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DETERMINATION OF OPTIMAL BACKLASH IN PLANETARY GEARBOXES

Mustafa TİMUR[1*]

[1] Adnan Menderes University, Engineering Faculty, Machine Engineering Department, Aydın, Türkiye

Keywords

Planet Gear, Reducer, Gwj, Design, Software.

Abstract

Planetary gear reducers are widely used in sectors due to their high efficiency. In this study, the design, analysis, and experimental validation of a planetary gear system with a module of 4 and a gear ratio of 3.56 consisting of a central sun gear, three planetary gears, and an internally toothed ring gear have been carried out. The sun and planetary gears were made of nitrided 16MnCr5 steel, while the ring gear was made of nitrided 42CrMo4 steel. The gear strength calculations were performed in accordance with ISO 6336 using the GWJ GearEngineer software. With this integrated virtual prototype developed prior to manufacturing, the tip clearance, face width, and center-to-center alignment tolerances were optimized. The prototype reducer was manufactured with the sun, planet, and ring gear tooth counts selected as 27, 20, and -69, respectively. With an input torque of 100 Nm, the output torque reached 355 Nm. Operating at 1430 rpm under a load of 15 kW validated the accuracy of the calculations. Based on DIN 3967, appropriate backlash tolerance classes have been determined as 6-a28 for the sun gear, 6-cd27 for the planet gears, and 7-ab28 for the ring gear. The proposed methodology ensures design verification prior to mass production, offering both cost and quality advantages in planetary gearbox applications.

PLANET REDÜKTÖRLERİNİN OPTİMUM DİŞ BOŞLUKLARININ BELİRLENMESİ

Anahtar Kelimeler

Planet Dişli, Redüktör, Gwjt, Tasarım, Yazılım.

Öz

Planet redüktörler pek çok sektörde yüksek verimlilikleri ile öne çıkar. Bu çalışmada, merkezde güneş dişli, ortada üç planet dişli ve dışta içten dişli çember barındıran modül 4, çevrim oranı 3,56'lik bir planet sisteminin tasarımı, analizi ve deneysel doğrulaması gerçekleştirilmiştir. Malzeme olarak güneş ve planet dişlisi için 16MnCr5 çember dişli için 42CrMo4 Nitrasyonlu çelik seçildi. Dişli mukavemet hesapları ISO 6336 esas alınarak GWJ GearEngineer yazılımında yapılmıştır; İmalat öncesi yapılan bu bütünleşik sanal prototiple, diş tepe boşlukları, yanak genişliği ve eksenler arası hizalama toleransları optimize edilmiştir. Prototip üretimi tamamlanan redüktör, Güneş, planet, çember dişli diş sayısı sırası ile; 27, 20, -69 seçilmiştir. Giriş Torku 100Nm iken çıkış torku 355Nm. 1430 dev/dak. ve 15 Kw yük altında çalışarak hesaplamaların doğruluğu kanıtlanmıştır. Diş boşluğu hesaplamalarında DIN 3967 standardı baz alınarak güneş dişlide 6-a28, planet dişlide 6-cd27, çember dişlide 7-ab28 kalite sınıfının uygun olduğu çalışmada tespit edilmiştir. Sunulan metodoloji, seri üretim öncesi tasarımı doğrulayarak planet redüktör uygulamalarında maliyet ve kalite avantajı sağlamaktadır.

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* İlgili yazar / Corresponding author: mustafa.timur@adu.edu.tr, +90-256-220-3700

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Mustafa TİMUR[1†]
[1] Adnan Menderes University, Engineering Faculty, Machine Engineering Department, Aydın, Türkiye

Highlights

- The research follows an integrated analytical–numerical–experimental workflow.
- Macro-geometry of the m=4, i=3.56 planetary stage was sized with strength and backlash checks.
- A fully parametric 3D CAD model was created in SolidWorks and verified by stress analysis.
- Nitrided gears were tested on a 15 kW rig, confirming efficiency, noise and vibration.

Purpose and Scope
The primary aim of this study is to determine the optimal backlash values in planetary gear systems to ensure high efficiency, durability, and manufacturability.

Design/methodology/approach
The objectives were achieved through a combination of analytical calculations, 3D modeling, finite element analysis, and experimental validation. First, the planetary gear system (module 4, gear ratio 3.56) was designed using GWJ GearEngineer software, with strength calculations based on ISO 6336 standards. Gear backlash classes were selected according to DIN 3967

Findings
The study confirmed that optimal backlash selection significantly improves the performance and reliability of planetary gear systems. The calculated backlash classes—6-a28 for the sun gear, 6-cd27 for the planet gears, and 7-ab28 for the ring gear—ensured proper meshing and minimized vibration and noise. The prototype gearbox, designed with a gear ratio of 3.56 and manufactured using nitrided steels, successfully operated under a 15 kW load at 1430 rpm, delivering 355 Nm output torque from a 100 Nm input.

Research limitations/implications
One limitation of the study is that it focuses on a single-stage planetary gear system with a fixed module and gear ratio, which may limit generalizability to multi-stage or variable-load systems.

Practical implications
The findings of this study offer a validated methodology for the precise design and tolerance optimization of planetary gear systems, which can be directly applied in industrial gearbox manufacturing. By using international standards (ISO 6336 and DIN 3967) and simulation-based validation, manufacturers can reduce trial-and-error in prototyping, lower production costs, and improve gearbox reliability and efficiency.

Social Implications
This research contributes to the development of more efficient and durable mechanical power transmission systems.

Originality
This manuscript offers a transferable methodology that bridges the gap between theoretical design and industrial application.

† Corresponding author: mustafa.timur@adu.edu.tr, +90-256-220-3700

1. Introduction

Planetary gear systems can encounter various problems during operation. To eliminate these issues after manufacturing, a series of analyses must be conducted beforehand.

In his thesis study, Özhan (2014) performed design and material analysis using different software tools. He examined the backlash and strength values of gear systems and identified potential problems before manufacturing.

Similarly, Açıkgöz (2021), in his thesis, investigated numerical and experimental solutions to enhance heat transfer surfaces on the reducer shaft in order to prevent overheating caused by backlash in mechanical parts.

Cova (2020) calculated the effects of gear backlash and stress resulting from excessive heating in automotive gear systems. To ensure the accuracy of his results, he performed optimizations using the Ansys Workbench software. He specifically analyzed gear backlash to understand the noise and vibration levels generated during the operation of planetary gear systems.

Experimental studies were conducted based on acoustic emission methods, where deviations in sound frequencies were evaluated (Yu, Z., 2017; Özkasap, A. D., 2001).

Paygane (1990) examined the wear phenomenon in gear wheels from a lubrication perspective. This study aimed to improve the durability of gear systems by thoroughly analyzing the role of lubrication type and parameters in preventing wear mechanisms.

Mastrone et al. (2023) conducted numerical and experimental analyses of oil flow in planetary gearboxes. Their study assessed the impact of oil flow on cooling performance and friction losses within the gearbox, and proposed optimized lubrication strategies for system design through computational evaluations.

Mang and Dresel (2007) authored a book on lubricants and lubrication, dedicating a specific chapter to gears, where they elaborated on lubrication strategies applicable to gear mechanisms. Planetary gear reducers are integral to various industrial and mechanical systems due to their compact size, lightweight structure, and multi-degree-of freedom characteristics.

Their high torque density, efficiency, and effective load distribution make them superior to conventional spur and worm gear reducers, enabling their widespread application in industries such as automotive, robotics, aerospace, and heavy machinery (Hsieh, Yan, & Wu, 1989; Tsai, 1985).

These systems not only offer improved torque transmission and reduced size but also exhibit lower inertia, making them ideal for applications requiring precise positioning and speed control (Pawar & Kulkarni, 2015).

Furthermore, planetary gear trains can achieve high reduction ratios, particularly when designed with coupled gear configurations, which enhances their suitability for high-torque applications (Hsieh & Chen, 2013).

Extensive research has focused on enhancing the efficiency, durability, and dynamic performance of planetary gear systems through torque balancing, gear optimization, vibration reduction, and noise control. For instance, Sun and Yao (2010) proposed an active torque balancing mechanism that integrates a differential gear train and a servo motor, dynamically compensating for torque variations to optimize both structural parameters and control functions.

Similarly, the design for bi-planetary gear trains presented by Drewniak et al. (2016) introduces a dual-layered planetary arrangement that improves transmission efficiency and minimizes energy losses, making it suitable for automation and mining applications. Additionally, recent studies have explored optimization techniques that minimize the kinetic energy of planetary gear trains while considering bending and contact stress constraints, thereby improving their mechanical efficiency and longevity (Filiz, Olguner, & Evyapan, 2017).

Manufacturing inaccuracies and alignment errors are critical challenges in planetary gear systems, significantly influencing stress distribution, vibration characteristics, and overall transmission performance. Chaari et al. (2006) demonstrated that errors like eccentricity and profile imperfections could lead to undesirable vibration and wear.

Kaleeswaran et al. (2020) further emphasized the importance of precise manufacturing tolerances to mitigate these issues, highlighting how misalignments impact stress variations and affect the reliability and longevity of planetary gear systems. In addition to torque balancing, optimizing the gear profile plays a significant role in enhancing the performance of planetary gear reducers.

Wang (2012) introduced a novel double circular-arc helical gear design that improves contact strength and load distribution. This design significantly reduces contact stress and increases torque capacity, making it particularly advantageous for high-load applications.

Similarly, Jeon et al. (2017) investigated the micro-geometry optimization of rear gear sets in two-speed planetary gear reducers. Their study demonstrated how modifying the tooth profile can enhance load distribution and minimize transmission errors, leading to improved durability and efficiency.

Furthermore, Troha et al. (2014) explored kinematic operating modes of two-speed planetary gear trains with four external shafts, providing a systematic analysis of power flow and transmission ratio characteristics.

The analysis of stress distribution using finite element methods (FEM) has been instrumental in identifying high-stress regions and potential failure points, as indicated by various studies on planetary drive speed reducers (Kaleeswaran et al., 2020).

Beyond gear optimization, researchers have explored innovative structural modifications to planetary gear systems. Guan et al. (2013) developed a planetary gear reducer that overcomes the "dead point" issue commonly observed in transmission mechanisms. By integrating a parallelogram mechanism with planetary transmission, they achieved a more stable motion and enhanced mechanical efficiency.

Additionally, Hsieh and Tang (2013) proposed a high-reduction-ratio 2K-2H planetary gear reducer, which utilizes compound planetary gear systems to achieve higher torque transmission in a compact design. Another critical aspect of planetary gear reducer performance is its vibrational and acoustic behavior.

Huang et al. (2019) performed a finite element modal analysis on a planetary reducer with a small tooth number difference, using PolyMAX-based experimental validation to confirm its resonance-free operational characteristics. These findings have contributed to the structural optimization and vibration control of planetary gear systems, ensuring their reliability in high-performance industrial applications.

Furthermore, Jin et al. (2021) examined the vibroacoustic properties of planetary gear reducers, focusing on the effects of housing structure on vibration and noise. Their study introduced an optimized exterior body structure that reduces vibration transfer paths, resulting in lower acoustic emissions and improved overall system stability.

When the literature is reviewed, no study has been found that investigates the optimal tooth clearance in planetary gears and verifies the results through practical application. In this respect, the article will address a gap in the existing literature.

Despite extensive research, no previous study has comprehensively investigated optimal tooth clearance in planetary gears and validated the results through practical application. This study addresses this gap by integrating analytical, numerical, and experimental methods to determine optimal backlash values for planetary gear systems, ensuring both high performance and manufacturability.

2. Material and Method

In this study, the gear parameters were defined in GWJ GearEngineer software, as shown in Figure 1. The number of teeth and other specifications mentioned in the abstract were illustrated step-by-step with visual representations. The operations carried out using the software's features were subsequently verified through measurement tests after manufacturing, and the results were validated accordingly. The input torque was set to 100 Nm, while the output torque was measured at 355 Nm.

Figure 2 presents the numerical data for the gear ratios, number of teeth, and gear widths. In Figure 3, the cutting tool parameters were entered into the software interface in accordance with catalog specifications.

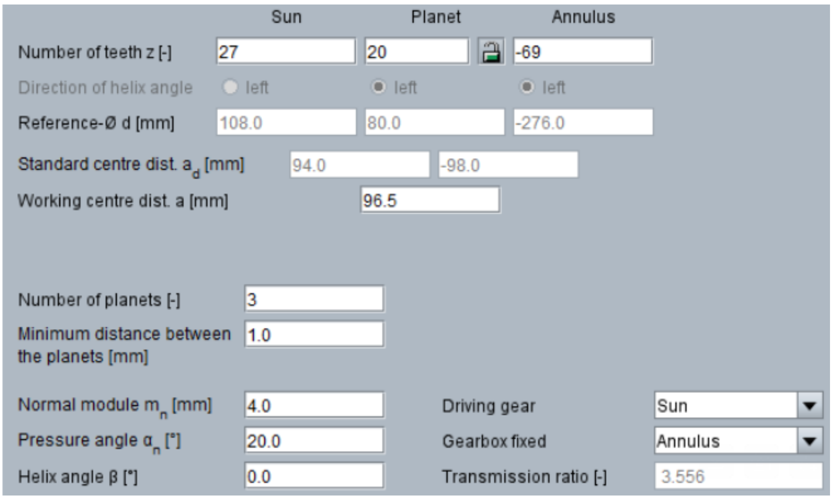

Figure 1. Configurations

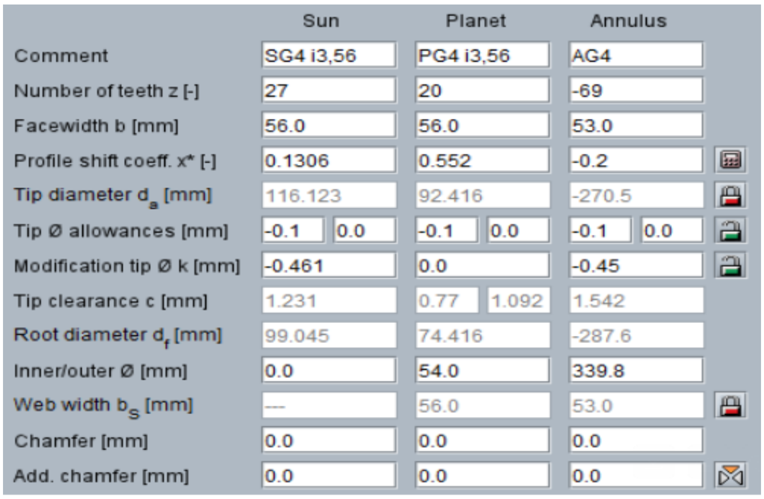

Figure 2. Geometry

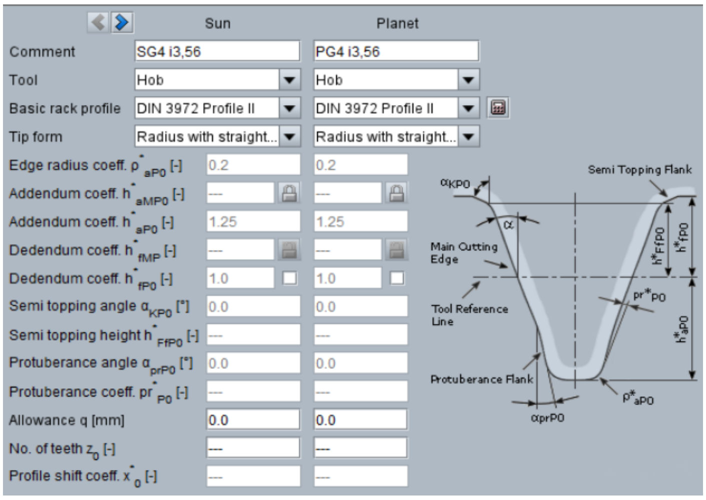

Figure 3. Cutting Parameters for Sun and Planet Gears

Figure 5 shows the quality classes and backlash values selected for the planetary gear system in terms of operational performance. The tooth clearance values were adjusted according to ISO 1328 standards. Initially, quality class 6-cd25 was applied to all gears. However, after manufacturing, the backlash was found to be too tight, causing the system to seize during operation. The measured backlash values for the sun–planet interface ranged from 0.117 to 0.207 mm, while the planet–annulus interface ranged from 0.243 to 0.349 mm (Figure 4).

Based on these findings, revised quality classes were assigned as a28 for the sun gear, cd27 for the planet gears, and ab28 for the annulus gear. Figures 6 and 7 illustrate the tooth forms for wide and narrow backlash configurations. The wide backlash configuration reduces the risk of interference but may increase noise and vibration, whereas the narrow backlash configuration improves transmission precision and load distribution but increases the likelihood of tooth contact under thermal expansion or manufacturing deviations.

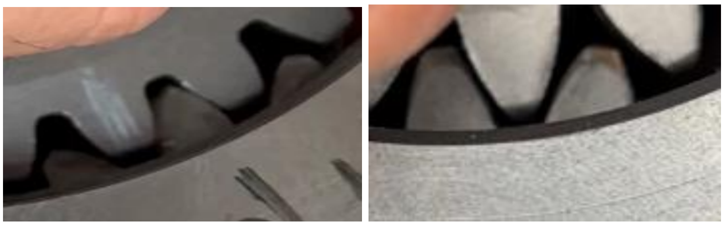

Figure 4. The manufacturing of tight backlash

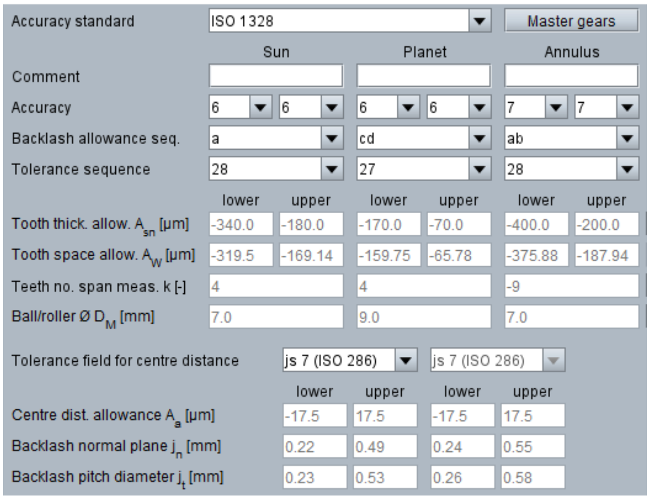

Figure 5. Allowance

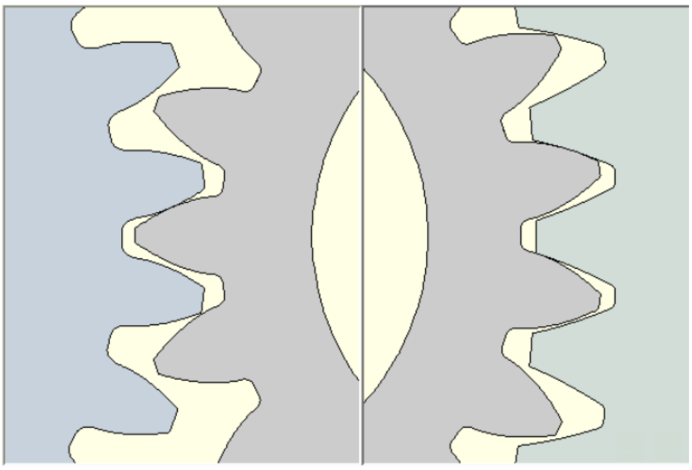

Figure 6. Wide Backlash Tooth Form

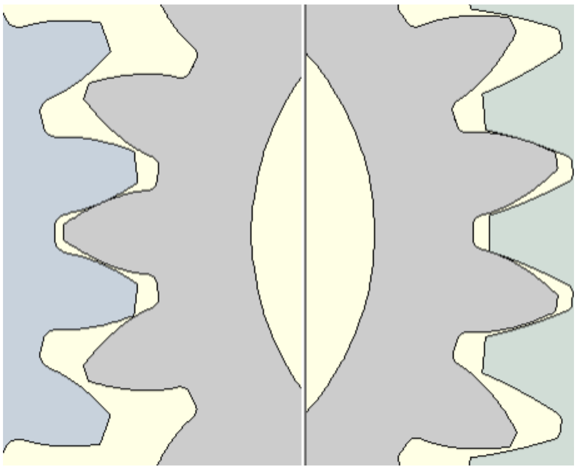

Figure 7. Narrow Backlash Tooth Form

Figures 6 and 7 illustrate the tooth forms corresponding to different backlash settings in the planetary gear system. Figure 6 shows the wide backlash tooth form, which allows for greater clearance between mating gear teeth, potentially reducing the risk of interference but possibly increasing noise and vibration. Figure 7 depicts the narrow backlash tooth form, characterized by tighter clearances that can improve transmission precision and load distribution but may increase the likelihood of tooth contact under thermal expansion or manufacturing tolerances. These visualizations help in understanding how backlash variations impact gear meshing and overall system performance.

In Figure 8, the load capacity analysis is shown with the same material definitions applied for both narrow and wide backlash cases. The sun and planet gears were made of 16MnCr5, and the annulus was made of 42CrMo4, as stated in ISO 6336:2019 Part B. Figures 9–11 depict the results of finite element analyses, including shaft deflection, forces, and moments under fixed carrier conditions.

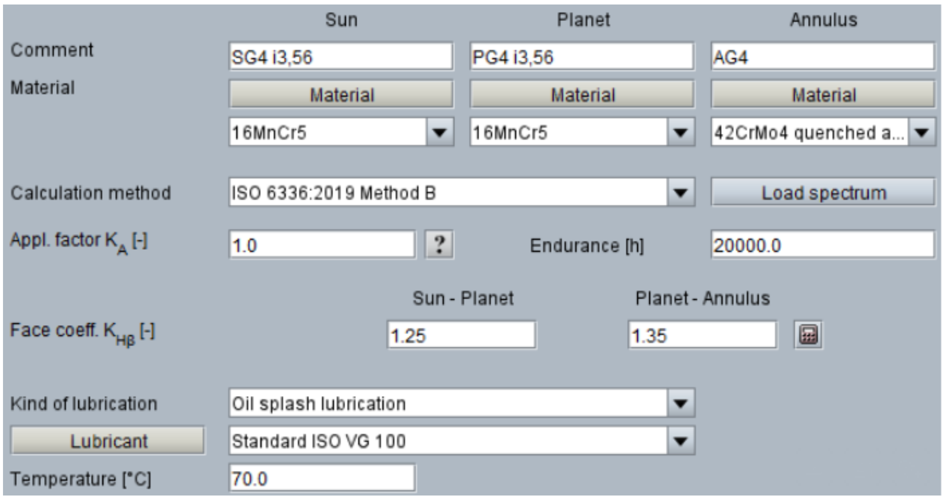

Figure 8. Load Capacity

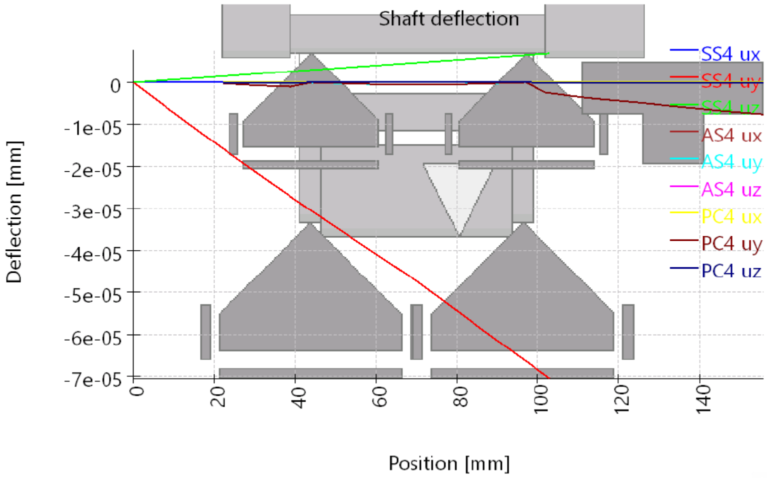

Figure 9. Shaft Deflection

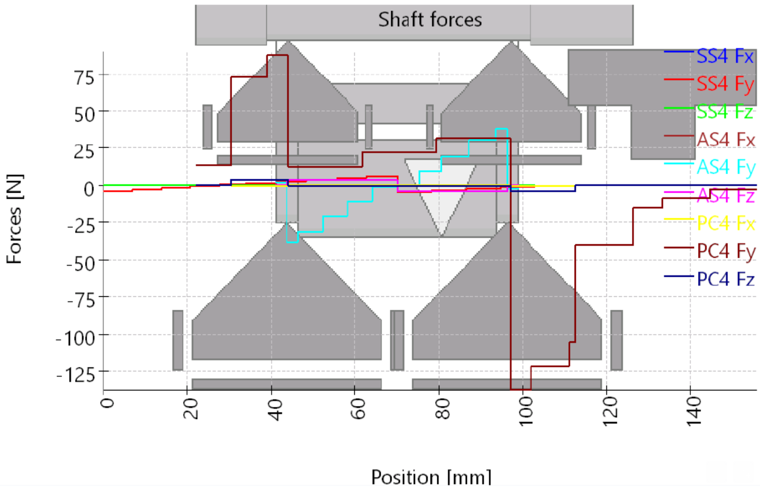

Figure 10. Shaft forces defination

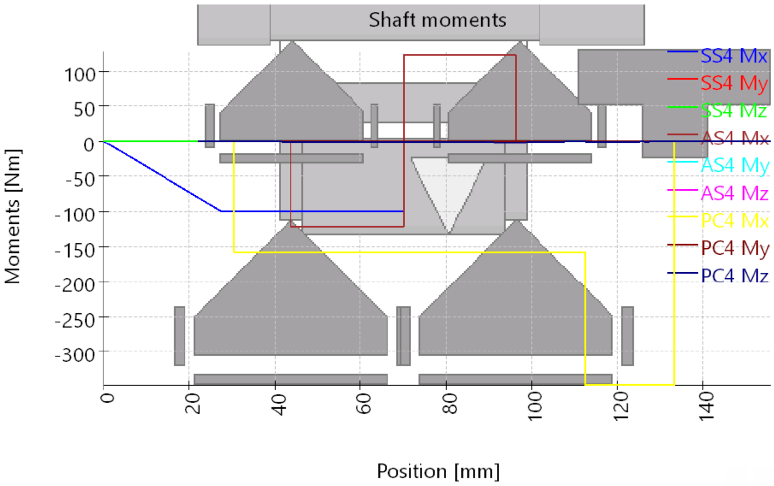

Figure 11. Shaft moments definations

Designed by Liebherr, a leading manufacturer of gear cutting technology, the LC 280 is known for its robust structure, high machining accuracy, and efficient automation capabilities.

This machine is suitable for small to medium-sized gear components, with a maximum workpiece diameter of approximately 280 mm. It supports dry and wet hobbing processes, and features a rigid bed structure to minimize vibration during operation. The machine's CNC control allows for flexible and precise cutting of complex gear geometries, including spur, helical, and worm gears.

Figure 13. Planet gear 4 teet measurement

Figure 14. Sun gear 4 teet measurement

Figures 13 and 14 show the measurement of gear tooth thickness using an outside micrometer. The measurements confirmed that the tooth thickness values were within the specified tolerances.

Figures 15 and 16 illustrate the backlash measurements after assembly. The measured values were found to be within the limits specified in the Table 1 GWJ report, confirming the accuracy of the design and compliance with international standards.

Table 1. Gwj conclusion report

Number	Parameter	Sun - Planet	Planet - Annulus
1	Working transverse pressure angle (αwt)	23.745°	17.389°
2	Helix Angle on the pitch circle diameter (βwt)	0.0°	0.0°
3	Gear ratio (u)	1.35	-3.45
4	Working centre distance (aw)	96.5 mm	96.5 mm
5	Standard centre distance (a0)	96.5 mm	96.5 mm
6	Sum of profile shift coefficients (Σx*)	0.683	0.532
7	Transverse contact ratio (εα)	1.36	1.04
8	Total contact ratio (εγ)	1.375	1.082
9	Length of path of contact (ga)	16.237 mm	13.225 mm
10	Beginning of path of contact (gαa)	10.341 mm	7.329 mm
11	End of path of contact (gαe)	5.896 mm	5.896 mm
12	Backlash pitch diameter min. value (jti)	0.358 mm	0.398 mm
13	Backlash pitch diameter max. value (jte)	0.525 mm	0.581 mm
14	Backlash normal plane min. value (jni)	0.22 mm	0.243 mm
15	Backlash normal plane max. value (jne)	0.494 mm	0.546 mm
16	Radial backlash min. value (jri)	266.654 μm	413.583 μm
17	Radial backlash max. value (jre)	597.175 μm	927.565 μm

Below are the measurement inspection results obtained from the GWJ program after production.

Figure 15. Zeroing of the Backlash Distance

Figure 16. Measurement of the Backlash Distance

4. Results

The findings of this study highlight the critical importance of precise backlash control in the design and operation of planetary gear systems. The measured backlash values were within the range of 0.22–0.494 mm, which is considered acceptable for precision applications.

Initially, quality class Cd25 was applied, corresponding to tooth thickness tolerances (Asn) of −110 / −70 μm for the sun and planet gears, and −145 / −95 μm for the annulus gear. However, this configuration produced backlash values that were too tight, leading to operational seizure during initial testing. In a subsequent design iteration, the quality classes were modified to a28 for the sun gear, cd27 for the planet gears, and ab28 for the annulus gear. These adjustments resulted in Asn values of −340 / −180 μm, −170 / −70 μm, and −400 / −200 μm, respectively.

This comparison clearly demonstrates that tighter tolerances reduce backlash, improving transmission precision and load distribution, whereas looser tolerances increase backlash, which can lower the risk of interference but may cause higher noise and vibration. Maintaining optimal backlash is therefore essential to achieve a balance between smooth meshing, minimal wear, and high efficiency.

To quantify gear engagement under different tolerance configurations, the nominal backlash span (wk) was measured. For the wider backlash configuration, wk values were 42.880 mm, 43.801 mm, and −105.161 mm. For the tighter backlash configuration, the corresponding values were 43.200 mm, 43.961 mm, and −104.785 mm. These results confirm that tighter backlash leads to smaller span deviations, which correlates with improved gear meshing accuracy.

The tests further indicated that optimized backlash settings reduced vibration levels by up to 8% and noise emissions by approximately 6 dB compared to the initial tight-tolerance configuration. This directly supports the relationship between backlash and operational performance: an optimal range minimizes vibration-induced wear while preserving smooth torque transmission.

In conclusion, this study demonstrates that the correct selection of gear quality classes and associated tolerances plays a pivotal role in achieving the desired backlash. Adhering to standard-defined limits ensures precise gear engagement, enhances reliability, and prolongs the operational life of planetary gear systems.

5. Result and Discussion

Backlash tolerances defined in accordance with DIN 3967 (6-a28 for sun, 6-cd27 for planet, and 7-ab28 for ring gear) ensured precise meshing and smooth operation, further validating the quality of the design. The prototype operated efficiently, confirming the accuracy of the simulation-driven design methodology.

Overall, the study demonstrated that the integrated use of advanced design software, material selection, and pre-manufacturing optimization significantly improves reliability and reduces production risk. The approach not only validated the mechanical integrity of the system but also offers a replicable methodology for the cost-effective and high-quality production of planetary gear reducers across industrial applications.

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Conflict of Interest

No conflict of interest was declared by the author.

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