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ANALYSIS OF A NEW TYPE OF ELECTRIC POWER STEERING GEAR WITH TWO PINIONS ENGAGED ON THE SAME SET OF TEETH ON THE RACK

ANALIZA NOWEGO TYPU PRZEKŁADNI KIEROWNICZEJ ZE WSPOMAGANIEM ELEKTRYCZNYM Z DWOMA ZĘBNIKAMI I WSPÓŁDZIELONĄ LISTWĄ ZĘBATĄ

Key words: steering gear, electric power steering, power steering, gearbox, pinion and rack, friction, noise.

Abstract: Electric power steering is the most commonly used solution in passenger cars. It is a more economical and reliable solution than the hydraulic equivalent. Its main parts are usually the rack, pinion, and worm wheel, which are subject to wear during driving. A steering gear that works incorrectly poses a direct threat to the safety of the driver and other road users. The paper presents various types of electric power steering gears, with a particular emphasis on the problems that arise during the design of the pinion and rack. In this paper, a new electric power steering system consisting of a steering gear with two pinions working on a common toothing of the rack (TPEPS) is proposed. The benefits of placing two pinions on one tooth set of a steering rack are described, which eliminates many problems during production, and thus allows the reduction in production costs. As part of the analysis, design challenges for a new type of transmission are presented, taking into account key customer requirements, with a particular emphasis on durability and ensuring the desired noise level, which is important due to the replacement of cars with an internal combustion drive with an electric drive. This paper presents selected friction and noise test results for a new power steering system. A comparison is made with a system that has two pinions and different teeth on the rack (DPEPS). The results indicate that the new system could become an alternative solution due to its lower friction value and lower noise.

Słowa kluczowe: przekładnia kierownicza, wspomaganie elektryczne, przekładnia zębata, zębnik, tarcie, hałas.

Streszczenie: Elektryczne wspomaganie kierownicy jest najczęściej stosowanym rozwiązaniem w samochodach osobowych. Jest to rozwiązanie bardziej ekonomiczne i niezawodne niż hydrauliczny odpowiednik. Jego głównymi częściami zazwyczaj są zębatka lub ślimak, które podczas jazdy ulegają zużyciu. Przekładnia kierownicy działająca nieprawidłowo stwarza bezpośrednie zagrożenie dla bezpieczeństwa kierującego pojazdem i innych uczestników ruchu drogowego. Wpływa to również na hałas. W pracy przedstawiono różne rodzaje przekładni kierowniczej ze wspomaganiem elektrycznym ze szczególnym uwzględnieniem problemów, które pojawiają się podczas projektowania zębnika i listwy zębatej. W pracy zaproponowano nowy układ elektrycznego wspomagania kierownicy składający się z przekładni kierowniczej z dwoma zębnikami pracującymi na wspólnym uzębieniu listwy zębatej (TPEPS). Opisano korzyści płynące z umieszczenia dwóch zębników na jednym uzębieniu listwy zębatej, które niwelują wiele problemów podczas produkcji, a tym samym pozwalają na obniżenie kosztów wytworzenia. W ramach analiz przedstawiono wyzwania konstrukcyjne dla nowego typu przekładni z uwzględnieniem kluczowych wymagań klienta. W pracy przedstawiono wybrane wyniki badań tarcia i hałasu dla nowego układu wspomagania kierownicy. Porównano jest z układem, który posiada dwa zębniki na różnym uzębieniu na listwie zębatej (DPEPS). Wyniki wskazują, że nowy układ może stać się alternatywnym rozwiązaniem ze względu na niższą wartość tarcia oraz mniejszy hałas.

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INTRODUCTION

The vehicle steering system performs two functions. First, it transfers the road and vehicle state information to the driver through the steering wheel. It also changes the driving direction. Most modern passenger cars are equipped with Electric Power Steering (EPS) systems. Following the introduction of the first steering systems with an electromechanical servo unit (electric-power-assisted steering) at the end of the 1980s, they have become increasingly widespread in recent years to the point of dominating the market in 2020s **[L. 1]**. Novel Electric Power Steering system has been replacing conventional hydraulic power assist steering systems due to its many advantages **[L. 2]**. However, large vehicles still use hydraulic power steering, despite weight and complexity **[L. 3]**. The advantage of using an EPS is its impact on sustainability and the environment because providing assistance on-demand can improve fuel economy and CO_2 emissions by up to 4%. Also, this system helps to reduce over 100 kg/year of CO_2 per vehicle **[L. 4]**.

The main components of an EPS system typically include the rack, pinion, bearings, and worm wheel. Despite the development of this technology, there still are issues under study. In addition, in recent years, driver's steering feel has become an essential factor in determining the vehicle quality and ride comfort. The primary source of the steering feel issue comes from component configuration and control strategies. Some papers propose motor torque control methods like H2 and H∞ considering road torque. This minimizes the effect of disturbance of a high-frequency component of road torque **[L. 5]**. There also are control systems using sliding mode control **[L. 7]** and LQG control **[L. 8]**. Another approach is frequency domain-based called loop-shaping. The application of this system provides the desired steering torque that depends on the rack force **[L. 9]**.

The main problem that affects the selection of an appropriate control algorithm is the variability of conditions during the movement of vehicles. This affects the disturbance in the steering system and, thus, the volatility of the rack force. Also, the tire reaction force is difficult to model because of the nonlinear characteristics of the tires **[L. 10]**, especially when the vehicle is in parking maneuvers. The value of the rack force is affected primarily by friction. One of the models is the Stribeck friction model, but mostly it gave insufficient results with changes in the steering speed and in the low-speed range **[L. 11]**. This is because it assumes that friction is independent of load value. For this reason, the LuGre is a better model **[L. 12]**. An increase in friction generally will cause an increase in torque and hysteresis. The issue of friction in gears is a difficult one. It usually has the character of mixed or hydrodynamic friction, and its value depends on such parameters as gear sliding velocity, dynamic viscosity or density of lubricant, gear width, gear force, surface roughness, and others **[L. 13]**. In addition, there is the impact of such issues as the effect of bearing friction, position-dependent friction, stick-slip phenomenon, worm gear mesh friction, and preload.

In modern vehicles, the steering device enables various driver assist functions e.g. lane keeping systems or side wind assist. In the case of autonomous vehicles, a conflict can occur between the human and the machine when there is an unintended takeover of the steering control by the driver. This additionally complicates the control algorithms **[L. 14]**. By understanding and addressing these challenges, researchers and engineers can develop more efficient and reliable steering systems and new design solutions that enhance vehicle performance, safety, and driver comfort.

This paper introduces an alternative mechanical design compared to other solutions available on the market. It is based on the concept of two pinions working in parallel on shared rack bar teeth. The proposed solution is an alternative to well-known methods in carrying cost and performance advantages.

In the first section, based on the literature review, the authors present current design solutions within automotive steering system technology, their advantages and limitations. The second section describes proposed design details based on parallel pinions working together. The third section – discussion – compares well-known solutions with the proposed ones. Finally, conclusions and recommendations for further studies are presented towards the end of the article.

TYPES OF STEERING SYSTEMS

The technology of the steering system used in vehicle depends on several factors. Among them, one of the most critical is the vehicle mass and size **[L. 15]**. Another aspect is cost and complexity of the steering system. Taking into consideration these and other factors, the contemporary industry recognizes the following types of steering systems:

- Column EPS (CEPS),
- Single Pinion EPS (SPEPS),
- Dual Pinion EPS (DPEPS),
- Rack EPS (REPS).

Solutions for typical steering systems are shown in **Fig 1**. They can be divided into several categories. Those that are installed in the cabin or under the hood. Another division takes into account the assist mechanism. There is a worm gear or ball nut/belt mechanism. A new type of a Steer-by-wire (SBW) is also being developed at present, in which the mechanical connection between the vehicle's steering wheel and tires is eliminated. It is envisioned as the next generation of steering systems in the automotive manufacturing industry. While numerous advantages are foreseen for this modification, there still are some technical and safety-related challenges under research that need to be addressed **[L. 16]** and this paper omits this solution. The choice of the type of a steering system is also determined by the force between the rack and pinion – **Fig. 2**. An increase in categories from A to D, all the way up to SUV-FST, means a higher rack force value. Single pinion system is dedicated to class B or Small SUV cars like Opel Corsa, Peugeot 208/2008, Citroen C3/C3 Cross. Dual pinion system is dedicated to class C (compact)

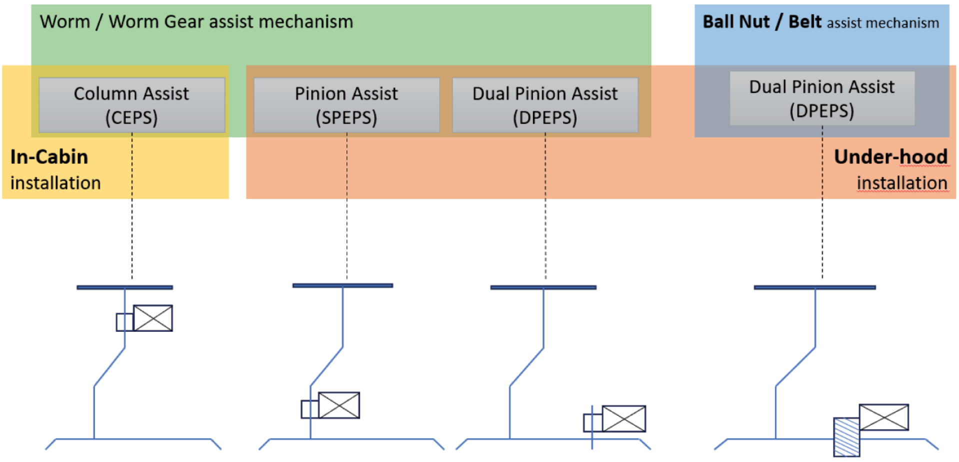


Fig. 1. Types of steering systems
Rys. 1. Rodzaje przekładni kierowniczych

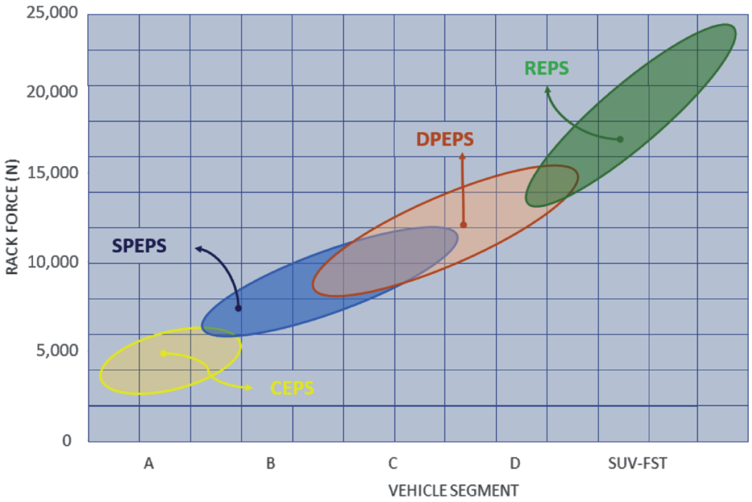


Fig. 2. Rack force vs vehicle segments – including typical steering systems
Rys. 2. Siła międzyzębna a segmenty pojazdów dla różnych układów kierowniczych

or Middle SUV Cars like Opel Astra, Peugeot 308/3008 Citroen C4/C4 Cross. In turn, rack assist is intended for vehicles with the highest weight.

CEPS is the oldest EPS type in regular use. It entered mass production as early as 1988. It was first used only in minis and compact cars, where rack forces were very low. CEPS is used today in middle-class vehicles **[L. 15]**. The column of the EPS unit is based on the assist mechanism consisting of a worm and worm gear. The motor and controller power unit provide the desired assist through the worm shaft and worm gear onto the output shaft. Forces are then transmitted through the intermediate shaft to the mechanical steering gear. The CEPS unit is assembled in the vehicle cabin and, as a result, is not exposed to severe weather conditions in the under-hood. Therefore, this system is the most cost-effective among steering system technologies. Due to load path transfer through the intermediate shaft, CEPS usage is limited to small vehicle applications. Also, in-cabin installation presents technical challenges, like crash behavior or natural frequency issues.

SPEPS power steering is used in small and middle-range vehicles **[L. 1]**. In the case of the single-pinion, the assist unit is positioned directly on the steering pinion. Integrating the torque sensor, power unit, and reduction gear into the steering pinion results in a compact system, which has some disadvantages. The Single-Pinion unit is limited to some maximum force due to the rack and pinion gear ratio. Typically, this ratio is mandated by the vehicle manufacturer as it is critical to vehicle maneuverability. Also, the Assist load transferred through the rack and pinion gear affects the load on the traction rods. One of the advantages of the Single-Pinion EPS is its lower complexity compared to Dual Pinion EPS and Rack EPS technology, affecting the cost of the system.

In the case of the Dual-Pinion EPS, there is a steering pinion and a second pinion for assistance. This steering is very well suited for medium or upper-middle-class vehicles. Such steering system was first used on the VW GOLF platform in 2002. Unlike Single-Pinion EPS, Dual-Pinion technology uses the advantage of the second pinion not constrained by the vehicle manufacturers' steering ratio. This allows for maximizing system output, using the most preferable rack and pinion ratio, the so-called C-factor. Typically, Dual-Pinion EPS can generate 10–15% higher output than SPEPS. Another advantage of the technology is higher packaging flexibility. The assist mechanism and power unit are independent of the driver pinion axis. Therefore, several combinations of positions are available, allowing the best adaptation in the installation space. Higher mechanical system complexity, mainly related to second pinion and lash cancellation components, causes the cost of Dual-Pinion EPS to be higher than SPEPS.

REPS is applied in dynamic sports cars, upper-middle-class cars, and high-load vehicles, such as cross-country vehicles and transporters. The unit comprises an electric motor and an electronic control unit (ECU), arranged parallel to the steering gear axial. A pinion on the motor shaft drives a toothed belt, which transfers the torque to the nut of a ball screw drive, which is merged with the steering rack. REPS system technology covers a wide range of output loads and is characterized by high efficiency and low friction. The disadvantage is the cost, which, due to additional components and complexity, causes the system to be the most expensive among others presented above.

NEW MECHANICAL DESIGN

The alternative solution for DPEPS could be a Parallel pinion power steering system called Tandem Pinion Electric Power Steering (TPEPS). This solution could give the same range of assist as DPEPS and, at the same time, a more compact and cheaper solution. This design is shown in **Fig. 3**.

The TPEPS system includes a driving pinion (1), which is coupled with a steering shaft (2). The driving pinion 1 rotates in direct response to steering input by a driver. The steering shaft (2) includes an upper shaft (3) that is coupled with a lower shaft (4) with a torsion bar (5). In the presented system, the driving pinion (1) is rotated in response to the rotation of the lower shaft (4). The driving pinion (1) is in meshed engagement with teeth (6) formed on the rack (7). The rack (7) is coupled at the ends with other steering components that converts the translation of rack (7) to the angled movement of the wheels to control the vehicle's direction. To assist the steering shaft, an assist mechanism (8) is provided. The assist mechanism (8) includes an electric motor (9) that receives input from the controller and triggers the rotation of an assist pinion (10). The assist pinion (10) is in meshed engagement with the teeth (6) of the rack (7). Rotation of the assist pinion (10) results in an assist force on the rack (7) that reduces the effort

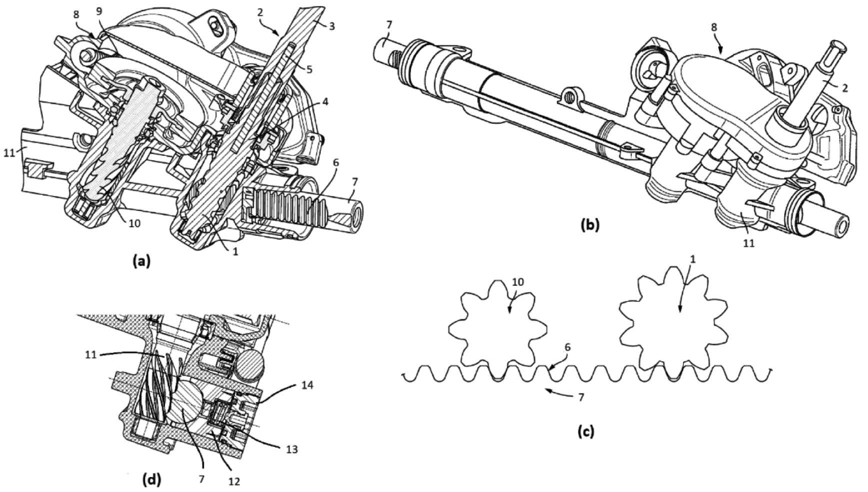


Fig. 3. Design of Tandem Pinion Electric Power Steering (TPEPS)
Rys. 3. Konstrukcja układu wspomagania kierowcy z dwoma zębnikami i współdzieloną listwą zębatą

required by the driver and may provide feedback to the driver in response to steering maneuvers. The rack (7) is located in the rack housing (11), which is adjacent to an assist mechanism housing.

The rack housing (11) partially connects the driving pinion (1) housing and the assist pinion (10) housing. In other words, packaging is improved when compared to systems requiring a separate assist mechanism housing on the opposite side of the driving pinion or anywhere else.

In **Fig. 3c**, the driving pinion (1), the assist pinion (10), and the rack (7) are shown in cross-section. The rack (7) has a single set of teeth with identical design parameters (i.e., within manufacturing tolerances and variability), such as a constant pitch and geometry along the length. Therefore, pinions 1 and 10 may have the same set of teeth 6. Pinions 1 and 10, also may rotate at different speeds due to different numbers of teeth. Therefore, driving pinion 1 maintains a ratio desired by a customer, while assist pinion 10 provides a maximized output. Also, certain advantages related to manufacturing, assembly, and overall size can be gained by maintaining the pinion axes as parallel. It is also permissible that these axes be non-parallel (within a certain range of angles) with no loss of function. Primary parameters that may vary are the number of pinion teeth. All other pinion parameters, such as pressure angle, helix angle, main and pitch diameters, tooth thickness, addendum and dedendum circle in gear, face width, and center distance, are restricted by the parameters of rack tooth.

CHARACTERISTICS OF NEW POWER STEERING

Steering is a type of transmission. While the value of the gear ratio is important from the point of view of the gears in the case of steering systems, the so-called C-factor (CF) is used – **Fig. 4**. It is a ratio between the rack travel in mm per one revolution of the pinion. The customer usually imposes the CF, and the Assist pinion is analyzed to optimize motor output requirement, but the limitation is a pitch on the driver pinion.

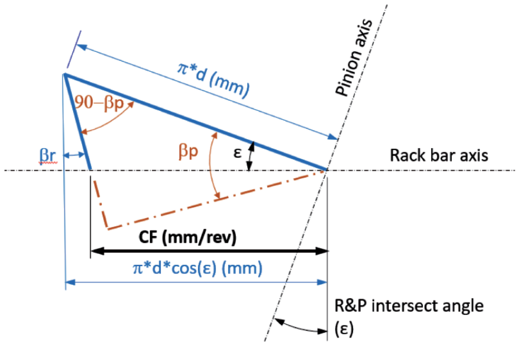


Fig. 4. Determination of the ratio in the steering gear using the CF parameter
Rys. 4. Określenie przełożenia w przekładni kierowniczej z wykorzystaniem parametru CF

The relationship between angles and geometry to determine the CF parameter is:

$$\varepsilon = \beta_p - \beta_r \tag{1}$$

$$CF = \pi d \tag{2}$$

In the DPEPS gear, where the sets of teeth on the rack are separated from each other, the only limitation in the design of the Assist pinion gear is the fatigue torsion resistance due to the size of the pinion tooth root diameter; for this reason the smallest C-Factor within 47mm/rev is usually used. That is why the Assist pinion in the DPEPS gear usually has 47mm/rev C-factor. In the new solution, an additional limitation is that both pinions are placed on the same toothing of the rack. Therefore, both pinions must have the same module and, thus, the same pitch. Also, the only possibility to reduce the C-factor on the power steering pinion is to reduce the number of teeth by 1, 2 or 3, depending on the C-factor value adopted on the driver's pinion. **Fig. 5** shows the relationship between the C-factor adopted on the driver pinion and the C-factor of the Assist pinion as a result of limiting the number of teeth. The figure also shows the range in which the benefit from the lower C-Factor is the greatest – the area between the lines CF min and CF Max.

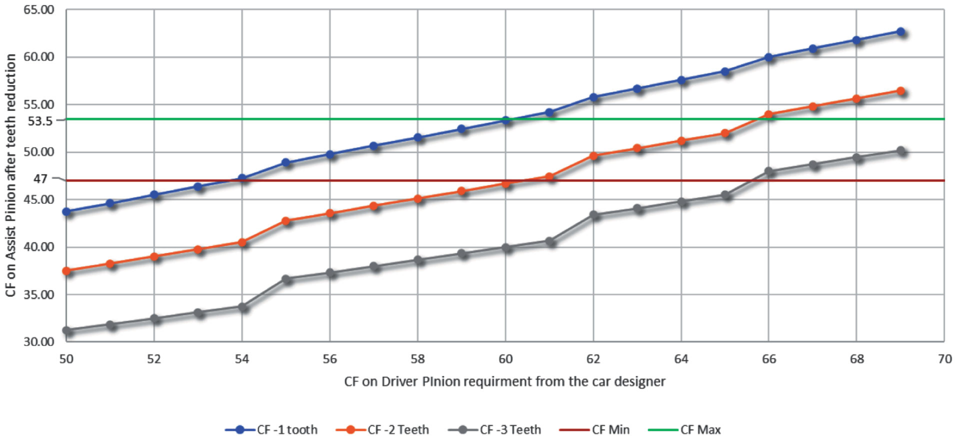


Fig. 5. Graph of the relationship between C-factor (CF) on the Driver pinion and Assist pinion
Rys. 5. Wykres zależności pomiędzy Parametrami CF na zębniku kierowcy i zębniku wspomagania

RESEARCH RESULTS

The advantages of the new design can also be observed in friction tests. These tests were carried out on the test stand, the diagram of which is shown in **Fig. 6**, and they concerned a new solution with two pinions and a common rack and a steering gear with two pinions operating on separate teeth of the rack.

The study considered the influence of the clearance in the bearing node shown in **Fig. 3d**. Rack 7 slides on Rack bearing 12 and engages with Pinion 11. The Rack bearing is pushed by spring 13, and the Adjuster plug compresses the spring to achieve a certain clearance. The tested clearance ranged from 20 to 140 µm in 20 µm steps for TPEPS. The tests showed lower friction force values than in currently used gears (DPEPS), which may suggest that the new solution will be more effective in terms of energy losses. The existing designs of steering systems had an average friction of 450 N. In contrast, the new solution has a friction of approximately 350 N with an adequate clearance setting in the bearing node. The results are shown in **Fig. 7**.

Another characteristic for which the new type of a steering system was tested was noise. The tests were carried out at the FDR (Field Data Replicator) station in an anechoic chamber shown in **Fig. 8**. The gear was attached to the FDR electro-magnetic exciter through an arm to which a steering tie rod was attached and connected to the rack. The exciter transmitted vibrations to the steering gear that simulated various types of surfaces on which a car can drive. The vibrations caused the steering gear to generate noise, which was recorded by a microphone directed at the place where the rack and pinion engaged. Additionally, accelerometers

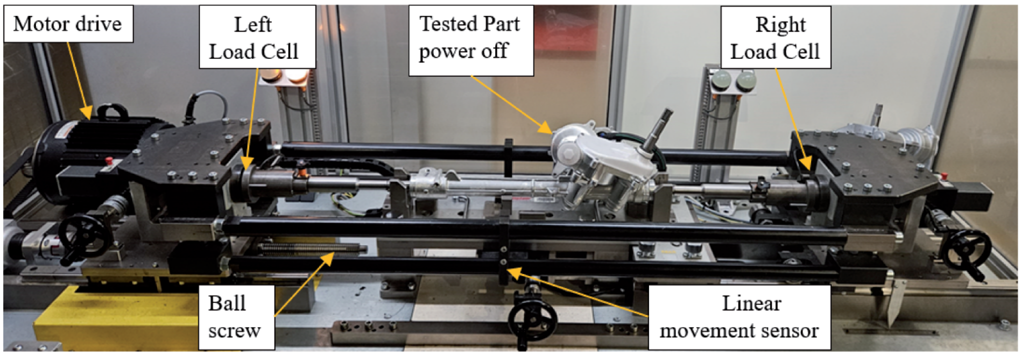


Fig. 6. Stand for testing the friction of steering systems
Rys. 6. Stanowisko do badania tarcia układów kierowniczych

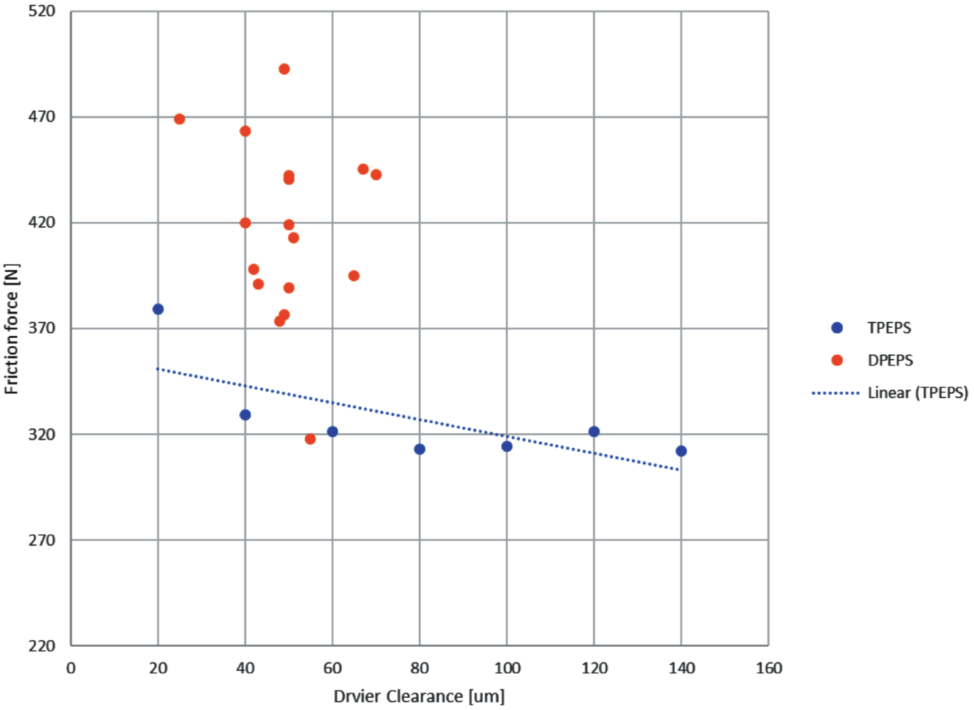


Fig. 7. Impact of the clearance in the bearing node on the level of the friction force at a testing speed of 16 mm/s to the clearance set on the bearing node in µm
Rys. 7. Wpływ luzu w węźle łożyskującym na wartość siły tarcia przy prędkości testowania 16 mm/s do luzu ustawionego na węźle łożyskowym w µm

measuring the vibration level were mounted in this place. Gear noise was measured in Sones; the relationship between decibels and Sones can be calculated from the following equation:

$$dB = 33.2 \times \log10(Sones) + 28 \quad (3)$$

7 Sones = 56.06 dB.

The noise level is closely related to the clearance set in the bearing node shown in **Fig. 3d**. Due to the close location of the pinions in the TPEPS Gear, the microphone was directed at both pinions of this system. In the DPEPS system, due to the distance between both pinions, the microphones were directed at both pinions separately. In the DPEPS system, where we have two separate bearing nodes for both pinions, the clearances for each of them were set separately and the noise level was measured for both pinions (Assist side and Driver side). The graph in **Fig. 9** (b), presents the noise results in Sones unit for the DPEPS Steering gear, which shows the noise level measurement depending on the measurement place. A-Driver means that the microphone was pointed at the Assist side and noise was measured at the driver node. D-Driver means that the microphone was pointed at the Driver side and noise level was measured at the driver node. In the TPEPS system, where the bearing node is under the driver pinion and the second power steering pinion is in close proximity to it, there was no need to separate the measurement. As it can be seen, the preliminary tests of the prototype show that with a similar bearing clearance setting, the TPEPS system generates lower noise levels – **Fig. 9** (a). With the Rack Clearance (RC) set to 130 µm, the highest noise level recorded was 9.7 Sone. On the other hand, in the DPEPS system with the Clearance set to 100 µm on the Assist side and 137 µm on the Driver side, the result was 11.4 Sone measured with a microphone on the Driver side and 10.9 Sone microphone placed on the Assist side.

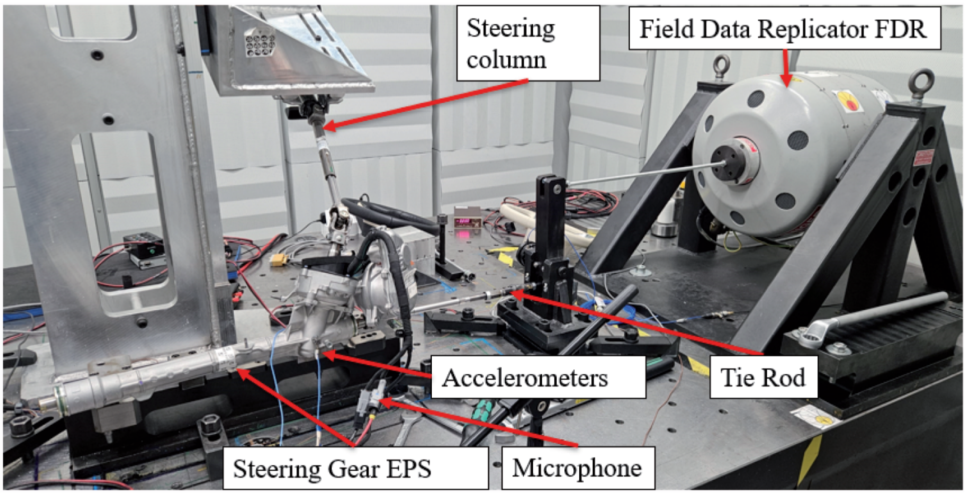
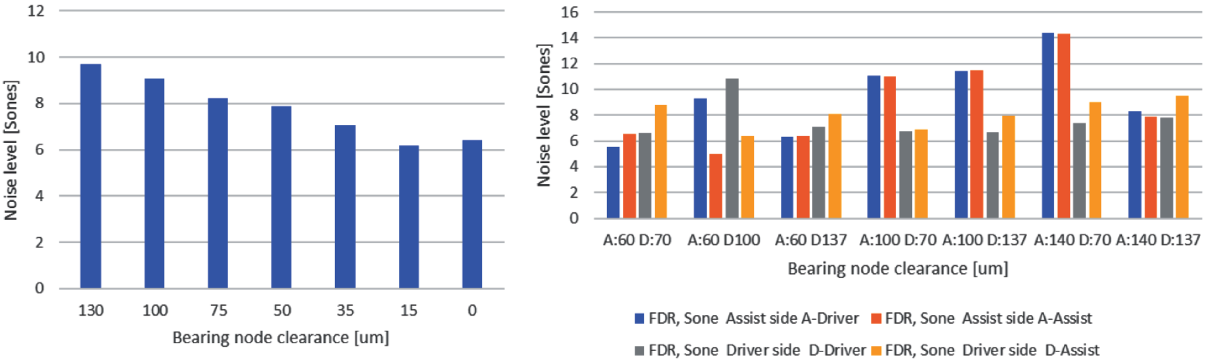


Fig. 8. A stand for testing the noise of steering systems
Rys. 8. Stanowisko do badania hałasu układów kierowniczych



(a) (b)

Fig. 9. Noise level comparison between the new type of Steering Gear (TPEPS) and the currently used Steering Gear (DPEPS)
Rys. 9. Porównanie poziomu hałasu pomiędzy nowym typem przekładni kierowniczej TPEPS i obecnie stosowanym typem przekładni kierowniczej DPEPS

CONCLUSIONS

The Design of a Parallel Pinons steering system could be a very competitive alternative for DPEPS, especially in terms of lower cost because of the reduced number of components, easier-to-produce housing, and simpler steering rack design, which has only one teeth set. While in DPEPS two separate teeth sets are problematic in machining, especially milling of the second teeth set at a certain angle and then to keep that angle after heat treatment operation with required accuracy . However, compared to the DPEPS, in the Parallel Pinion steering system the selection of C-factors for Assis and Driver side is not so flexible. However, as shown in **Fig. 5**, it is possible to cover a wide range of C-factors, which allows us to keep the same effectiveness of assist as it is in the DPEPS. The preliminary tests of the first prototypes showed that the friction level of the new steering gear TPEPS could be lower than that of the currently used system. The noise level results may suggest that the noise level might be lower, but this test was done on the first prototype only and needs to be confirmed on a wider range of assemblies.

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