

Design and Analysis of a Lightweight High-Torque Gearbox for Electric Vehicles

Doris Klein¹

¹Faculty of Engineering, University of Cape Town (UCT), South Africa. E-mail: klein.doris@engfacuct.ac.za

Abstract---This paper presents an optimization technique for high-torque gearbox (GB) cutting in electric cars, emphasizing input torque and torque fluctuations. This method facilitates vibration attenuation in Electric Vehicle (EV) GB. The research employs Tooth Contact Assessment (TCA) and Loaded TCA (LTCA) to examine the localization of meshing points, considering changes in GB tooth surfaces and distortions resulting from load. The research then formulates the maximum contact force equation using impact physics theory. A dynamic approach for the helical GB motion in the GB input phase is formulated utilizing the centralized mass approach, facilitating a comprehensive analysis of high-torque GB vibration features. Utilizing a genetic approach, the research enhances the tooth shape and parabolic modifying factors of the tooth flank, yielding excellent vibration-dampening surfaces to the teeth. Experimental findings across diverse input forces and torque indicate that the total vibration magnitude remains stable and less than traditional GB shaping techniques. Under varying circumstances, the root mean square of vibrational acceleration across the meshing line is 59.13 m/s and 21.44 m/s, respectively. The vibration torque along the connecting line is 21.44 m/s and 21.13 m/s under different torques, with 21.44 m/s being the minimum value. The mean amplitude of the melding force of impact is considerably reduced to 5026.3. This high-torque GB reshaping technique improves GB dynamics and dependability by accounting for input torque and torque variations and significantly reduces vibrations in EV GB arrangements. The research offers significant insights and approaches for creating and optimizing EV shifts, emphasizing a thorough acceleration enhancement.

Keywords--- Electric Vehicles, High-Torque, Gearbox, Lightweight.

Received: 07 - 12 - 2024; **Revised:** 24 - 01 - 2025; **Accepted:** 14 - 02 - 2025; **Published:** 31 - 03 - 2025

I. Introduction

The automotive sector is undergoing rapid transformation concerning drivetrain electrification. In the last decade, battery Electric vehicle (EV) (Tiwari et al., 2023) sales have risen markedly, comprising 2.8% of the worldwide market share in 2019. The International Energy Agency forecasts a global yearly growth of 35% in EV sales, culminating in 250 million total vehicles by 2030—a more than thirtyfold increase from 2020. The Automotive Research Institute reports that sales of light-duty electric drive cars in the USA increased more than twofold from 2020 to 2022, rising from 105k to 245k units. The EV transmission market is projected to expand to US\$18.7 billion by 2028, with an average yearly growth rate of 19.9% throughout the forecast period.

EVs using single-torque transmissions now prevail in the marketplace. The single-torque design of EVs like the Chevrolet Bolts and Chevrolet Sparks was intended to provide simplicity, cost-effectiveness, sufficient acceleration, and maximum torque. A single-ratio Gearbox (GB) (Hinov et al., 2021) has several disadvantages, since it cannot consistently maintain the Electric Machines (EM) (Roshandel et al., 2022) and inverters within the optimal efficiency range.

The efficacy of a multi-torque GB for EV is often assessed using three principal quality indicators: responsiveness, energy efficiency, and driving comfort. Quantifying comfort while driving is the most problematic aspect, despite several attempts to predict this component (Tselentis & Papadimitriou, 2023). To enhance convenience and diminish vibration, harshness, and noise, the acceleration and torque of the electrical motor must be meticulously regulated to prevent jolting during GB transitions. The shift plan must be established to avoid shift hunting, which refers to unnecessary GB changes to sustain comfort and performance. In the development of a multi-torque GB, it is essential to account for the downshifting mechanism during slowing down to optimize the system's regeneration, the GB ratio distribution, the diminished overall effectiveness relative to a single-GB structure, and the co-design of the incorporated engine, which includes the EV, inverter, and batteries. The research employs Tooth Contact Assessment (TCA) and Loaded TCA

(LTCA) (Liu et al., 2023) to examine the localization of meshing points, considering changes in GB tooth surfaces and distortions resulting from load.

II. Background

Gears are essential elements of slewing GB, and fine gears challenge the accurate identification of response integration, highlighting the need to improve computing precision in dynamic modeling, particularly with micro-cracking. Research performed simulations to compute signals for teeth at various depths, considering diverse dental properties. The influence of cracks was evaluated using fault identification indexes, Root Mean Square (RMS) (Wan et al., 2022) standards, kurtosis, and crest components. Research presented a quadruple linkage shaping technique that utilizes the synchronized motion of four cutter blades to form GB. This methodology starts with formulating a mathematical framework, proceeds to an analysis of the cutting management, and concludes with trials that validate the method's efficacy.

The efficacy of EV is intrinsically connected to the precision of GB shape, with enhancements in GB dependability leading to fewer vibrations and noises during high-torque operations. Studies created an innovative two-part GB lubrication dynamical model that includes Tooth Profile Modifications (TPM) (Zhou et al., 2022) to reduce GB friction tremors further. The results demonstrate that excessive and inadequate power indices exacerbate vibration contact stress, and uncertainty significantly impacts fatigue life. The GB shape has been recognized as an efficient method for resolving this problem. Mesh contact evaluation produces precise findings under modeled real-world settings, including corrections and error processing (Singler et al., 2025). Therefore, research has presented an integrated optimization design methodology to mitigate spiral vibrations and noises.

III. Proposed Lightweight High-Torque GB for EV

3.1 Trimming of Tooth Faces

This research discusses modifying the tooth profile using GB tooth contact evaluation, converting the conventional tooth profiles into a parabolic configuration that intersects the coordinate basis. The formula for the angle of the pinion face is obtained by coordinate change, enabling the orientation of the circular GB tooth shape. The positioning system S_a is defined on the standard tooth contour of the instrument and is mobile with the instrument; the positioning system S is defined on the typical tooth edge of the tool and shifts with the instrument; the collaborate structure S is set up on the diagonal tooth exterior at the center of the tooth length and pitch; the S_a is the afterwards coordinate structure defined by the pinions; and the S_a is the stationary collaborate system created by the shaft. D_0 represents the standard tooth thickness at the midpoint of the pitch circle, whereas α_y denotes the standard pressure angle.

3.2 Optimization of Shape Modifications

The research's GB teeth interaction analysis indicates that the tooth profile is adjusted within the TCA framework to get an ideal vibration suppression characteristic. This research utilizes a genetic algorithm to maximize the contour of the tooth and the parabola trimming parameters in the plane of the tooth. The genetic approach is a strategy for optimization based on the concepts underlying biological evolution, generally used to address optimization problems, such as determining a variable's lowest or highest values. Genetic techniques emulate the method that occurs in biological development by representing the possible solutions to an issue as a population of creatures. In every generation, people are assessed for fitness using the measure of fitness, and those with superior fitness ratings are chosen to reproduce in the following generations, according to a defined selection strategy.

Mutation and crossing processes produce new individuals, increasing the population's variety. This work utilizes genetic techniques to optimize GB cutting to minimize the RMS value of vibration torque in the GB arrangement during critical operation situations. This method seeks to significantly reduce sounds and vibrations inside the GB system. The process starts with forming a population of diverse randomly selected tooth profiles and parabola trimming factors for the tooth flank. The variety of this first population is essential for a comprehensive investigation of the search area. The system assesses and picks people based on their accomplishments in each generational iteration. Each person's health is evaluated based on the vibration efficiency of the GB system, which acts as a measure of fitness.

The optimization process includes both mutation and crossover activities. The crossover process enables people to swap parts of their genetic composition, generating innovative solutions. The mutation process introduces novel genetic variety by randomly altering specific genes within a person. These activities are crucial for preserving genetic variety and preventing a premature shift to optimal locations. This iterative method continues until either a certain number of rounds is achieved or the enhancement in the solution proves insignificant, dropping below a defined threshold. The solution adeptly traverses the intricate optimization terrain using this technique, substantially decreasing noise and vibratory levels inside the GB structure. This is crucial for improving GB characteristics in EV. The method for optimizing the parabolic cutting parameters of tooth profiles and tooth orientation using a genetic approach is portrayed in Figure 1.

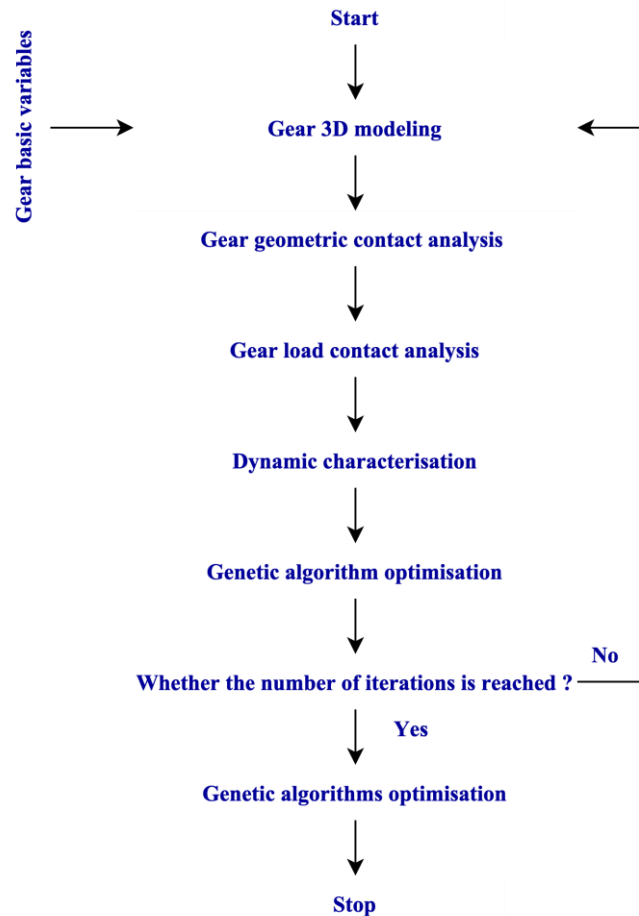


Figure 1: Workflow of the Model

IV. Results and Findings

Figure. 2 depicts the RMS readings for vibration torque along the intersection line for both unshaped and shaped GB characteristics at varying rotational torque. Examining these numbers emphasizes the efficacy of GB adjustments in mitigating vibrations. At 6000 rpm, Scheme 1 attains a substantial decrease in tooth torque RMS, recorded at 47.88 m/s, reflecting a 47.5% drop from the unshaped profile. This significant decrease underscores Scheme 1's ability to effectively mitigate vibrations at this operating torque. In contrast, Scheme 2 demonstrates optimal efficacy at intermediate torque, particularly at 6500, 7500, and 8500 rpm, with measured RMS torque of 43.15 m/s, 42.76 m/s, and 45.41 m/s. These results indicate that Scheme 2 exhibits superior performance in the specified torque domain, positioning it favorably for applications primarily within this range. Scheme 3, which includes full-torque domain cutting, does not consistently provide the smallest value of RMS at certain torque intervals; it demonstrates a steady decrease in vibration intensity throughout the spectrum. Significantly, at rotational rates of 4500 rpm and over 12000 rpm, Scheme 3 exhibits effective vibration control. The scheme's mean RMS of 51.4 m/s, the lowest of all the examined profiles, validates its

overall efficacy throughout the torque spectrum. The statistics indicate that strategic adjustments to GB profiles are essential for reducing vibrational effects at various operating torques. Scheme 3's optimized design exemplifies its capacity for offering the most consistent vibration decrease, which is crucial for improving the dependability and efficiency of GB systems in engineering settings.

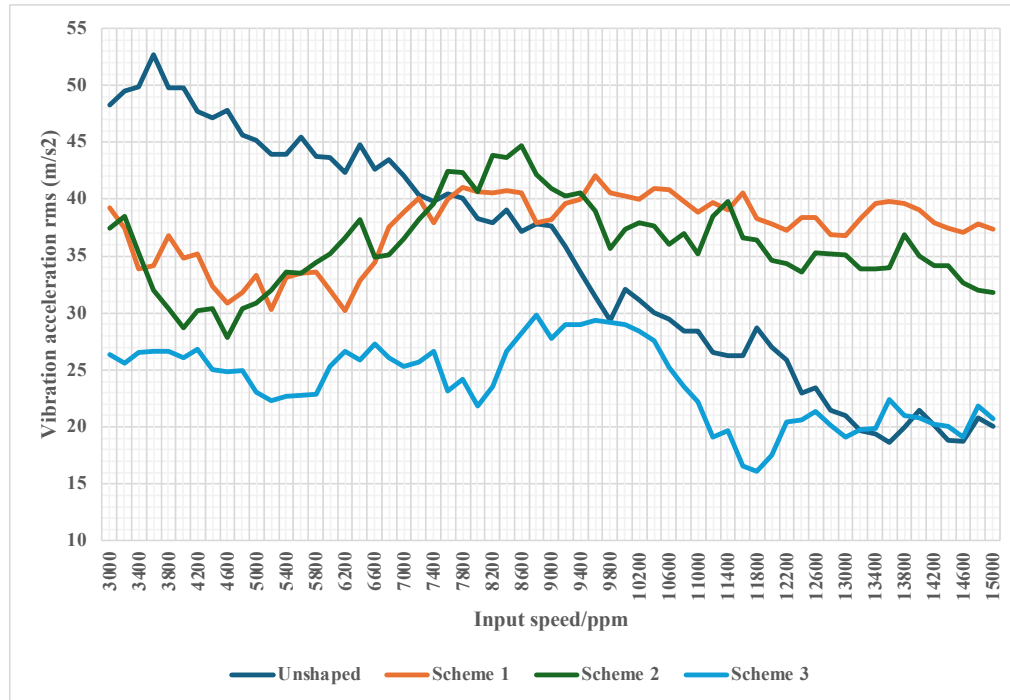


Figure 2: Vibrational Acceleration Analysis

V. Conclusion

This research optimizes the high-torque category GB using TCA and LTCA, utilizing genetic techniques to refine the tooth shape and parabolic parameters. This method lets us get the most efficient trimmed tooth designs under multi-torque and full-torque circumstances.

A comparative investigation of profile trimming strategies under specific loads and torque showed that the modified GB enhances vibration management in experiments. The current approach yields a 48.90% decrease in vibration relative to untamed GB across various input torques, surpassing conventional trimming techniques. Similarly, at varying input torque, the method achieves a 33.19% decrease in vibration relative to untrimmed shifting, once again exceeding single-condition approaches. The total vibration magnitude in both scenarios is less unstable and sustained at a lower level, illustrating the efficacy of improving the dynamic stability of the GB systems.

Thus, the EV GB reshaping technique, which considers input torque and torque, demonstrates markedly superior reshaping outcomes and overall flexibility compared to approaches concentrating on a singular operational state.

References

- [1] Tiwari, N., Verma, P., Kumar, S., Kumar, S., Dutt, H., Ahmad, S., & Chauhan, S. S. (2023). Converting gasoline vehicle into an electric vehicle (EV)-A review. *Materials today: proceedings*, 79, 379-388. <https://doi.org/10.1016/j.matpr.2022.12.161>
- [2] Hinov, N., Punov, P., Gilev, B., & Vacheva, G. (2021). Model-based estimation of transmission gear ratio for driving energy consumption of an EV. *Electronics*, 10(13), 1530. <https://doi.org/10.3390/electronics10131530>

- [3] Roshandel, E., Mahmoudi, A., Kahourzade, S., & Soong, W. L. (2022). Efficiency maps of electrical machines: A tutorial review. *IEEE Transactions on Industry Applications*, 59(2), 1263-1272. doi: <https://doi.org/10.1109/TIA.2022.3210077>
- [4] Tselentis, D. I., & Papadimitriou, E. (2023). Driver profile and driving pattern recognition for road safety assessment: Main challenges and future directions. *IEEE Open Journal of Intelligent Transportation Systems*, 4, 83-100. 10.1109/OJITS.2023.3237177
- [5] Liu, Z., Li, F., Xu, Z., & He, Q. (2023). Semi-analytical loaded tooth contact analysis method for spiral bevel gears. *International Journal of Mechanical Sciences*, 253, 108329. <https://doi.org/10.1016/j.ijmecsci.2023.108329>
- [6] Wan, X., Sun, W., Chen, K., & Zhang, X. (2022). State degradation evaluation and early fault identification of wind turbine bearings. *Fuel*, 311, 122348. <https://doi.org/10.1016/j.fuel.2021.122348>
- [7] Zhou, R., Luo, B., & Li, W. (2022). A new dynamic modeling method for a spur gear pair with tooth profile modification. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 44(9), 438. <https://doi.org/10.1007/s40430-022-03742-1>
- [8] Singler, M., Burgert, M., Preu, R., Clement, F., & Lorenz, A. (2025). Enhancing inline quality control: Machine learning for full scale 3D prediction of screen-printed silver contacts. *Solar Energy Materials and Solar Cells*, 286, 113592. <https://doi.org/10.1016/j.solmat.2025.113592>