

3. A Test Rig for Efficiency Measurements of Spur Gear Transmissions in a Micro-Drive System

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The paper presents preliminary results obtained on a laboratory test rig designed for analyzing the efficiency of spur gear transmissions. The investigated object was a simple gear pair consisting of two gears with a module of 1, made of C45 steel. The analysis covered efficiency measurements as a function of load torque and rotational speed, under both ‘dry’ operation and after lubrication with ŁT-4 grease. The obtained results indicate that the efficiency of the gear increased with the load torque, reaching a maximum of over 99.7%. It was found that lubrication improved efficiency by 0.5–1 percentage points compared to dry operation, especially at higher speeds. The results confirm the correctness of the test rig operation and its suitability for further studies on different types of gears and lubrication conditions.

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1. Introduction

Gear transmissions are among the most commonly used power transmission elements in engineering, and their efficiency significantly affects the overall performance of drive systems. In the era of device miniaturization and mechatronics development, research on small gear transmissions is gaining importance, particularly in mobile robotics, automation, and precision equipment.

The efficiency of a gear transmission depends on many factors: gear geometry, materials, manufacturing quality, lubrication conditions, and load [1]. Experimental studies are essential for verifying theoretical models of power losses.

Previous test rigs allowed the analysis of material and geometrical properties of gears efficiency [2–4]. However, those setups were relatively large, costly, and

not easily adapted to educational purposes. Moreover, they were mainly intended for testing multi-stage gearboxes rather than single meshing pairs [5].

For instance, the Łukasiewicz – Institute for Sustainable Technologies in Radom has designed a number of tribological rigs for testing various types of gear systems. The T-30 test rig enables the analysis of scuffing and pitting wear mechanisms in spiral bevel gears under controlled thermal and load conditions, enabling the evaluation of gear oils and low-friction coatings [6]. Another system, the T-34 test rig, allows the measurement of start-up friction torque and friction torque under dynamically steady conditions in a climatic chamber operating from $-50\text{ }^{\circ}\text{C}$ to $+50\text{ }^{\circ}\text{C}$, making it possible to assess gear losses in extreme thermal conditions [7].

Similarly, studies carried out at Silesian University of Technology [8] have contributed to the development of experimental infrastructure for testing bevel and planetary gears, focusing on the tribological performance, load-carrying capacity, and influence of lubrication. These systems, although advanced, are typically designed for large or medium-sized gearboxes and industrial applications, often requiring high-power electric drives and complex instrumentation.

The aim of this work was to design and build a compact test rig enabling efficiency measurements of small spur gears in a micro-drive system. The paper presents the device construction, measurement methodology and exemplary test results.

2. Research methodology

The test rig was based on the classical power recirculation method, in which the energy supplied by an electric motor circulates through the test and reference gears in a closed-loop system. The flow of mechanical power in such a system is shown in Fig. 1. In the power recirculation method, power circulates between

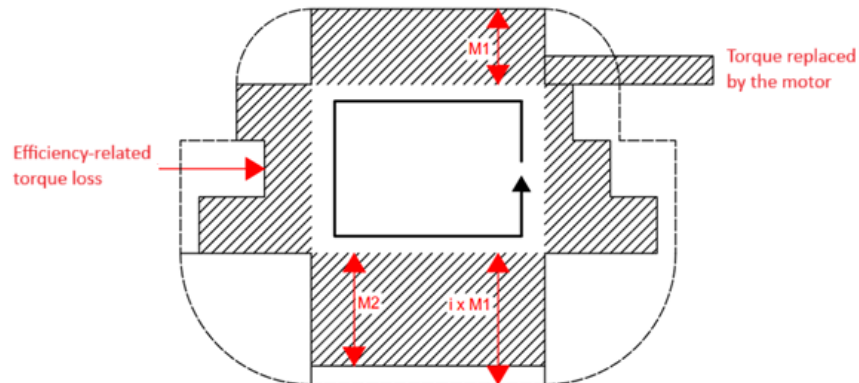


Fig. 1. Power flow in the power recirculation system.

the elements of the mechanism, being dissipated as friction and viscous losses, while the motor compensates for the losses. The mathematical description of the method was adopted from [5]. Since total losses in the mechanical system can be divided into load-dependent and load-independent components, $P_{\text{total}} = P_M + P_S$ where P_M is the load-dependent power loss and P_S is the no-load loss, the use of a two-step measurement allows for their separate determination.

In the measurement with a preloaded clutch, $M_{cl} \neq 0$ the motor must overcome both types of losses, $P_{T1} = P_M + P_S$. In the measurement with an unloaded clutch, $M_{cl} = 0$ the motor compensates only for no-load losses $P_{T2} \approx P_S$. Thus, the load-dependent losses can be determined as $P_M = P_{T1} - P_{T2}$, and the meshing efficiency is calculated as:

$$\eta_m = 1 - \frac{P_M}{2 \cdot M_{\text{sprz}} \cdot \omega_{\text{sil}}}.$$

The division by 2 results from the load being distributed between two gears. The total system efficiency is then:

$$\eta_T = 1 - \frac{P_{T1}}{2 \cdot M_{\text{sprz}} \cdot \omega_{\text{sil}}}.$$

During the tests, not only the motor current was recorded, but also the temperature in the gear contact zone and, in selected cases, the acoustic emission of the system. Temperature monitoring enabled the observation of changes in operating conditions over time, which was particularly important for longer test cycles. Acoustic monitoring was considered an auxiliary parameter, providing potential for future extensions towards vibration analysis and gear condition diagnostics.

The testing procedure involved mounting the selected gear pair, applying the preload torque using a lever with weights, and starting the motor. After stabilizing the operating conditions, measurements were taken at various torque and speed values. The obtained data were used to generate efficiency characteristics as a function of load, which were then compared.

3. Test rig design

The developed test rig was designed as a compact laboratory device, with a primary focus on ease of operation and quick exchange of test gears. The construction was based on a steel frame, providing sufficient stiffness and stability during measurements. The frame carried a drive unit based on a DC motor, along with fixtures for mounting both the test and reference gears. The drive motor is an 80 W maxon motor DCX32L brushed DC unit providing a nominal torque

of 120 mNm at 6640 rpm. The maximum load applied during testing has been determined at 10 Nm at the stationary gear shaft.

Special attention was given to the precise adjustment of the center distance, achieved using a linear guide enabling smooth displacement of one module. The screw used to alter the axis distance is equipped with a locknut, ensuring preload stability under vibration conditions. The other half of the screw has been manufactured to tight tolerances, making sure any play present is omissible. This solution allowed for testing different gears without major modifications to the setup. The overall concept was inspired by the FZG test machine, widely used for similar research [9], and described in detail in [10].

The measurement system was integrated with the structure in a simple and reliable manner. Efficiency calculations were based on measuring the current drawn by the motor, which eliminated the need for strain gauge torque sensors, significantly simplifying and reducing the cost of the rig. Additionally, the setup provided for temperature monitoring in the contact zone via an IR temperature sensor and noise level measurement via a MEMS microphone, offering opportunities for future expansion. For lubrication, a peristaltic pump was implemented to dose grease in a controlled and repeatable way, ensuring stable test conditions and enabling comparative studies of different lubricants. By extending the measurement time and applying cyclic torque loads, the test rig can serve as a platform for investigating fatigue damage and wear processes in small gear pairs.

Despite its laboratory scale, the rig was designed with ergonomics and modularity in mind, allowing for straightforward replacement of test gears and future modifications, such as extending the load range or adding more measurement channels. The CAD model of the device is shown in Fig. 2, while the prototype is presented in Fig. 3.

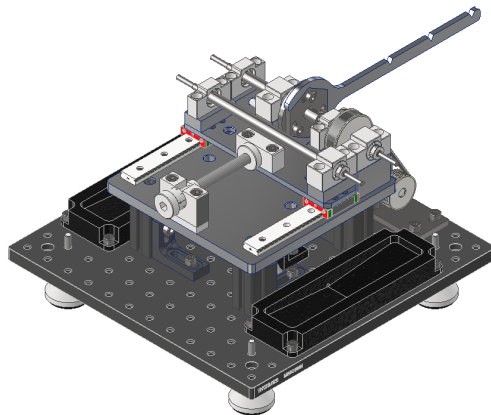


Fig. 2. CAD model of the device.

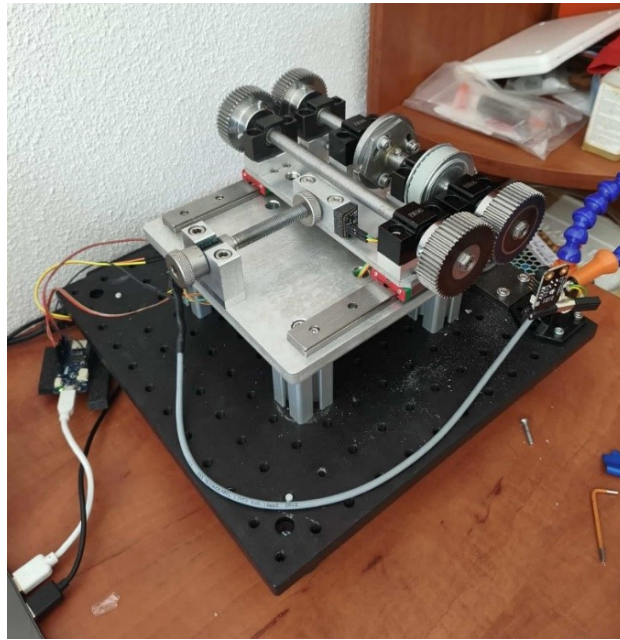


Fig. 3. Prototype of the test rig.

4. Test results – sample gear transmission

To verify the correct operation of the test rig, preliminary measurements were carried out using a spur gear pair made of C45 steel, with 48 teeth each and a module of 1. This was the smallest gear size that could be tested on the rig. The geometry was selected to replicate operating conditions typical of small drive systems. A photograph of the tested gears is presented in Fig. 4.

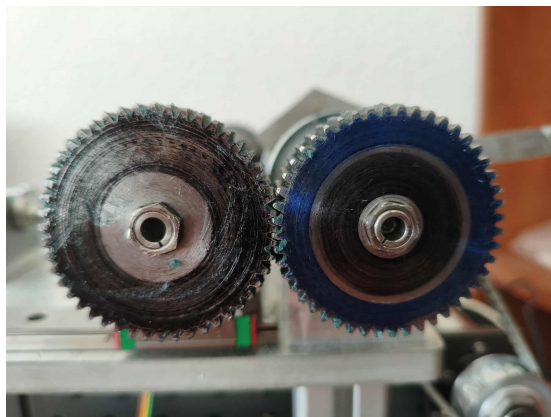


Fig. 4. Tested spur gear pair.

Measurements were performed at various load torque and speed values to determine efficiency characteristics. Each measurement involved motor startup, speed, and temperature stabilization, followed by recording motor current, gear contact temperature, and acoustic variations. Input and output powers were then calculated, and gear efficiency was determined. Table 1 presents efficiencies under dry conditions, while Table 2 shows results after lubrication with ŁT-4 grease. In both cases, efficiency increased with load torque. Under dry conditions, efficiency decreased at higher speeds, while lubrication maintained values above 99% across a wide speed range. Data were collected for approximately 30 seconds at each operating point and averaged.

Table 1. Efficiency results under dry operation.

Dry operation						
M_sprz [Nm]	1.15	4.35	5.5	1.15	4.35	5.5
in [RPM]	n_m [%]			n_t [%]		
50	98.73	99.05	99.67	97.20	98.56	99.29
100	98.80	99.09	99.66	97.13	98.55	99.25
200	98.78	99.07	99.62	96.87	98.45	99.15
300	98.46	98.95	99.55	96.39	98.28	99.05
400	97.99	98.77	99.33	95.89	98.09	98.82
500	97.64	98.55	99.13	95.51	97.86	98.61

Table 2. Efficiency results under lubricated operation (ŁT-4 grease).

Lubricated operation (ŁT-4)						
M_sprz [Nm]	1.15	4.35	5.5	1.15	4.35	5.5
in [RPM]	n_m [%]			n_t [%]		
50	99.34	99.43	99.77	97.79	98.92	99.39
100	99.45	99.55	99.79	97.82	99.02	99.39
200	99.46	99.56	99.83	97.74	99.00	99.41
300	99.44	99.52	99.77	97.46	98.87	99.29
400	99.35	99.41	99.74	97.27	98.73	99.23
500	99.16	99.31	99.63	96.96	98.59	99.09

Figures 5 and 6 show efficiency characteristics as a function of rotational speed, at different torque values. It can be clearly seen that efficiency increases with load torque. Under dry operation, efficiency decreased with increasing speed, whereas under lubrication, a peak efficiency occurred at medium speeds, followed by a decrease at higher speeds. This behavior is consistent with typical gear transmission characteristics, where frictional losses dominate at low loads, but decrease with increasing torque. At very high speeds, the hydrodynamic effects of the lubricant become the main source of losses.

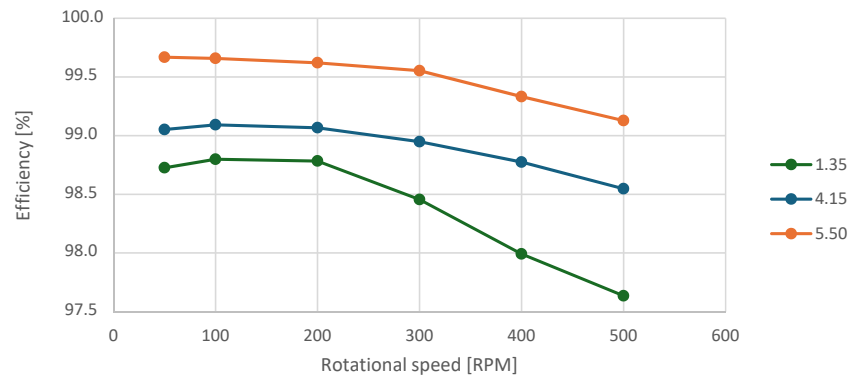


Fig. 5. Efficiency as a function of the rotational speed during dry operation.

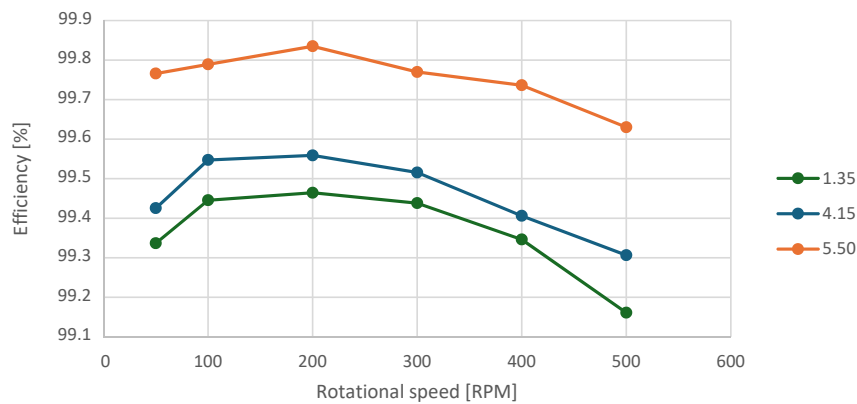


Fig. 6. Efficiency as a function of the rotational speed during lubricated operation.

5. Discussion

The conducted tests confirmed the correct operation of the test rig and the consistency of the obtained characteristics with theoretical predictions and literature reports [2, 5, 11]. It was shown that gear efficiency increases with load torque, resulting from the decreasing relative contribution of frictional losses [2].

The comparison of dry and lubricated operation demonstrated that LT-4 grease significantly improves gear performance, particularly by reducing boundary friction losses and stabilizing the load transfer in the meshing zone. At the same time, at the highest speeds, a drop in efficiency was observed due to increasing viscous losses in the lubricant, consistent with observations by other authors [5, 11].

Temperature and acoustic analyses confirmed stable operation of the gear pair under all tested conditions. The absence of anomalies indicated correct meshing conditions and proper manufacturing quality of the gears.

The obtained results should be considered preliminary. The study was limited to spur gears with a small module; thus, further research should include gears with different modules, helix angles, and lubricants. An interesting direction would also be a comparison between spur and helical gears, where axial forces and friction conditions differ significantly.

6. Conclusions

The objective of this study was to validate the developed test rig by analyzing the efficiency of spur gears with a module of 1, made of C45 steel. The obtained results confirmed both the functionality of the measurement system and its capability to perform tests over a wide range of speeds and loads.

The conducted experiments showed that:

- gear efficiency increases with load torque due to the decreasing relative share of frictional losses at higher loads,
- under dry conditions, efficiency decreases with speed, while under lubrication, a maximum occurs at medium speeds, with a decrease at high speeds caused by viscous losses,
- lubrication with ŁT-4 grease improved efficiency by 0.5–1 percentage points compared to dry operation, clearly demonstrating its beneficial influence on gear operation,
- acoustic and temperature measurements confirmed stable operation throughout the tested range, with no indications of meshing irregularities.

In summary, the developed test rig enables obtaining reliable efficiency characteristics of spur gears and forms a solid basis for further comparative studies. Future work should be extended to other gear types (helical, bevel), different materials, and various lubricants, providing a broader dataset for design analysis and better representation of operational conditions.

References

1. Skoć A., *Podstawy konstrukcji maszyn. Tom 3. Przekładnie mechaniczne*, 1st ed., Wydawnictwo Naukowe PWN, Warszawa, 2018.
2. Petry-Johnson T.T., Kahraman A., Anderson N.E., Chase D.R., An experimental investigation of spur gear efficiency, *Journal of Mechanical Design*, **130**: 062601, 2008, <https://doi.org/10.1115/1.2898876>.
3. Niza M.E. *et al.*, Test rig for micro gear and experimental analysis on the meshing condition and failure characteristics of steel micro involute gear and metallic glass one, *Mechanism and Machine Theory*, **45**(12): 1797–1812, 2010, <https://doi.org/10.1016/j.mechmachtheory.2010.08.008>.

4. Anderson N.E., Loewenthal S.H., *Spur-Gear-System Efficiency at Part and Full Load*, Technical Paper 1622, NASA, Cleveland, OH, 1980.
5. Chase D.R., Development of an efficiency test methodology for high-speed gearboxes, Master's thesis, The Ohio State University, 2005.
6. Tuszyński W., Kalbarczyk M., Michalak M., Badania tribologiczne kół zębatych stożkowych. Cz. I – Urządzenie i metodyka badawcza, *Tribologia*, **242**(2): 83–96, 2012.
7. Tuszyński W. *et al.*, New test rig for measuring the friction torque of gearboxes in extreme thermal conditions, *Tribologia*, **296**(2): 57–64, 2021, <https://doi.org/10.5604/01.3001.0015.5869>.
8. Michalczewski R. *et al.*, The effect of a gear oil on abrasion, scuffing, and pitting of the DLC-coated 18CrNiMo7-6 Steel, *Coatings*, **9**(1): 2, 2019, <https://doi.org/10.3390/coatings9010002>.
9. International Organization for Standardization, Gears – FZG test procedures – Part 1: FZG test method A/8,3/90 for relative scuffing load-carrying capacity of oils, ISO 14635-1:2023(en), 2023.
10. Chyliński A., Konstrukcja urządzenia do pomiaru sprawności przekładni zębatych, Engineering thesis, Politechnika Warszawska, Warszawa, 2025.
11. Li X., Sosa M., Andersson M., Olofsson U., A study of the efficiency of spur gears made of powder metallurgy materials – ground versus super-finished surfaces, *Tribology International*, **95**: 211–220, 2016, <https://doi.org/10.1016/j.triboint.2015.11.021>.

