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Effect Analysis of Machining Errors of the Axle Wheel Hub Planet Carrier on Function and Durability-Related Parameters †

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Abstract: The wheel hub planetary gearset, a reduction gearbox of driven axles, is a susceptible driveline unit thanks to the number of gear meshes and its high manufacturing requirements. Due to its complexity, the planet carrier can be a potential source of functional parameter non-compliance (efficiency, noise, and vibration) in the short term; in the long term, there can be a reduction in the service life of the planetary gearset. This paper introduces a real case study that analyzes the calculated and experimental effects of planet carrier machining quality from a functional property and service life point of view, and compares two parts, which represent the original and the developed status of the pin hole drilling process.

Keywords: planetary gearset; planet carrier; machining errors; angle misalignment

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1. Introduction

Although the planetary gearset is not a new invention—it originated from the ancient Greeks in around 500 B.C.—it is the most power-dense gear drive to date; it is used in several different fields of mechanical drives, including in miniature and special demand robotic drives, such as aeronautic equipment or medical devices. However, planetary drives are also used in enormous industrial machines, like the wind turbines of power plants. Thanks to its inimitable properties like its cost-effective production, numerous operating modes, and high volume/power ratio, it is also preferable in the commercial and passenger vehicle industry. A wide variety of planetary gearsets have been well known in automatic transmission gearboxes for decades, but they are also the main torque and speed modifier driveline elements of modern, high-tech, fully electric or hybrid vehicles [1].

Planetary gearing is a gear system consisting of one or more planet gears, revolving around a central sun gear. Typically, the planet gears are mounted on a carrier, which itself rotates both around and coaxially to the sun gear. Planetary gearsets have an inner-toothed ring gear, which meshes with the planet gears. Planetary gearsets typically have two classes—simple or compound planetary gearsets—depending on the number of planet stages and gear meshes [2].

2. Materials and Methods

In modern agriculture, efficiency and productivity are the main priorities. To meet the demands, agricultural machinery must perform under varying conditions. Availability, operational safety, and low maintenance are the key.

Of course, from the design point of view, at the research and development sites, cost-effective, highly integrable components and low-weight solutions are needed where highly automated production methods are applicable. Planetary gearsets can serve these demands, so they are preferentially used in the propulsion system of power machines, tractors, harvesters, etc. In the case of one of the agricultural flagship 3-stage axle products of Rába Plc., the Hungarian axle manufacturer, in the planetary gearsets—due to the extreme level of pulling force in this category—the commonly used three- or four-planet

gear would not resist the load; therefore, five planet gears per gearset are used to meet service life requirements.

The planet carrier has a combined function in terms of the functional and durability parameters of the whole planetary system. First of all, in the carrier units, the tangential force of the planet gears is located in a single output torque that acts around the center axis of the planetary system; it also structurally contributes to the proper operation of the system, defining and sustaining the exact position of each planet gear rotation axis by the planet pin holes. The load of the carrier comes from the superposition of the gear forces from the individual planet gear meshes [3].

The non-load-dependent misalignments, axis inclination, and skew come from the accuracy of the machining steps, especially from the planet pin hole drilling process. The analysis of the manufacturing, tooling, and fixture design regarding the carriers or the evaluation of the actual machining process at Rába is not the objective of this paper, but the explained study introduces the real measurable misalignments and the calculated effect of the functional properties, as well as how this influences the durability of the gears [4].

At Rába, regarding the planetary carriers, Zeiss and Wenzel coordinate measurement machines (CMMs) are paired with the appropriate evaluation and visualization supports, as Figure 1 shows. Regarding the planet carriers of the mentioned axle product of Rába, which is the focus of this paper, the CMM report provides a perfect way to investigate the performance-influencing manufacturing deviations. The non-load-dependent axis misalignment of the planet pin holes strongly affects the angular deviation of the planet pins from the nominal and, eventually, the contact condition of the planet gears with the meshing sun and ring gear.

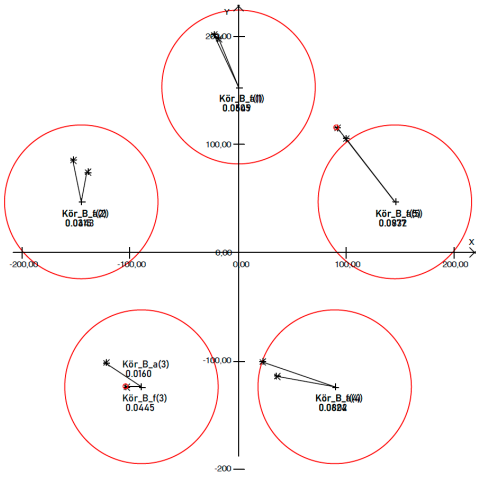


Figure 1. Measurement report of planet pin position errors of a carrier.

The center distance deviation can be measured if the actual distance between the axis of the planet pin holes and the center axis of the carrier deviates from the nominal value. This deviation can be found in either a positive or negative direction—both ways can be harmful to the gear contacts. The negative center distance on the sun gear contact side can cause tip clearance reduction, whereby even the meshing gears may collide, as the tip of the planet gear touches the root area of the sun gear. On the ring gear contact side, the negative center distance deviation can reduce the size of the contact pattern; in extreme cases, the planet gear can exit out of contact and overload the other four planets, as the planet load distribution is not even. The positive deviation can cause the same problems but in the opposite way. Practically, if the center distance deviation is not at the same level on the planet pin holes located opposite to each other, an inclination exists as the axes of the meshing gears are on the same plane, but are not parallelly located, creating an angle between them [3].

Planet pitch error occurs when the angular distribution between the five planet gears is not equal. Theoretically, the five planet gears mesh with the sun gear and the ring gear in different phases of contact, but the phase shifts are equal. Practically, planet pitch error modifies this balance and some gear teeth are overloaded, while the rest of them are underloaded. If the pitch error has a different value, or even a different direction (e.g., one is counterclockwise, while the opposite one is clockwise), a skew exists [3].

3. Results and Discussions

Compared to the nominal design, the real produced parts and assemblies have numerous deviations as a result of several factors, like machine and tool condition, material contamination, fixture design, etc. The well-known design engineer's tool KISSsoft® (Release 2023-SP5) is preferentially used by development departments in Rába as it can take into consideration these deviations and implement them in the calculations of functional behavior and durability estimations of any drivetrain, such as the focused planetary gearset of the agricultural axle.

The results on Figures 2 and 3 show the difference between a low-quality machined planet carrier (with the evening out of the drawing tolerance field; maximum of 0.08 mm position error for the pin holes), and a high-quality, improved machining planet carrier (where all measured dimensions are within the tolerance field); calculations are carried out using the KISSsoft® Contact Analysis module [5]. The presented parts represent production batches before and after machining improvement. In this paper, the worst case parts are presented, which were investigated through CMM measurement.

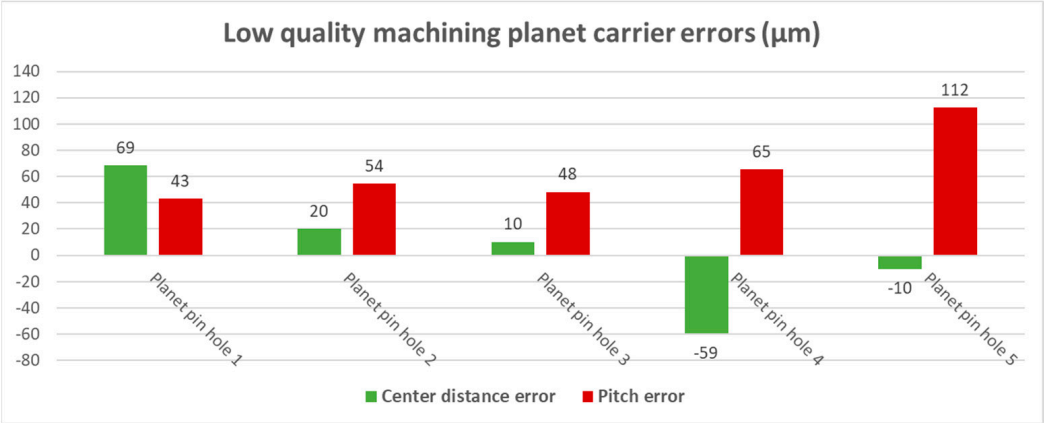


Figure 2. Planet carrier errors in the case of a low-quality machining.

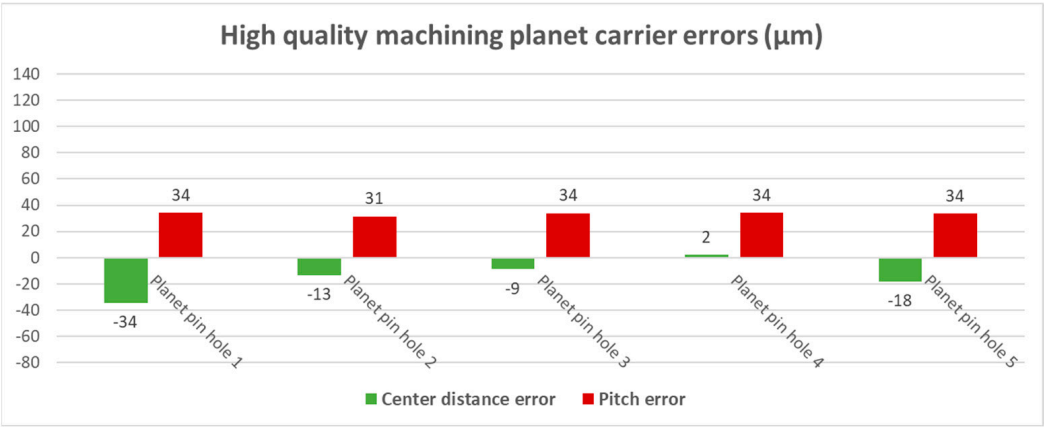


Figure 3. Planet carrier errors in the case of a high-quality machining.

Comparing the measured planet carrier errors, it can be seen that the center distance error exists in the case of both levels of quality, but the improved machining results in lower values. For the high-quality machining, the pitch error shows a more balanced value, practically at the same level on every planet pin hole.

Of course, the values of the high-quality machining are still not ideal, but they are closer to those of the nominal design, where the error values would be zero.

One of the best ways to represent the unfavorable effect of machining misalignment is by checking the load distribution between each planet gear. Figure 4 shows the planet load distribution in the rotation of the sun gear, comparing the different levels of carrier machining quality.

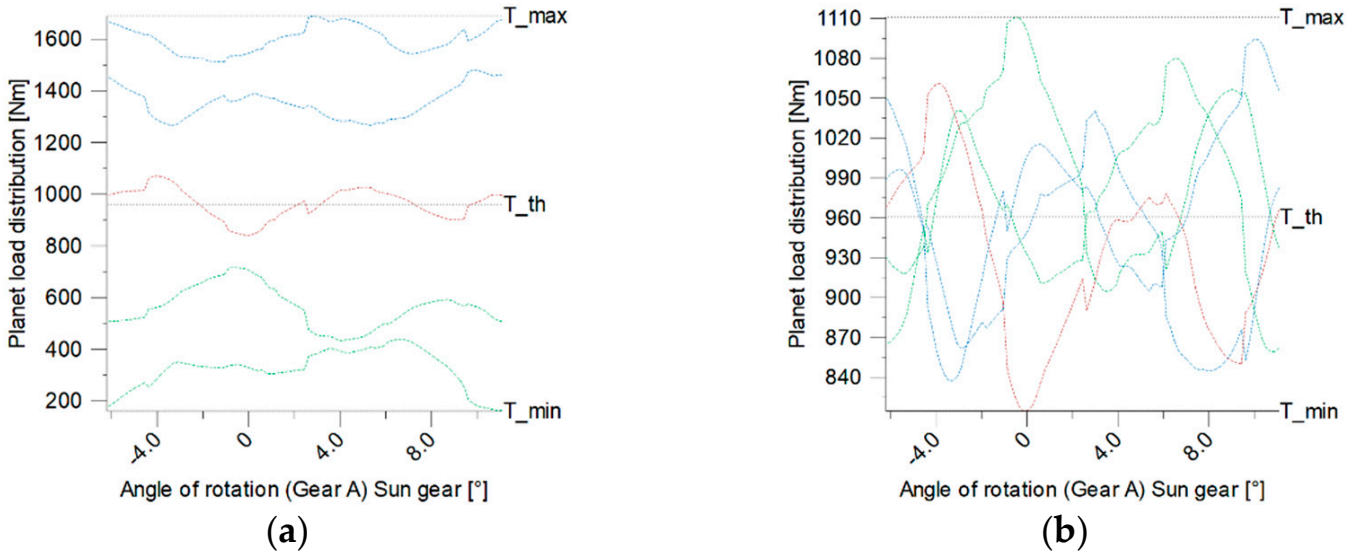
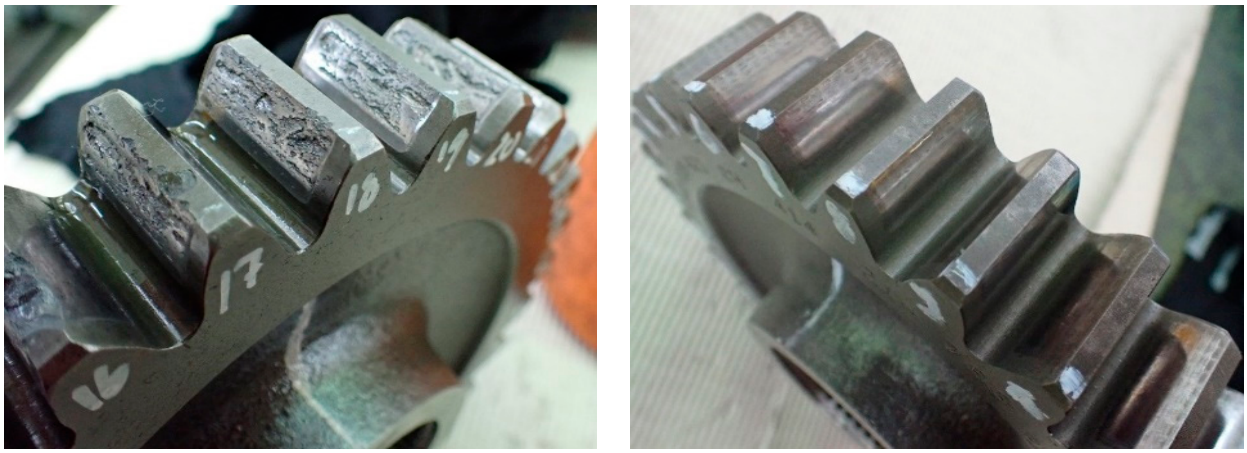


Figure 4. Comparison of planet load distribution diagrams. (**a**) Planet load distribution diagram with low-quality machining carrier; (**b**) planet load distribution diagram with high-quality machining carrier.

Although the amplitude of the torque curves is low, a huge difference can be observed between the planet gears at the level of the load. This phenomenon exists because some planet gears have such a center distance error that they become underloaded, as they are out of the proper gear mesh; therefore, the rest of them will be overloaded, as they try to transfer the whole load [6].

This significant uneven load distribution can easily lead to a low service life on the overloaded planet gears (as well as the mating gear), as the Hertzian contact pressure exceeds the permissible limit [7]. The result of the high contact pressure can be seen in Figure 5. In the planetary gear system, the input sun gear always has the dominant status in indicating contact problems, as it meshes with the five planet gears simultaneously. From these experimental results of the complete axle driveline durability test, it is obvious that the sun–planet gear mesh was overloaded, and knowing the CMM measurement results, this can be attributed to the carrier misalignments. The two sun gears performed the same 1200 h field load spectrum durability bench test in the axle's left and right wheel hubs. The significant difference between the two sides is that the machining quality of the planet carrier was considerably lower on the left side (Figure 5a) than on the right side (Figure 5b). Due to the previously introduced uneven load distribution, at some sun–planet gear meshes, the tooth flanks suffered from a high Hertzian pressure; therefore, the pitting fatigue appeared sooner.



(**a**) (**b**)

Figure 5. Comparison of sun gear pitting durability. (**a**) Sun gear pitting with low-quality machining carrier; (**b**) sun gear pitting with high-quality machining carrier.

Another great indicator of the benefits of the planetary gearset is the transmission error (TE). This metric shows the difference between the theoretical and the actual angular position of the driven gear at constant speed.

According to the investigations, the value of the transmission error can be an indicator of the noise and vibration characteristics of a gearbox and a planetary gearset. This is why its value is so important in today's NVH-focused electric and conventional drives. The transmission error is influenced by several error parameters of the gearset, and the carrier machining quality also contributes to it [8]. As the diagrams in Figure 6 show, not just the maximum value of the transmission error, but the minimum–maximum deviation has decreased thanks to the better machining quality.

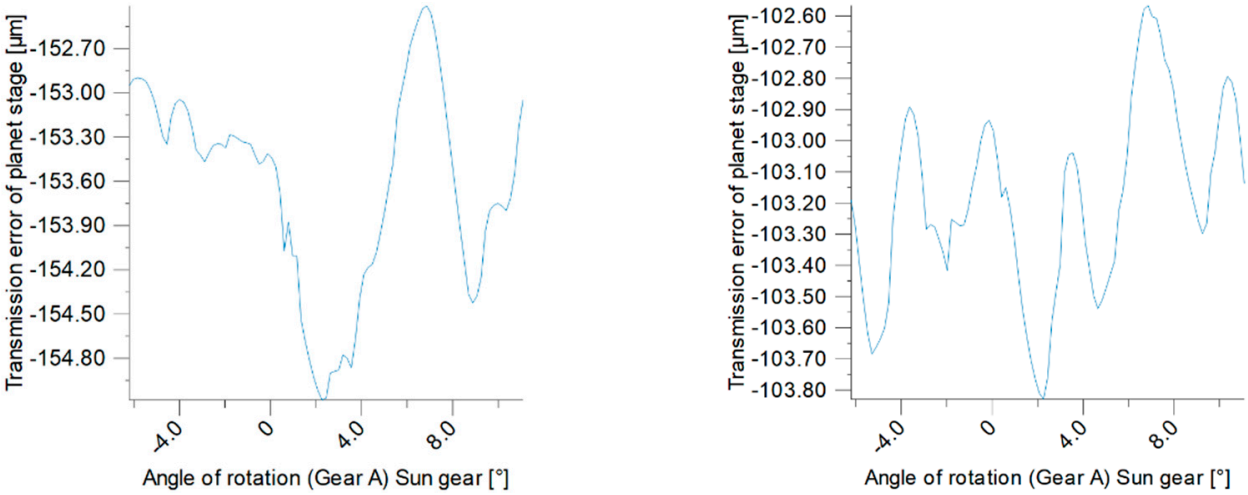


Figure 6. Comparison of transmission error (TE) diagrams. (**a**) TE of planetary gearset with low-quality machining carrier; (**b**) TE of planetary gearset with high-quality machining carrier.

Not just the maximum value of the transmission error, but the power spectrum of it can be meaningful. The power spectrum (also known as the amplitude spectrum) chart reveals how the different error components contribute to the value of the transmission error. The transmission error caused by the rotation center error, the gear eccentricity, and the gear meshing frequency were equally reduced, as can be seen when comparing the charts in Figure 7, and the proportion of them has changed. In addition to these values, it is worth

focusing on the modulation of the spectrum because it can be a warning sign of a gear whine problem, like in Figure 7b [9]. According to the experiences, these kinds of multi-stage axle drives are strongly inclined to noise-related problems, as the separate vibration phenomena of the stages can reinforce each other, resulting in a noise superposition. Therefore, it is recommended to focus on NVH potential in relation to this kind of axle application [10].

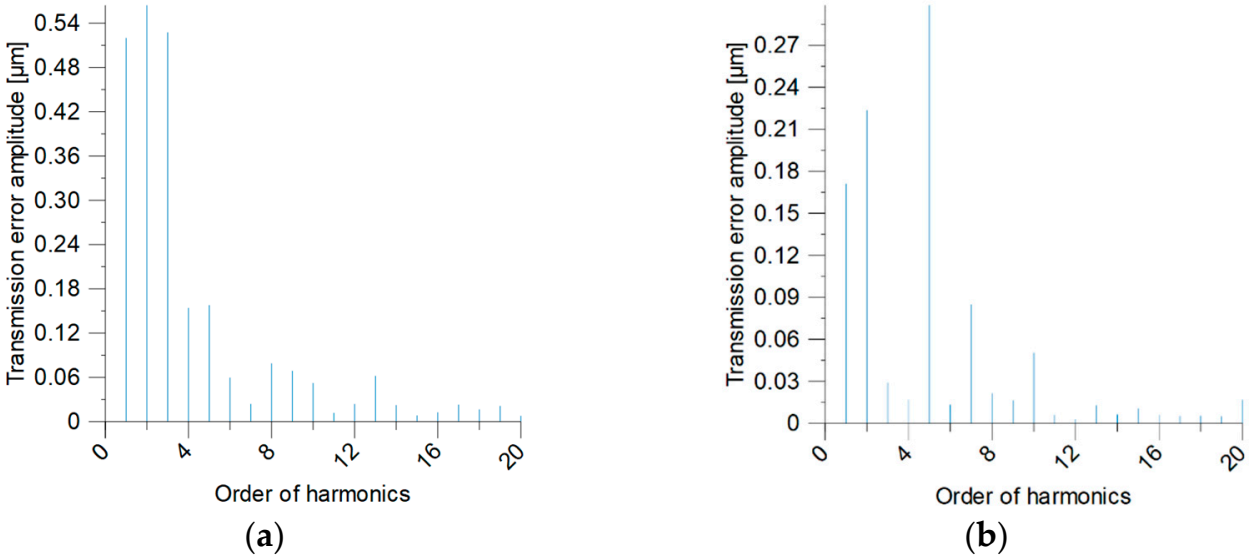


Figure 7. Comparison of transmission error (TE) amplitude diagrams. (**a**) TE amplitude of planetary gearset with low-quality machining carrier; (**b**) TE amplitude of planetary gearset with high-quality machining carrier.

4. Conclusions

The presence of planetary gearsets in the automotive industry still has outstanding importance, due to their indisputable advantages in torque-to-weight ratio and versatility. Both high-speed applications like electric passenger cars, and traction-oriented power machines use them. The high-quality manufacturing of the gearset components ensures the long-term and specified functional operation of the vehicle's propulsion system. The presented calculation results and durability test experiences provide insight into the planet carrier's role in the proper operation of the planetary gearset. Obviously, in addition to the appropriate design and optimization of the macro- and micro-geometry of the mating gears, it is crucial to prepare a comprehensive manufacturing and quality assurance process for the surrounding parts, like the planet carrier, during the validation phase and also in the serial production. Apparently, small manufacturing errors can cause significant operational disorders, like gear whine noise in specific speed ranges and loads, or early fatigue appearance on the tooth flank surface.

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References

1. Schulze, T. Design and Optimization of Planetary Gears Considering All Relevant Influences. Available online: https://www.geartechnology.com/articles/21985-design-and-optimization-of-planetary-gears-considering-all-relevant-influences (accessed on 24 September 2024).
2. Fagan, A. Once More Around the Sun. Available online: https://www.geartechnology.com/articles/30674-once-more-around-the-sun (accessed on 24 September 2024).
3. Brecher, C.; Löpenhaus, C.; Theling, J. Influence of Planet Carrier Misalignments on the Operational Behavior of Planetary Gearboxes. Available online: https://www.geartechnology.com/articles/22681-influence-of-planet-carrier-misalignments-on-the-operational-behavior-of-planetary-gearboxes (accessed on 2 July 2024).
4. Siemens. Transmission Error: The Metric for Gearbox NVH Quality. 2014. Available online: https://www.plm.automation.siemens.com/en_us/Images/Transmission_error_the_metric_for_gearbox_NVH_quality_tcm1023-220935.pdf (accessed on 8 July 2024).
5. KISSsoft Offers LTCA Feature in Software Update. Available online: www.geartechnology.com/articles/30460-kisssoft-offers-ltca-feature-in-software-update (accessed on 24 September 2024).
6. Predki, W.; Jarchow, F.; Lamparski, C. Load Distribution in Planetary Gears. Available online: https://www.geartechnology.com/articles/21626-load-distribution-in-planetary-gears (accessed on 24 September 2024).
7. *ISO 6336*; Parts 1–6. International Standard. ISO: Geneva, Switzerland, 2019.
8. Davoli, P.; Gorla, C.; Rosa, F.; Rossi, F.; Boni, G. Transmission Error and Noise Emission of Spur Gears. Available online: https://www.geartechnology.com/articles/20307-transmission-error-and-noise-emission-of-spur-gears (accessed on 24 September 2024).
9. Smith, R.E. The Relationship of Measured Gear Noise to Measured Gear Transmission Errors. Available online: https://www.geartechnology.com/articles/20920-the-relationship-of-measured-gear-noise-to-measured-gear-transmission-errors (accessed on 9 July 2024).
10. Chen, Y.; Ishibashi, A. Investigation of the Noise and Vibration of Planetary Gear Drives. Available online: https://www.geartechnology.com/articles/20347-investigation-of-the-noise-and-vibration-of-planetary-gear-drives (accessed on 9 July 2024).

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