https://doi.org/10.14669/AM/196325

WORM GEAR STRUCTURES WEAR WITH RESPECT TO NOISE GENERATION DURING THE PRODUCT LIFECYCLE OF THE ELECTRIC POWER STEERING SYSTEM

IRENEUSZ DAWID GŁĄB[1], JAKUB FRANIASZ[2]

Abstract

The study focuses on the noise generation due to wear in worm gear systems used in Electric Power Steering (EPS) mechanisms. EPS systems, widely adopted for their precision and environmental benefits, often employ worm gear transmissions that are susceptible to wear under fatigue loads. This wear contributes to undesirable noises which affect vehicle comfort and safety. The research investigates noise related to worm gear wear through kinematic analysis and bench testing, simulating real vehicle conditions. The methods consider acquiring kinematic behavior of EPS at the vehicle level to introduce test conditions for the explained scenario into the bench level. While the durability test is being performed, at certain steps, noise test bench simulation utilizing is beneficial due to its possible correlation with the vehicle level, therefore such testing is significantly more efficient (faster, avoids main issue over the design phase period – vehicle availability). The study finds that worm gear noise increases non-linearly with wear, with significant noise escalation occurring at 80% to 90% of the vehicle's defined life. The findings highlight the need for robust NVH (Noise, Vibration, Harshness) performance assessments during the EPS design process, emphasizing customer satisfaction and product reliability. This work underscores the importance of experimental evaluation which support and lead to mitigating noise issues in EPS systems.

Keywords: Electric Power Steering; EPS; durability; worm gear; NVH; noise

[1] NVH Central Engineering, Nexteer Automotive Poland Sp. z o.o. Tychy, Poland, e-mail: ireneusz.glab@nexteer.com; Faculty of Mechanical Engineering and Robotics, AGH University of Krakow, Krakow, Poland, e-mail: dziekanat@imir.agh.edu, ORCID: 0009-0001-9796-7562

[2] Mechanical Core Engineering, Nexteer Automotive Poland Sp. z o.o., Tychy, Poland, e-mail: jakub.franiasz@nexteer.com; Faculty of Mechanical Engineering and Robotics, AGH University of Krakow, Krakow, Poland, e-mail: dziekanat@imir.agh.edu, ORCID: 0009-0003-4842-5163

https://doi.org/10.14669/AM/196325

1. Introduction

Modern vehicle market trends show the power steering system is the standard equipment of any passenger vehicle. Power steering system makes the control more convenient and precise. Also, from safety standpoint it allows to apply some safety or comfort features, like e.g. lane departure assist, automatic parking mode, etc. Mentioned features are especially achievable for Electric Power Steering systems. They are widely used due to direct and precise steering, easiness of tuning, manufacturing and are environment friendly (compared to hydraulic power steering systems). Most of EPS systems are equipped for the transmission that multiplies motor torque to carry high load. Most of EPS systems for small and middle-size passenger vehicles use worm gear transmission as the assist mechanism. This kind of mechanical gear is widely used hence there are many high level papers focusing on various aspects. Part of the work make research on meshing and contact pattern [1–3], the others present the importance of efficiency improvement in the design process [4, 5] either optimization utilizing genetic algorithm method [6]. Besides there is interesting research focused on vibration and noise analysis of a new type of worm gear – the spiroid worm gear, where researches made a design and physical measurements of the running noise [7]. Like any mechanical component under fatigue load [8], the worm gear is also exposed for wear. In this paper the worm gear wear is considered in terms of noise related to assumed vehicle life. Noise generation due to worm gear wear is described and related conclusions are listed. At this point the fundamental question appears: why should care about the noise? According to World Health Organization noise has a significant impact on public health and its contribution is constantly increasing therefore the parent topic of the paper refers to safety in road transport and safety issues for electric and hybrid vehicles [9–11].

There are many possible sources of noise coming from assist mechanism (ASM) what is a subsystem of EPS. In this paper authors are focused on one, particular place of those undesirable sounds effects, outlined in Figure 1, which is worm – worm gear mesh. In that connection of worm and gear components, two main types of noise are reversal clunk (RC) and rattle. For the clarity, to avoid misunderstanding regarding terminology, it should be mentioned that main contributor of EPS manufactures for these two noises names are in another mechanical connection, between rack and pinion in the mechanical gear, what has been described and published by JTEKT company in their internal, periodic journal [12]. Neither that case, neither other noises coming from worm gear called rotational noise, for instance caused by improper worm treatment, like washing or burnishing are not considered in this work. Just for reference purpose, diagnostic and investigation of noise issues related to the rotational movement are easier and widely described [13]. Back to the topic, RC occurs when the driver is changing immediately the direction of spinning move, its amplitude is related to an angle and wheels position. Most common occurrence of that is while static conditions or vehicle speed is close to 0 km/h, therefore when the driver makes parking maneuvers. The second type of noise covering the topic of this work – the rattle, occurs at vehicle speeds above 0 km/h. It is strictly related to type of the road and car velocity. The fastest way to excite vibrations which are audible as rattle

https://doi.org/10.14669/AM/196325

phenomenon is to drive on the road which surface is irregular, most common name for such type is the cobblestone. The example of severe road, not being an artificial one made as part of proving ground is that shown on Figure 2. The vehicle speed range which causes the EPS rattle noise, disturbing the driver, is most often between 10 to 30 km/h. The phenomenon of rattle noise and its subjective evaluation is described by Society of Automotive Engineers [14]. The importance of torsional vibrations and method of its analysis in the case of other type of vehicles is also pointed out in various publications [15].

Fig. 1. View of worm gearing in the EPS system

https://doi.org/10.14669/AM/196325

Fig. 2. Severe, natural cobblestone road

The scope of this paper is to explain the method of noise increases assessment over defined vehicle lifetime. NVH performance degradation correlates to EPS system components wear which is described in this article. Noise evaluation methods are described (including subjective in-vehicle and objective FDR stand testing). Components wear was generated using specialized test stand to reflect real vehicle usage.

2. Methods

2.1. Kinematics – wear of EPS at the vehicle level

Each EPS steering system is designed to carry certain load which cannot be exceeded under the risk of improper performance, excessive wear or components damage. This load is determined by vehicle mass, road surface roughness (higher require more assist), but also tyre pressure too low generates excessive resistance [16]. Mentioned parameters may vary depending on vehicle usage conditions, driver habits, environment and many others. It is hard to predict how the steering system will be operated, so typically its life is defined by some normalized maneuvers sequenced in defined order. Some or most of maneuvers assume maximum load capacity, which may not reflect vehicle real usage, however it is safe to assume worse case conditions. For example the parking maneuver might be considered as the most demanding in terms of wear, especially for the worm – worm gear used to transfer assist torque to the steering wheel. Considering constant load coming from tyre versus road friction during static parking maneuver, the steering system kine-

https://doi.org/10.14669/AM/196325

matic chain design makes the load distribution uneven over rack travel. Worm gear loading on its circumference is adequately uneven as it transfers proper torque to carry the load. Steering system tie rods connected to steering knuckles are working at various angles depending on steering wheel position. Steering system rack bar has to carry more load when the tie rods work at higher angle. Below int the Figure 3, the exemplary photo shows difference between tie rods angle (α_{11}, α_{21}, α_{12}, α_{22}) when steering wheel is set on center Figure 3a) and at end of travel Figure 3b):

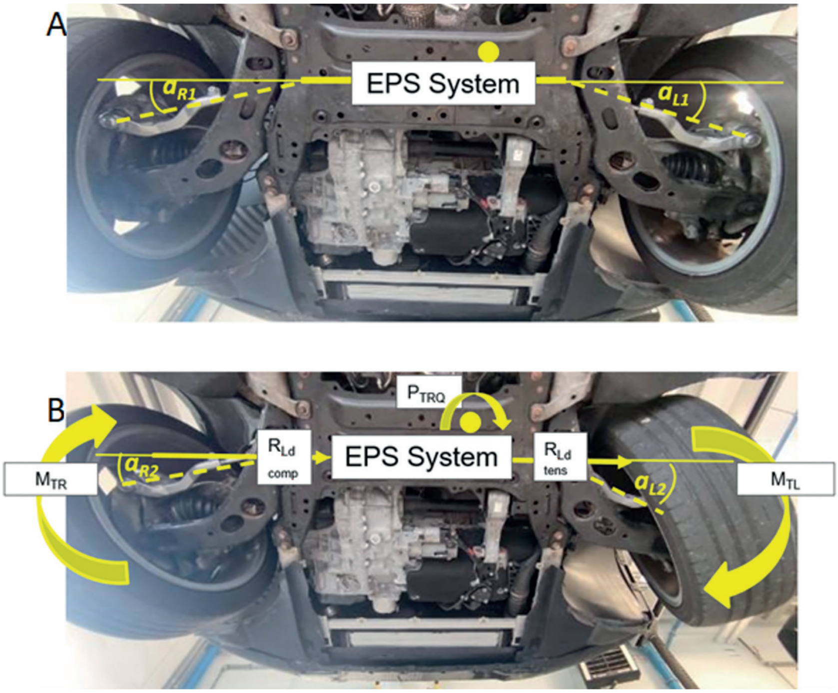


Fig. 3. Example of different tie rods angle comparing steering wheel in center position (A) and end of travel position (B)

Constant friction torque of tyres versus road surface (M_{TL}, M_{TR}) and varying tie rods angles ($\alpha_{L1} \rightarrow \alpha_{L2}$; $\alpha_{R1} \rightarrow \alpha_{R2}$) which are strictly related to worm gear position, results in non-linear loading over the rack bar movement. When turning the steering wheel, one of tie rods is compressed ($R_{Ld\ comp}$), the opposite one is tensiled ($R_{Ld\ tens}$). The more turned steering wheel, the higher tie rod angle is, the higher load has to be carried by EPS system. Like mentioned above, the worm gear is loaded adequately – normalized parking maneuver is shown on the graph in Figure 4, which shows relation of torque versus worm gear angle. Especially this curve is used for testing purposes.

https://doi.org/10.14669/AM/196325

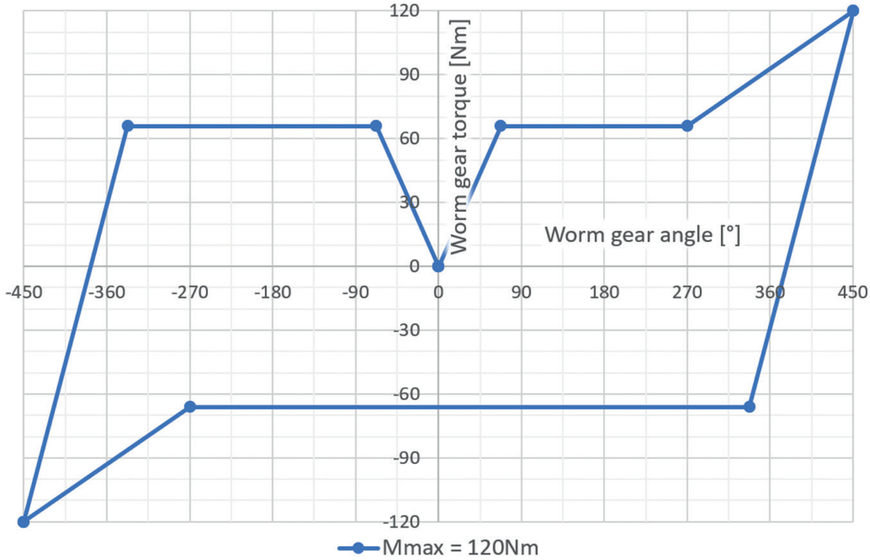


Fig. 4. Torque relation to worm gear angle at parking maneuver

2.2. Test bench wear simulation level

The exemplary parking maneuver was defined for maximum worm gear torque of 100 Nm which performed certain number of times will generate worm gear wear, finally leading to its fracture. Worm gear transmission applied to EPS system should be properly designed to provide precise and quiet steering ability. In considered application of EPS system to large utility vehicle, the 25:1 worm gear transmission meets durability and NVH requirements. However, to assess its usefulness to other applications (like e.g. passenger vehicles), the NVH performance over life has been considered. Different application may require different number of cycles reflecting product life. Typically, utility vehicles are designed to withstand harder conditions than passenger cars, but might be less sensitive for noise issues. However, in this paper considered is the noise performance related to worm gear wear. The worm gear transmission has been separated from entire EPS system and worn to show isolated noise increase and its effect to the vehicle driver. The test stand has been used to set wear cycles to the worm gear transmission, which simulate its real behavior when used in EPS system. The test stand scheme is shown in Figure 5 and picture of the test station in Figure 6.

https://doi.org/10.14669/AM/196325

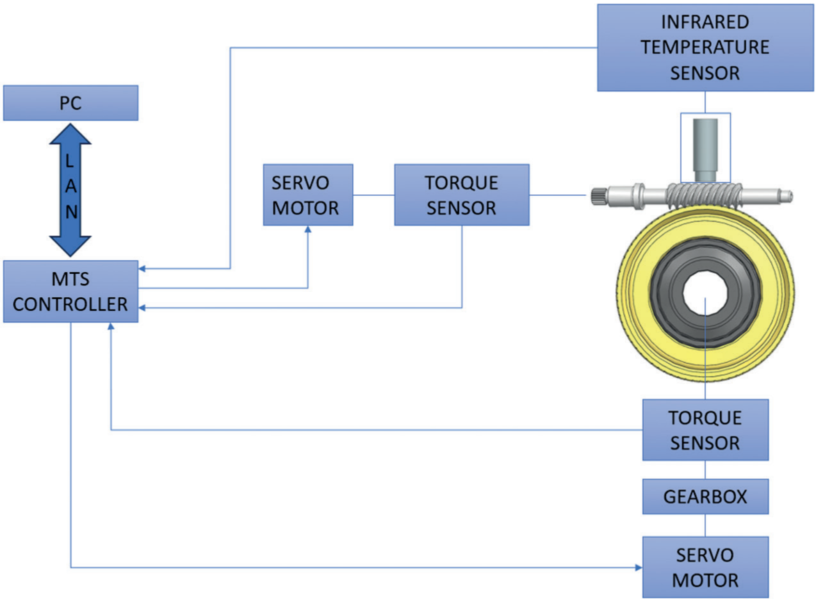


Fig. 5. Scheme of the wear test station

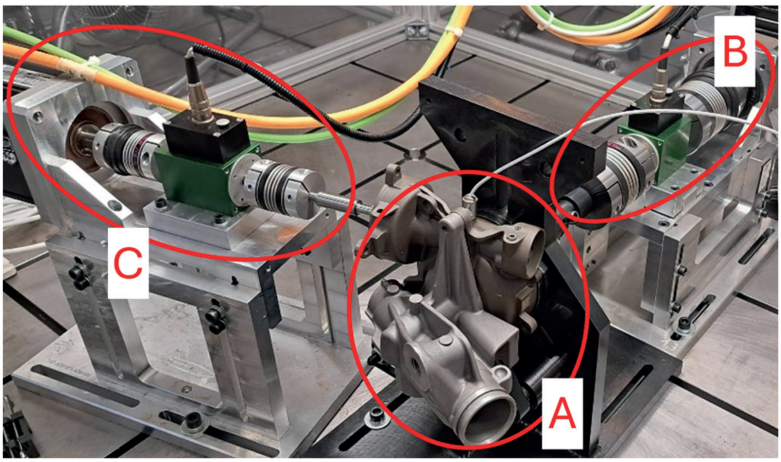


Fig. 6. Photo of the testing bench showing tested worm gearing mounted in a housing (A), loading drivetrain (B), angle (speed) command drivetrain (C)

Considered test profile shown in Figure 4 was applied with time intervals after each two following parking maneuvers. Test profile overlaid on the time scale is presented in Figure 7.

https://doi.org/10.14669/AM/196325

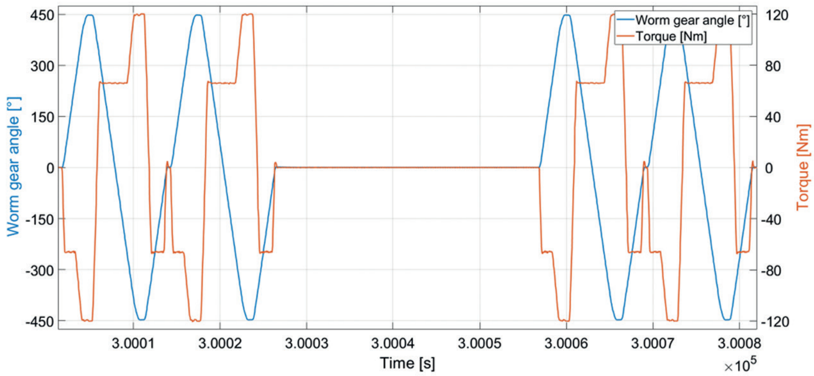
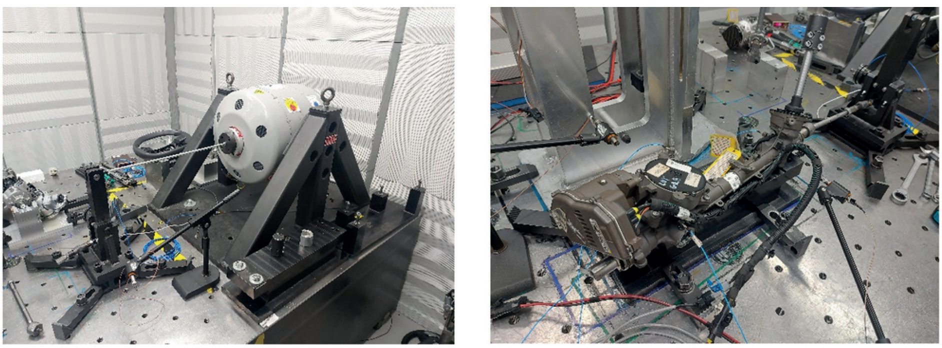


Fig. 7. Test profile overlaid on the time scale

2.3. Test bench noise simulation level

The vibration testing has a long history and it is possible since electro mechanical shakers have been designed and different kinds launched [17]. It has made possible to test components or subsystems before the final product (which tested subsystem or component is the part of) is available, to get ready robust product suited to required application. The important utility of electro mechanical shakers is to use them to reproduce severe road conditions and applied them in the anechoic chamber in regards to the noise verification. Such bench with configuration to test a NVH behavior of samples under force excitation is common known in the Automotive Industry as Field Data Replicator (FDR). The example of bench placed in anechoic chamber environment is shown in Figure 8a.



(a) (b)

Fig. 8. FDR bench: (a) electro mechanical shaker, (b) tested samples of DPEPS assembled

https://doi.org/10.14669/AM/196325

The idea and order of testing samples is following: a) data acquisition of particular road profile at the vehicle level with the force sensors or accelerometers in certain cases, b) determination of the forces acting on EPS systems when noise occurs, c) Signal filtering (5 Hz to 50 Hz), d) Determination of "Loudness" levels measured by standard ISO 532: 1975, e) verification if FDR results are corelated to the vehicle noise level. The assembled sample at the bench level with sensors setup is presented in Figure 8b. Such test setup and objective evaluation does not consider fibrous, sound absorbing materials assembled at the vehicle level and its variability over the time, however according to the research, it can be assumed that their properties are constant thus may be neglected [18]. The measurement device acquiring pressure signal during FDR test is PCB 378B02 ICP microphone with frequency range from 3.75 kHz to 20 kHz and sensitivity 50 mV/Pa (+/− 1.5 dB). The excitation unit is vertical shaker MB Dynamics, type Energizer Silver controlled by external load cell prepared internally. These devices are calibrated daily with control equipment according to IATF 16949 procedures and standards.

3. Results

Repeatable maneuvers were set as shown in Figure 4. The test was conducted up to 200% of defined vehicle life, including intermediate noise checks to explore worm gear behavior beyond needed performance. Noise coming from the worm gear transmission is mostly related to its wear. Exemplary worm gear tooth section is shown below that compares condition as new and after some wear.

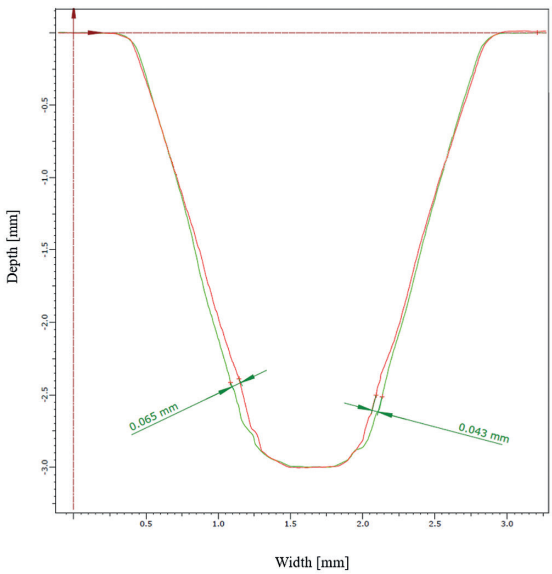


Fig. 9. Sectioned worm gear tooth condition as new (red) and after some wear (green)

https://doi.org/10.14669/AM/196325

The wear visible in the Figure 9, results in worm – worm gear engagement backlash growth that becomes noisy after some value exceeded. That causes annoying feelings to the driver that should not occur within defined vehicle life. Measured worm gear wear show linear relation to number of cycles. NVH checks show non-linear relation.

In the Figure 10 there is a clear conclusion that relation of the loudness results at the FDR bench level is not linear over the life time defined in percentile. The breaking point for the sudden deterioration of NVH performance is between 80% to 90% at the defined vehicle life.

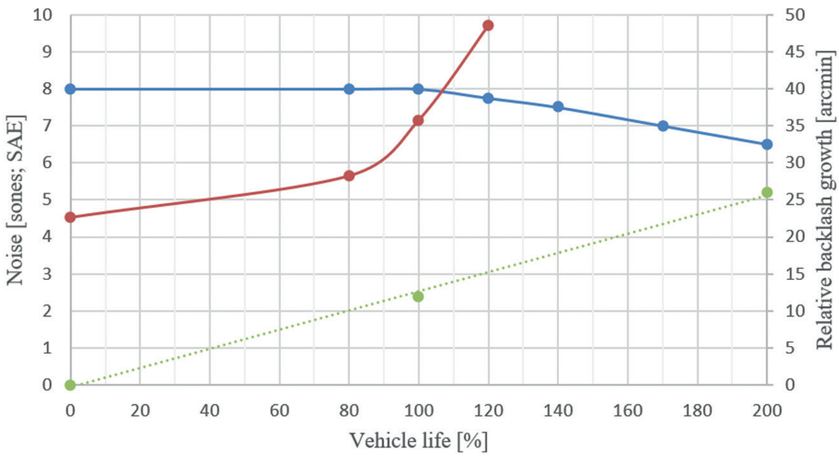


Fig. 10. Graph with relation Loudness and subjective evaluation to Life Time of the vehicle related to worm gear transmission backlash growth

On the other hand, the same graph, however in regards to the subjective evaluation from the customer scale shows that human perception is steady to the certain point and then starts to get worse with the linear relation to the defined vehicle life. The break point for that in the investigated case is 100%. Considering all above the threshold determined experimentally can be set for the testing EPS at the bench level – FDR.

Figure 10 shows backlash increase of worm – worm gear pair. It is expressed in arcmin unit that is 1°/60 of worm gear rotation under certain load applied (that is assumed to check the noise at). Typically, the backlash means real clearance between the teeth in the mesh, however considered EPS system is equipped for the compensator that keeps the worm gearing fully engaged. Proceeding teeth wear over life makes the compensator less efficient revealing the backlash under the applied load. It is good practice to gather more data of backlash growth to avoid imprecise interpolation. Direct measurement of worm gear backlash installed on FDR bench seems to be imprecise since entire EPS system is exposed to vibration. On the

https://doi.org/10.14669/AM/196325

other hand, this is possible to measure worm gear tooth wear (Figure 9) to calculate backlash value, but interim measurement requires components disassembly and grease cleaning which's done improperly may affect the wear results and its correlation to NVH. That's why the measurement is limited to three attempts to confirm linearity of backlash growth over the product life.

4. Conclusions

- Worm gear transmission applied to EPS systems are working under non-standard conditions that most of worm gearings are considered in the literature, where the transmission life is defined by working hours at constant torque value [19–21], also in regards to simulations [22]. That's why the wear and its impact on noise performance must be evaluated separately during the system designing process.
- Depending on several factors (for example selected material), the worm gear teeth wear might be linear or non-linear over its life [19]. Also, assuming linear growth of vibrations amplitude (due to linear wear), the created noise may become audible at certain worm gear wear threshold. It makes difficult the noise behavior prediction process related to wear. NVH performance must be evaluated experimentally for such application like power steering system.
- The most important rating of NVH for EPS system is the subjective customer evaluation therefore this is the outcome for EPS manufacturers. Thus design of the product, materials selection and process robustness shall consider firstly the customer expectations, the rest parameters, features and thresholds are resulting ones. For example, the friction is a resultant parameter that rises when some potential noisy EPS system nodes are expected to work quietly over its life and have to be extra tightened to reduce initial lash.
- Despite the relation between Loudness and customer subjective evaluation is not linear, still the threshold based on sones scale following objective measurements can be set, in order to forecast with high probability the acceptance level. This is crucial in design and validation process.
- Estimation of the Life Time cycle and its following assumptions in regards to quality is important in terms of product requirements received from Vehicle Manufacturers (OEM) [19]. Nowadays, in the times of transforming Automotive into EV, the competition at the market is particularly strong. Wrong decisions and failed assumptions exposes Tier 1 Automotive suppliers for fall down and bankruptcy.
- Multitude of factors that are determining NVH performance of the EPS system, makes the prediction almost impossible. Moreover, depending on the EPS system design, most of factors are unpredictable in terms of its sensitivity. Therefore, the subject complexity requires research on experimental way. Some of analysis can be performed using specialized test equipment, typically belonging to EPS systems manufacturers.
- Each case EPS system application to certain vehicle is individual and requires a lot of detailed analysis. Wide literature review is an indication where the analysis should lead to.

https://doi.org/10.14669/AM/196325

5. Acknowledgements

Authors would like to thank their employer, Nexteer Automotive Poland company which provided test stands and samples to do the research on.

6. Conflicts of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7. Nomenclature

EPS	Electric Power Steering
NVH	Noise Vibration Harshness
OEM	Original Equipment Manufacturer
EV	Electric Vehicle
FDR	Field Data Replicator
ASM	Assist Mechanism
RC	Reversal Clunk
DPEPS	Dual Pinion Electric Power Steering

8. References

[1] Seol I, Chung S. Design and Simulation of Meshing of New Type of Worm-Gear Drive with Localized Contacts. KSME International Journal. 2000;14(4):408–417. https://doi.org/10.1007/BF03186434.

[2] Roda-Casanova V, Gonzalez-Perez I. Investigation of the effect of contact pattern design on the mechanical and thermal behaviors of plastic-steel helical gear drives. Mechanism and Machine Theory. 2021;164:104401. https://doi.org/10.1016/j.mechmachtheory.2021.104401.

[3] Liu F, Chen Y, Xie H, Lu B, Chen B. Study on the meshing stiffness of plastic helical gear meshing with metal worm via point-contact. Mechanism and Machine Theory. 2022;176:105040. https://doi.org/10.1016/j.mechmachtheory.2022.105040.

[4] Honkalas R, Deshmukh B, Pawar P. A Review on Design and Efficiency Improvement of Worm and Worm Wheel of a Gear Motor. Journal of Physics: Conference Series. 2021;1969(1):012023. https://doi.org/10.1088/1742-6596/1969/1/012023.

[5] Rai P, Barman A. Design optimization of worm gear drive with reduced power loss. IOP Conference Series: Materials Science and Engineering. 2019;635(1):012015. https://doi.org/10.1088/1757-899X/635/1/012015.

[6] Mogel Y, Wakchaure V. A Multi-objective Optimization Approach for Design of Worm and Worm Wheel Based on Genetic Algorithm. Bonfring International Journal of Man Machine Interface. 2013;3(1):8–12. https://doi.org/10.9756/BIJMMI.4403.

[7] Dudás I, Bodzás S. Geometric and Noise- and Vibration Analysis of New Type Spiroid Worm Gear Drive. Applied Mechanics and Materials. 2017;870:432–438. https://doi.org/10.4028/www.scientific.net/AMM.870.432.

https://doi.org/10.14669/AM/196325

[8] Hryciów Z, Wiśniewski A, Rybak P, Tarnożek T. Assessment of the effect of passenger car wheel unbalance on driving comfort. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2021;94(4):61–71. https://doi.org/10.14669/AM.VOL94.ART5.

[9] Harrer M, Pfeffer P. Steering handbook. Cham, Switzerland: Springer International Publishing, 2016. https://doi.org/10.1007/978-3-319-05449-0.

[10] Organización Mundial de la Salud. Environmental noise guidelines for European Region. WHO Regional Office for Europe, Copenhagen, Denmark. 2018.

[11] Menday M. An introduction to noise and vibration issues in the automotive drivetrain and the role of tribology. Tribology and Dynamics of Engine and Powertrain: Fundamentals, Applications and Future Trends. 2010:663–679. https://doi.org/10.1533/9781845699932.2.663.

[12] Taenaka M. Establishment of Evaluation Method for Rattle Noise of Steering Gear for Column Type Electric Power Steering (C-EPS ®) System. JTEKT Engineering Journal, English Edition. 2011. Available from: https://www.jtekt.co.jp/e/engineering-journal/1008/ (accessed on Jun. 17, 2024).

[13] Mohd Ghazali MH, Rahiman W. Vibration Analysis for Machine Monitoring and Diagnosis: A Systematic Review. Shock and Vibration, Hindawi Limited, 2021:9469318. https://doi.org/10.1155/2021/9469318.

[14] Sharma U, Wilson ST, Lalasure S, Rajakumar K. Quantitative Evaluation of Steering System Rattle Noise. SAE Technical Papers. 2017;2017July. https://doi.org/10.4271/2017-28-1952.

[15] Żardecki D, Dębowski A. Method of analysing torsional vibrations in the motorcycle steering system in the phase plane. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2017;76(2):137–154. https://doi.org/10.14669/AM.VOL.76.ART8.

[16] Janczur R, Kuranowski A, Nogowczyk P, Pieniążek W. Experimental studies of forces in the steering rods. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2015;68(2):61–70.

[17] Van Baren J, Macmillan B. Vibration Test Replication of Operating Environments Field Data Replication. Sound & Vibration Magazine. 2004;38(8)10–13.

[18] Białkowski P, Krężel B, Zapart Ł. Effect of the composite temperature and humidity test on the sound absorption coefficient of fibrous materials used in automotive applications. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2018;81(3):29–38. https://doi.org/10.14669/AM.VOL81.ART3.

[19] Kim GH, Lee JW, Il Seo T. Durability characteristics analysis of plastic worm wheel with glass fiber reinforced polyamide. Materials. 2013;6(5):1873–1890. https://doi.org/10.3390/ma6051873.

[20] Czerniec M, Świć A. Study of Contact Strength, Tooth Wear and Metal-Polymer Life of Worm Gears. Advances in Science and Technology Research Journal. 2022;16(3):143–154. https://doi.org/10.12913/22998624/149608.

[21] Zhao Y, Zhang Y. Reliability design and sensitivity analysis of cylindrical worm pairs. Mechanism and Machine Theory. 2014;82:218–230: https://doi.org/10.1016/j.mechmachtheory.2014.08.009.

[22] Daubach K, Oehler M, Sauer B. Wear simulation of worm gears based on an energetic approach. Forschung im Ingenieurwesen/Engineering Research. 2022;86(3):367–377. https://doi.org/10.1007/s10010-021-00525-3.