments. The findings emphasize the necessity of stringent manufacturing tolerances and precise assembly procedures to minimize misalignments in planetary gearboxes. Furthermore, the research highlights the critical importance of continuous condition monitoring and alignment verification techniques to detect and mitigate misalignment-related faults early in the operational cycle. Optimized gearbox designs capable of accommodating or compensating for certain misalignments can enhance robustness and operational safety, particularly in demanding industries such as aerospace, automotive, and wind power generation.

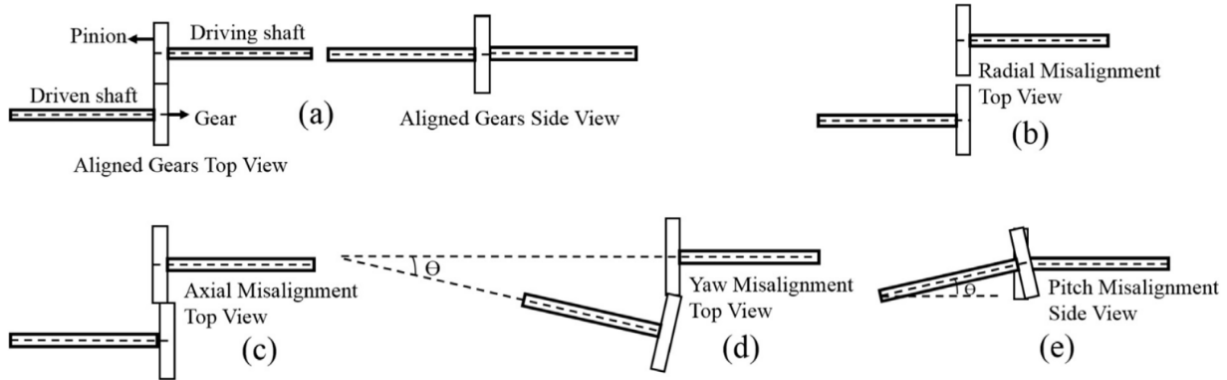
**Keywords:** Misalignment; Planetary Gearbox; Hertzian Stress; Transmission Error.

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## 1. Introduction

Gear systems are widely used in industries such as automotive, aerospace, wind energy, and heavy machinery for torque transmission, speed control, and efficiency improvement. Planetary gearbox-

es, valued for their compactness, load capacity, and efficiency, are highly sensitive to misalignment caused by manufacturing, assembly, thermal, or load effects. Misalignment alters load distribution, increasing stresses, wear, vibration, noise, and heat, thereby reducing service life and potentially causing catastrophic failure. It occurs as axial, parallel, or angular errors, which are often combined in practice, leading to more severe impacts (see Fig. 1).



**Figure 1.** Types of gear misalignment: (a) aligned engagement (b) radially misaligned (c) axially misaligned (d) angular misalignment in top view (e) angular misalignment in side view [1].

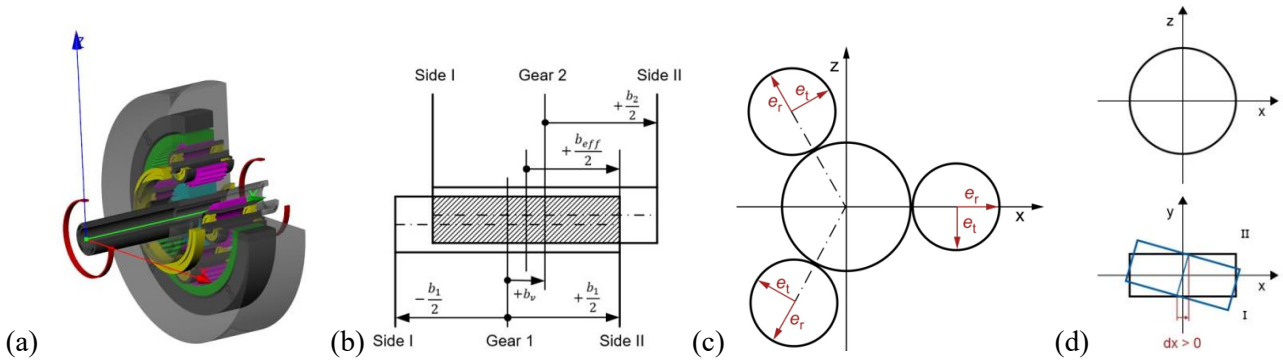
Many studies have investigated the significant impact of gear misalignment on the dynamic behaviour and vibration signals of gearboxes using methods such as discrete spectrum correction, statistical feature analysis, psychoacoustic characteristics, multi-degree-of-freedom dynamic models, and machine learning-based artificial intelligence techniques. Most prior research has focused on fault detection and condition monitoring of gearboxes, demonstrating effective identification of misalignment through vibration and acoustic signal analysis. For example, He (2016 [2]) introduced a novel discrete spectrum correction method to analyse vibration signals in wind turbine planetary gearboxes, while Dabrowski (2016 [3]) developed a hardware system combining vibration and thermography sensors for online fault diagnosis. Other studies have employed statistical parameters like RMS, kurtosis, and skewness (Khan, 2019 [4]), and psychoacoustic features (Kane, 2020 [5]) to enhance diagnostic accuracy. Dynamic models with multiple degrees of freedom considering misalignment effects on mesh stiffness and gear contact dynamics have also been developed and validated through experiments and finite element simulations (Yang, 2022 [6]; Wang, 2024 [7]). Advanced signal processing approaches like robust modulation spectrum correlation have further improved fault feature extraction (Guo, 2024 [8]).

Despite these advances, the vast majority of research concentrates on monitoring and diagnostics during gearbox operation, with limited comprehensive studies addressing the design and manufacturing stage considering gear misalignment effects. Therefore, there is a clear research gap in systematically incorporating misalignment impact analysis into the early design, manufacturing, and assembling phase of gearboxes, which is crucial for improving reliability, optimizing gear geometry, and preventing potential failures in operation. Addressing this gap could enhance gear system robustness by integrating dynamic misalignment considerations into design models and methodologies. The main objective of this study is to investigate the effects of gear misalignment—caused by manufacturing and assembly—on mechanical strength (including Hertzian contact stress and tooth root stress), performance behaviour (gear contact temperature), and transmission error (gear engagement error) with a focus on a planetary gearbox model. Three types of misalignments between gear teeth are analysed: axial, angular, and parallel (radial). After simulating the planetary gearbox in KISSsoft software (details in Section 2), a comprehensive parametric analysis is conducted on both spur and helical gears to determine the extent and nature of each misalignment type’s impact on stress, thermal behaviour, and transmission error (Section 3). Subsequently, by identifying influential factors on gearbox behaviour, the simultaneous effects of combined misalignments—closer to

real operational errors that reduce gear lifespan and cause premature failure—are analysed using a Small-Central Composite Design (Small-CCD) within a Design of Experiment (DoE) framework (Section 4).

## 2. Planetary Gearbox Simulation and Misalignment Definition

As the initial phase of the parametric study, a planetary gearbox has been modelled using the KISSsys module within the KISSsoft software (Fig. 2.a). Predefined template configuration has been employed, and key design parameters including the number of planets, gear type, and helix angle have been systematically adjusted. To complete the gearbox system model, input and output couplings are defined. Comprehensive details of the gearbox components, system parameters, and operating conditions are summarized in Tables 1-2.



**Figure 2.** (a) Gearbox model (b) axial misalignment setting (c) parallel misalignment setting (d) angular misalignment setting in KISSsoft.

**Table 1.** Geometrical specifications and materials of gearbox components.

Parameter/ Gear	Ring Gear	Planet Gears	Sun Gear
Number of teeth	87	23	36
Face width	60 mm	60 mm	60 mm
Profile shift coefficient	0.2301	0.8507	0.4702
Gear quality (DIN 3961)	6	6	6
Material	AGMA Grade 1 Steel	AGMA Grade 2 Steel	AGMA Grade 2 Steel
Heat treatment	Surface Hardened	Surface Hardened	Through hardening
Hardness	HB 400	HRC 58-64	HRC 58-64

**Table 2.** System and Loading Parameters

Parameter	Value
Gear Ratio	3.4:1
Module	3 mm
Pressure angle	20°
Helix angle	0° / 15° (spur/ helical gears)
Pitch circle diameter	92.0 mm / 93.5 mm
Number of planets	4
Input speed	6000 RPM
Power	350 kW

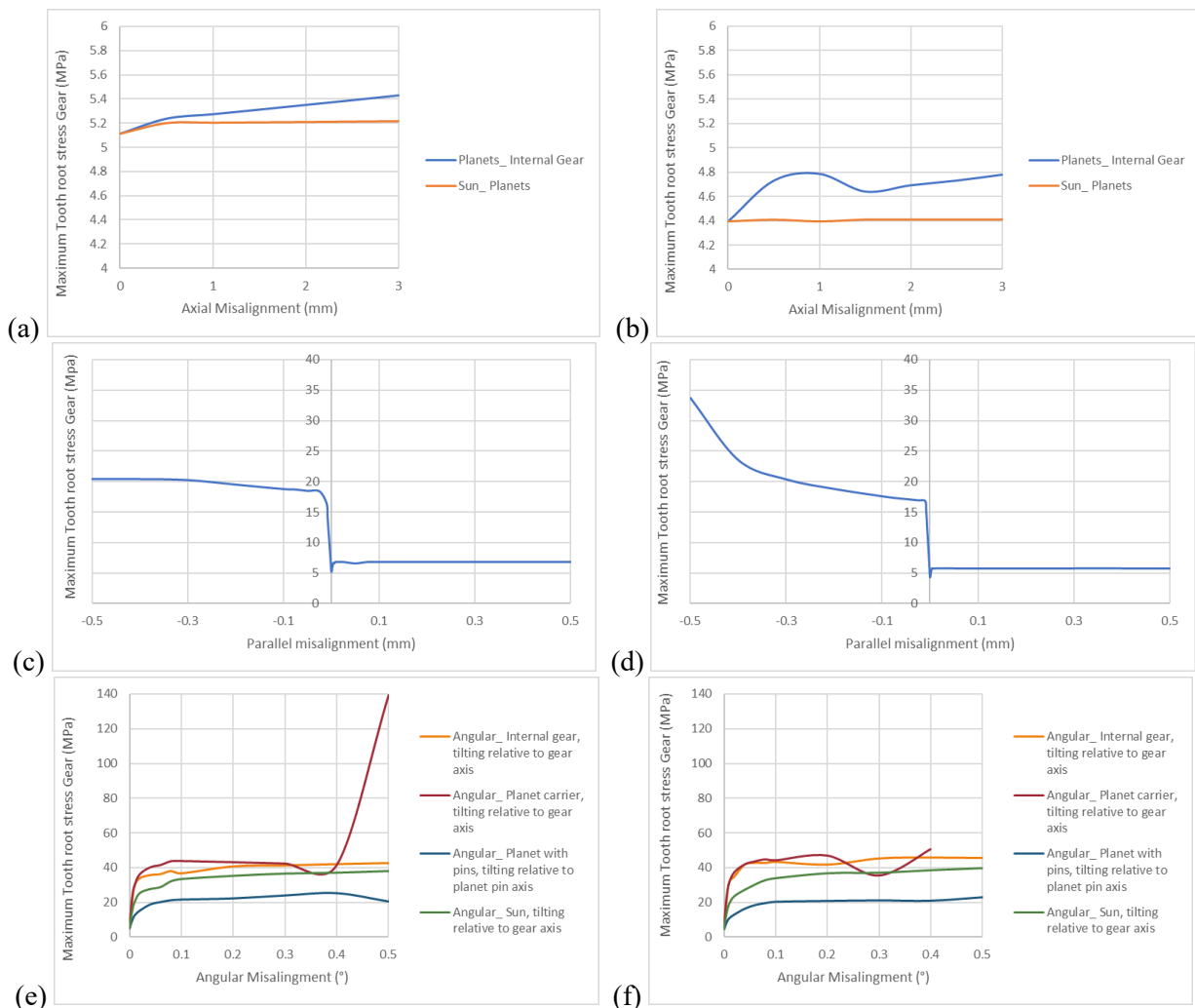
Misalignments are incorporated in the KISSsys modules as follows: axial offset is defined within Geometry module (Fig. 2.b), parallel misalignment is represented as a center distance error in Contact Analysis (Fig. 2.c), and angular misalignment is specified in Axis Alignment (Fig. 2.d). Angular misalignment is modelled using the Constant mode to accurately simulate installation errors.

### 3. Single-Type Misalignment on Gearbox Mechanical Behaviour

This section examines the effects of three types of single misalignment on maximum root stress, maximum Hertzian stress, maximum contact temperature, and maximum transmission error. Axial misalignment displaces gears along the axis, leading to uneven load and edge stresses. Parallel misalignment shifts gears laterally, keeping shafts parallel but offset. Angular misalignment occurs when shafts are not parallel, creating uneven tooth contact and critical performance issues. A parametric study of the main effects is conducted and compared for both spur and helical gears.

#### 3.1 Maximum Tooth Root Stress Analysis

Increased tooth root stress can lead to crack initiation and propagation at the root fillet, which ultimately results in tooth breakage and gear failure. Fig. 3 depicts effects of axial, parallel, and angular misalignment on maximum tooth root stress for both spur and helical gears.



**Figure 3.** Maximum tooth root stress for: (a) spur gears- axial misalignment (b) helical gears- axial misalignment (c) spur gears- parallel misalignment (d) helical gears- parallel misalignment (e) spur gears- angular misalignment (f) helical gears- angular misalignment.

Axial misalignment occurs in two ways (Fig. 3. a-b): in the first type, the gear ring shifts relative to the carrier set, and in the second type, the gear sun shifts relative to the rest of the carrier or experiences misalignment. For the first type of misalignment, the root stress increases by approximately 6% in spur gearboxes and 9% in helical gearboxes. In contrast, for the second type, the increase is about 2% in spur gearboxes and remained nearly constant in helical gears. Thus, it has been found

that the effect of the first type of axial misalignment is substantially greater than the second type, with varying impacts observed between spur and helical gearboxes.

In parallel type of misalignment (Fig. 3. c-d), the center distance between a planet gear and the sun gear changes. Considering the differences in contact conditions between the planet gear and the sun and ring gears, both positive and negative misalignment values are analyzed. The measured parallel misalignments ranged approximately from  $-0.5$  to  $+0.5$  mm, with a backlash of  $0.527$  mm. Positive misalignment caused differing proximity effects between the planet and ring gears, whereas negative misalignment affected the proximity between the planet and sun gears differently. In spur gearboxes, a  $+0.5$  mm misalignment increased root stress by about 30%, whereas a  $-0.5$  mm misalignment resulted in an increase of up to 300%. For helical gearboxes, the corresponding figures were 31% and 670%, respectively. These significant differences are mainly attributed to the size disparities between the gear ring and sun gear, leading to more favorable force distribution in the gear ring and reduced stresses compared to the sun gear. Overall, for parallel misalignment values, there is no critical increase in stress; however, attention is required to avoid negative misalignment or interference between the planet and sun gears.

Angular misalignment effects are also studied (Fig. 3. e-f), where four distinct forms of misalignment are identified, affecting various components such as the ring gear, carrier, and planet or sun gears relative to their respective axes. Considering the gearbox's coaxial nature, misalignments typically occur along a single axis only. The maximum applied angular misalignment in this category is  $0.5^\circ$ , since higher values tend to increase interference and compromise simulation accuracy. Specifically, in the first form of misalignment for spur and helical gearboxes, root stress increased by factors of approximately 8.4 and 10.5, respectively. In the second form, with an angular misalignment of  $0.4^\circ$ , the corresponding increases were roughly 10.5 and 11.5 for spur and helical gearboxes. Values exceeding these led to excessive interference and simulation issues. In the third form, bending stress increased by 4.0 times in spur gearboxes and 5.2 times in helical gearboxes, while in the fourth form, the increases were about 7.4 and 9.0 times, respectively. Among all forms, angular misalignment of the carrier exhibited the greatest impact, owing to its size and the induced misalignment in each planet gear. Consequently, the gear ring is the most critical component concerning misalignment severity due to its larger dimension relative to other rotating elements. The sun gear plays a significant role as the gearbox input and is most vulnerable to misalignment effects, with the planet gears ranking last.

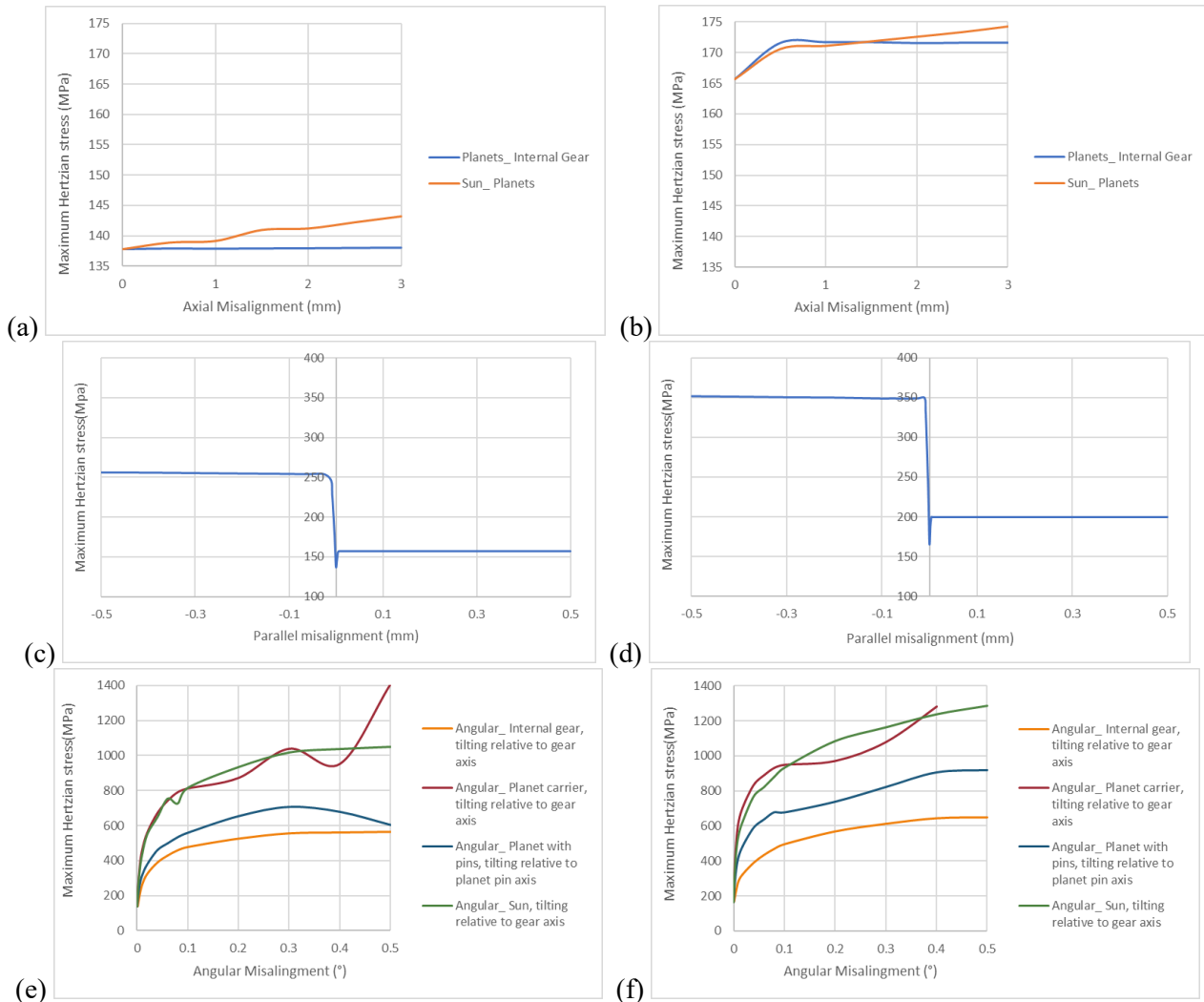
### **3.2 Maximum Hertzian Stress Analysis**

Maximum Hertzian stress is a key factor affecting gear life by influencing surface durability and the initiation of surface fatigue failure such as pitting and microcracks on gear teeth. Hertzian contact stresses occur locally at the gear tooth contact surfaces under load and describe the stress distribution in the contact area. Higher maximum Hertzian stress increases the likelihood of surface fatigue cracks due to cyclic compressive loading, leading to premature failure and shorter gear life. Effects of axial, parallel, and angular misalignment on maximum Hertzian stress for both spur and helical gears are illustrated in Fig. 4.

In the first type of axial misalignment (Fig. 4. a-b), peak Hertzian contact stress in the spur gearbox remained nearly constant, while it increased by about 5% in the helical gearbox. In the second type, stress increased by 5% in the spur gearbox and 4% in the helical gearbox. Overall, the misalignment effects on both gearboxes are similar, though angular gear positions can cause stress increases exceeding 20%. Considering Fig. 4. c-d, positive parallel misalignment values show moderate stress increases, but negative misalignment or interference between planet and sun gears leads to much higher stress rise, especially in the helical gearbox (up to 212%). For larger misalignment angles, stress increases dramatically—up to 10.2 times in the spur gearbox and beyond simulation limits in the helical gearbox due to very high stresses.

Angular misalignment (Fig. 4. e-f) of the carrier has the greatest impact on stress, followed by sun gear misalignment, which poses higher risks due to its influence on multiple gears. Although

the helical gearbox has better performance with aligned shafts due to more teeth in contact, it becomes more vulnerable to critical conditions under increased misalignment because of interference forces.



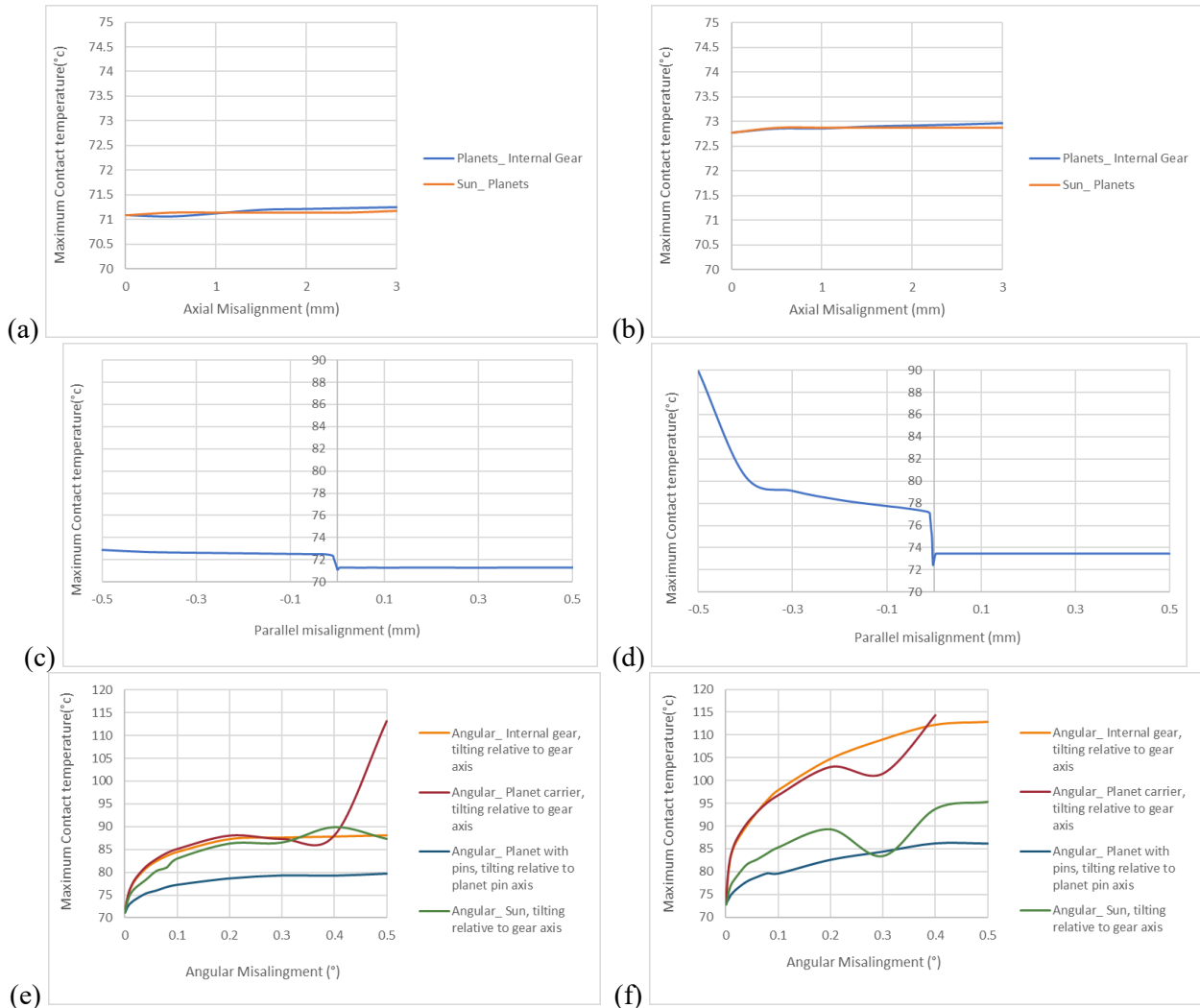
**Figure 4.** Maximum Hertzian stress for: (a) spur gears- axial misalignment (b) helical gears- axial misalignment (c) spur gears- parallel misalignment (d) helical gears- parallel misalignment (e) spur gears- angular misalignment (f) helical gears- angular misalignment.

### 3.3 Maximum Contact Temperature

Elevated contact temperatures reduce the hardness and strength of gear materials, leading to accelerated surface fatigue such as pitting and microcracking, which shortens the gear's service life. High temperatures can degrade lubricants, increasing friction and wear, which further exacerbates gear damage and reduces life. Fig. 5 depicts the effect of axial, parallel, and angular misalignment on maximum temperature for both spur and helical gears. Both spur and helical gearboxes exhibited temperature changes of less than 1°C due to axial misalignment (Fig. 5. a-b), indicating that misalignment has minimal impact on the temperature at the gear mesh contact points. However, because of different tooth meshing types in the helical gearbox, temperature increases at the contact location can reach up to approximately 2°C.

Parallel misalignment (Fig. 5. c-d) showed varying behavior depending on its direction. In the spur gearbox, at +0.5 mm misalignment, the peak temperature at the gear mesh increased by 0.2°C, while at -0.5 mm, it increased by 1.8°C. For the helical gearbox, the respective temperature increases were 0.7°C and 17.1°C. Overall, positive radial misalignment does not raise significant

concerns, but attention is required to prevent negative misalignment and interference between planet and sun gears. Notably, peak temperatures became roughly stable beyond misalignments greater than 0.004 mm.

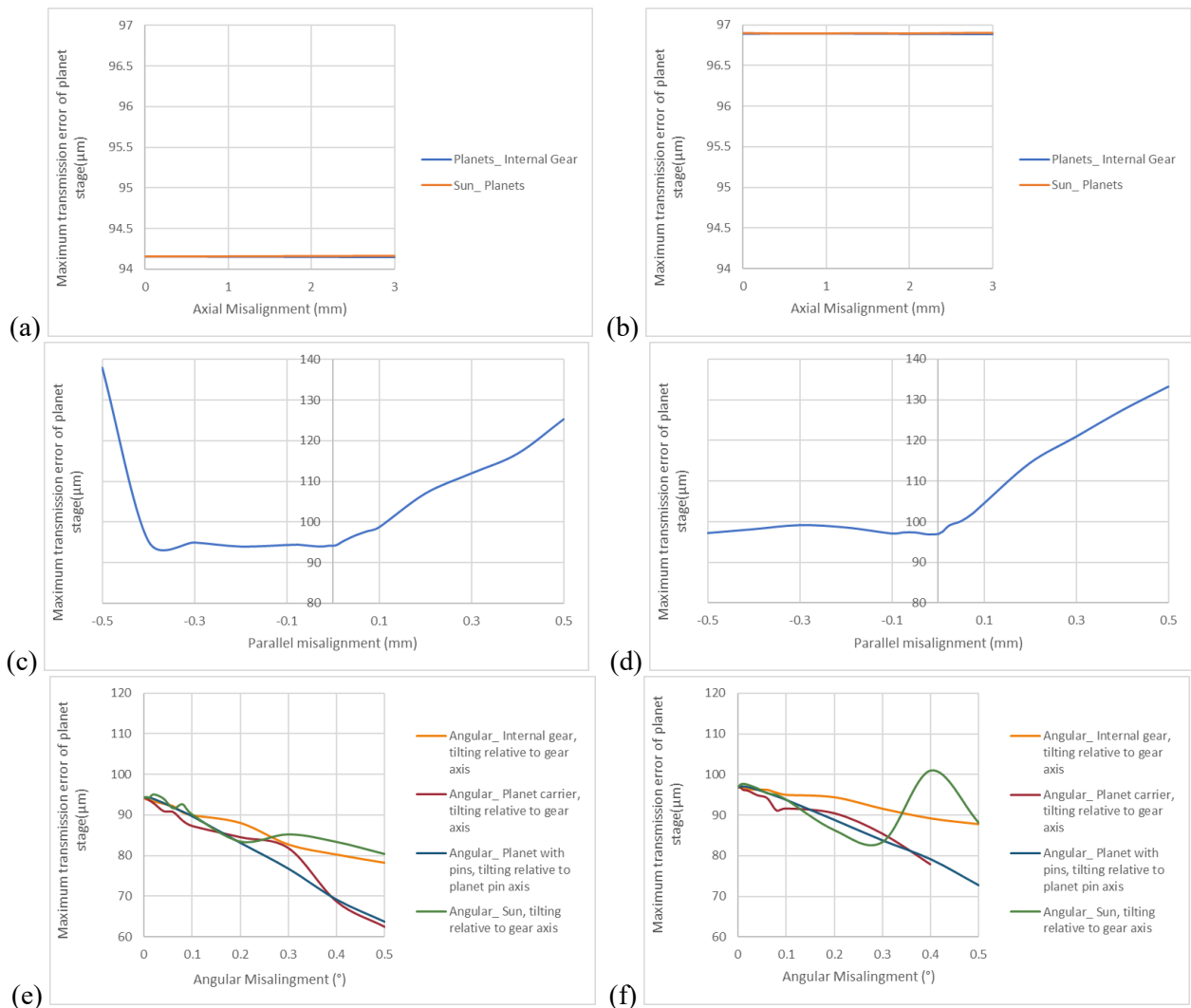


**Figure 5.** Maximum contact temperature for: (a) spur gears- axial misalignment (b) helical gears- axial misalignment (c) spur gears- parallel misalignment (d) helical gears- parallel misalignment (e) spur gears- angular misalignment (f) helical gears- angular misalignment.

For the first angular misalignment type (Fig. 5. e-f), the spur gearbox showed a maximum temperature increase of 17.0°C and the helical gearbox 30.1°C. At 0.4° misalignment, these values rose to 17.0°C and 41.6°C, respectively. Beyond this, temperature values increased sharply; in the spur gearbox reaching 42.0°C, while for the helical gearbox, simulation was limited due to extremely high stresses affecting software capabilities. In the third and fourth types of angular misalignment, the spur gearbox temperature increased by 8.6°C and 16.2°C, while the helical gearbox experienced increases of 13.5°C and 22.6°C, respectively.

### 3.4 Maximum Transmission Error

Transmission error (TE) is defined as the deviation between the actual and theoretical angular position of the driven gear in rotation, reflecting imperfections like tooth deflection, misalignment, or manufacturing errors. Maximum TE negatively impacts gear efficiency primarily by causing fluctuating load transmission and increased energy losses. TE Higher maximum TE leads to increased vibration, noise, and dynamic loading effects in the gear mesh. Effects of axial, parallel, and angular misalignment on maximum Hertzian stress for both spur and helical gears are shown in Fig. 6.



**Figure 6.** Maximum transmission error for: (a) spur gears- axial misalignment (b) helical gears- axial misalignment (c) spur gears- parallel misalignment (d) helical gears- parallel misalignment (e) spur gears- angular misalignment (f) helical gears- angular misalignment.

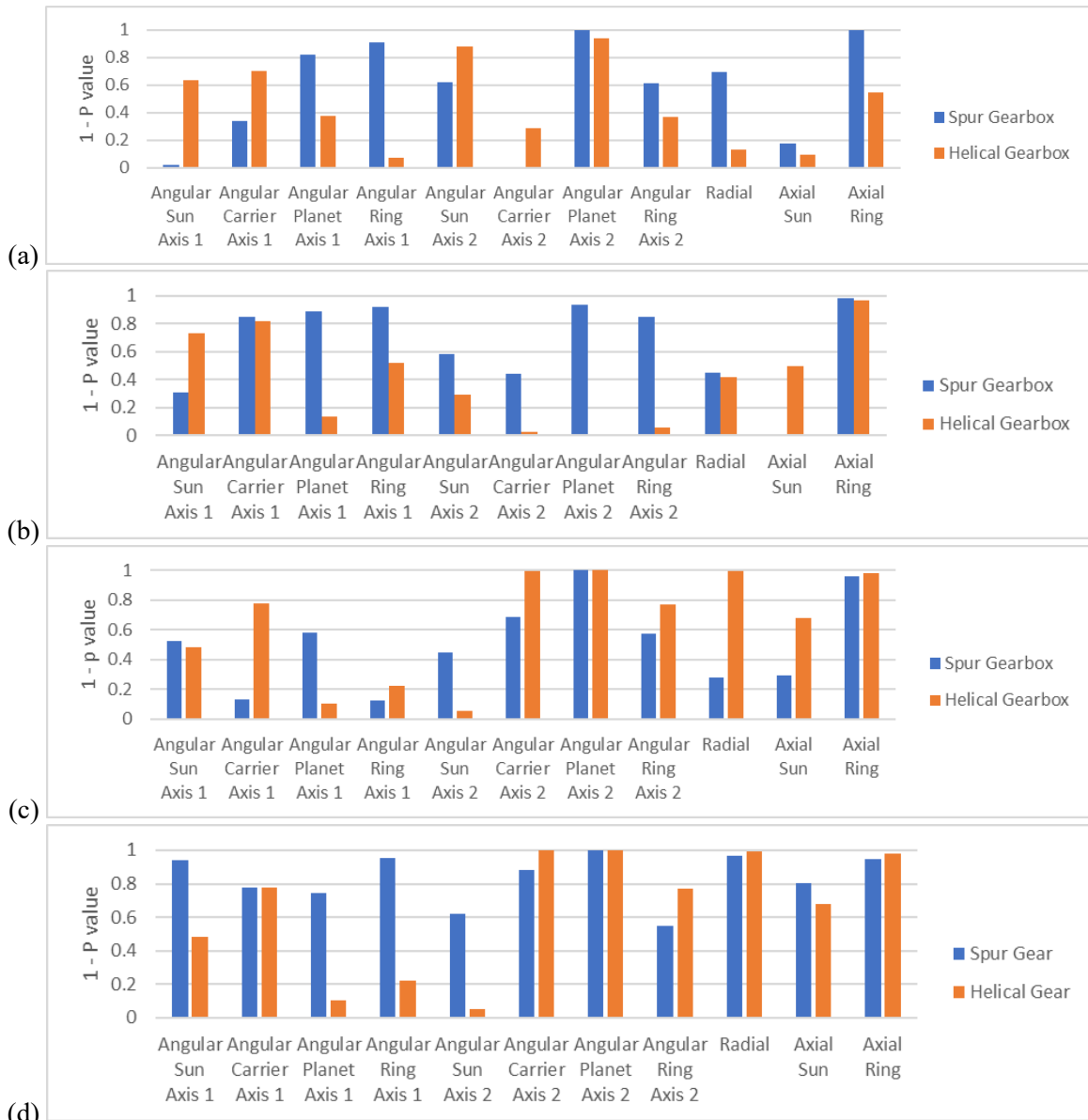
The peak transmission error in both spur and helical gearboxes showed only minimal variation due to axial misalignment (Fig. 6. a-b), indicating that axial misalignment effects on transmission error can be considered negligible. However, the transmission error magnitude in the helical gearbox was approximately two units higher than that in the spur gearbox.

Parallel misalignment (Fig. 6. c-d) exhibited different behavior depending on direction. In the spur gearbox, a +0.5 mm misalignment caused a 33% increase in peak transmission error, whereas a -0.5 mm misalignment led to a 47% increase. For the helical gearbox, the increase was about 38%. Overall, positive radial misalignment poses less concern, but attention is necessary to prevent negative misalignment or interference between the planet and sun gears. Transmission error stabilized beyond misalignments larger than 0.004 mm.

Angular misalignment effects on transmission error (Fig. 6. e-f) varied with the type of misalignment. Increasing angular misalignment generally reduced transmission error, with decreases up to 17% for the spur gearbox and 9% for the helical gearbox in the first misalignment type. In the second type, transmission error decreased by 28% and 20% in the spur and helical gearboxes, respectively. Further misalignment caused abrupt increases in error, with the spur gearbox showing a 34% decrease initially, but later increasing sharply; the helical gearbox software could not simulate accurately due to large changes. In the third and fourth types of angular misalignment, transmission error decreased by 22% and 15% in the spur gearbox and by 25% and 9% in the helical gearbox, respectively.

## 4. Combined Misalignment on Gearbox Mechanical Behaviour

This section investigates the combined effects of axial, parallel, and angular misalignments on stress, temperature, and transmission error in gearboxes. Using the Small-CCD, 11 misalignment factors have been analysed through 91 simulation experiments on spur and helical gears. Analysis of Variance (ANOVA) with p-values is applied to identify the most influential misalignment factors on gearbox performance. The p-value represents the probability of incorrectly rejecting the null hypothesis that a parameter has no effect on the output. In other words, the smaller the p-value, the lower the error in rejecting the null hypothesis, indicating that the corresponding factor has a more significant influence on the output. Fig. 7 presents 1 minus the p-value as a measure of the influence of various misalignments on the mechanical behavior of the gearbox.



**Figure 7.** Effect of different misalignment types on (a) mazimum root stress (b) maximum Hertzian stress (c) maximum contact temperature (d) maximum transmission error, under combined misalignments

Simultaneous misalignments have the greatest impact on tooth root stress in spur gears due to angular misalignment of the ring and planet gears, as well as axial misalignment of the ring (Fig. 7. a). In contrast, for helical gears, angular misalignment of the planet and sun gears predominantly affects tooth root stress.

Both spur and helical gears experience the most significant influence on Hertzian contact stress (Fig. 7. b) from the angular misalignment of the planet gear and axial misalignment of the ring gear, with spur gears also affected by ring misalignment. For spur gears, the factors impacting tooth root stress similarly affect Hertzian stress in the contact area. In helical gears, angular misalignment of the planet gear causes surface and root damage, while angular misalignment of the sun gear exacerbates root defects and axial misalignment of the ring gear intensifies surface flaws.

Helical gears exhibit sensitivity to a broader range of factors influencing gear temperature compared to spur gears (Fig. 7. c). Angular misalignment of the planet gear and axial misalignment of the ring increase temperature in both gear types. Additionally, in helical gearboxes, angular misalignment of the carrier arm and radial misalignment of the planet gear significantly affect thermal behavior.

Transmission error is more pronounced in spur gearboxes due to various misalignments (Fig. 7. d). In helical gearboxes, transmission error arises from angular misalignment of the carrier arm and planet gear, radial misalignment, and axial misalignment of the ring gear. For spur gearboxes, transmission error results from angular misalignment of the sun, ring, and planet gears, as well as radial and axial misalignments of the ring.

## **5. Summary/ Conclusion**

This study analysed axial, parallel, angular, and combined misalignments in planetary gearboxes using KISSsoft simulations. The results showed that angular misalignment is the most critical type, having the most severe impact by generating high stresses, temperature rises, and large transmission errors. Parallel misalignment produces moderate but consistent effects, while axial misalignment is the least critical, causing only localized stresses at tooth edges. Combined misalignments amplify negative effects, with simultaneous deviations significantly increasing stresses and transmission errors, especially when their directions reinforce each other. Statistical evaluations confirmed the strong influence of interactions between misalignments on gearbox performance. Overall, even small misalignments can reduce gearbox reliability. Therefore, careful alignment during design, assembly, and operation is essential. The results provide valuable insights for improving gearbox design and developing effective condition monitoring strategies. The findings of this paper are solely presented through simulations conducted in unique software and are interpreted from a physical perspective. Subsequently, the process of verifying these results has commenced, utilizing data obtained from laboratory experiments.

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