Strojnícky časopis – *Journal of* MECHANICAL ENGINEERING,
VOL 75 (2025), NO 3, 27 - 34

OPEN-SOURCE BASED SYSTEM FOR EXPERIMENTAL GEAR MESH STIFFNESS EVALUATION

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Abstract: This paper presents an automated test rig for static gear mesh stiffness measurement, innovating a previous manual setup. Utilizing open-source hardware (Raspberry Pi, ESP32, Arduino) and Python software with a GUI, the system automates controlled torque application and angular displacement data acquisition. Pilot measurements validate its functionality, demonstrating improved efficiency, repeatability, and data consistency compared to manual methods. The cost-effective open-source approach offers a replicable solution for enhanced gear analysis.

KEYWORDS: gear mesh stiffness, automation, test rig, open source, incremental rotary encoder, GUI.

1 Introduction

Gear mesh stiffness is a critical parameter for the analysis and optimization of gear drives, which are widely used in various industrial applications, [1, 2]. Understanding and accurately measuring gear mesh stiffness is essential for predicting gear dynamic behaviour, noise and vibration levels, and ultimately, the overall performance and lifespan of gearboxes. Traditional methods for determining gear mesh stiffness include both theoretical calculations, [3] and experimental approaches, [4, 5]. While analytical and numerical methods (such as Finite Element Analysis) provide valuable insights, experimental validation is crucial to account for real-world factors like manufacturing imperfections, mounting conditions, and material properties, [6].

Various experimental setups and techniques have been developed to measure gear mesh stiffness under different conditions. Early methods often involved static loading of gear teeth and measuring the resulting deflections using dial indicators or LVDT sensors, [7]. For instance, some studies focused on measuring the stiffness of a single tooth by applying a load and recording the deformation, [4]. Other approaches utilized optical techniques like photoelasticity to visualize stress distribution and infer stiffness, particularly in cases involving gear tooth cracks, [8]. Strain gauge techniques have also been employed to measure localized deformations on gear teeth under load, [9]. More advanced static methods have incorporated non-contact sensors, such as laser displacement sensors, to achieve higher precision in measuring microscopic deflections, [10]. These static test rigs typically involve applying torque using levers and weights and measuring angular or linear displacements.

In contrast to static tests, dynamic or running tests aim to measure gear mesh stiffness under operational conditions. These setups often employ motors to generate torque and high-resolution encoders to measure the dynamic transmission error (TE), which is directly related to mesh stiffness, [11]. Dynamic test rigs are more complex, often requiring gearboxes to adjust speed and torque, and braking systems to regulate load [12].

DOI: 10.2478/scjme-2025-0034, Print ISSN 0039-2472, On-line ISSN 2450-5471

While existing methods provide valuable data, many traditional experimental setups for static measurements are time-consuming and require significant manual intervention, leading to low efficiency and potential for human error. The need for automation in gear mesh stiffness measurement is driven by the requirement for improved speed, repeatability, and accuracy over manual methods.

This paper presents an innovative, cost-effective automated test rig utilizing open-source technologies to provide a more efficient tool for experimental gear analysis, [13].

2 Methodology

The test rig for static gear mesh stiffness measurement, initially developed in previous work, [14], was subjected to significant innovation and automation to overcome the limitations of the original manual methodology. As described in detail in [14], the initial manual procedure involved a time-consuming, step-by-step process that required manual adjustment of the gear specimen, application of static loads using weights, and manual recording of angular displacements at specific points of gear mesh. This approach was inefficient, prone to human error, and made extensive measurements impractical, highlighting the need for automation.

To address these limitations, the test rig underwent redesign and automation. The core of the innovation lies in the integration of controlled drives and a comprehensive data acquisition and control system built upon open-source hardware and software.

Structural modifications were implemented to enable automated operation. These included the integration of a stepper motor (Joy-it NEMA34-01) coupled with an ITH series gearbox and shaft couplings. This assembly automates the controlled rotation of the gear samples, allowing for precise application of torque through the loading lever. A stepper motor was selected specifically for its ability to maintain position at zero speed without requiring an external brake and its compatibility with open-loop control, which simplified the implementation process and reduced costs compared to more complex servo systems. To facilitate precise adjustment of the axial distance between gear samples, a motorized mechanism was implemented. An existing 3D printer Z-axis assembly, featuring a stepper motor and trapezoidal screw, was adapted for this purpose as a proof-of-concept, demonstrating the feasibility of automating this aspect. The final assembled state of the automated test rig is depicted in Fig.1.

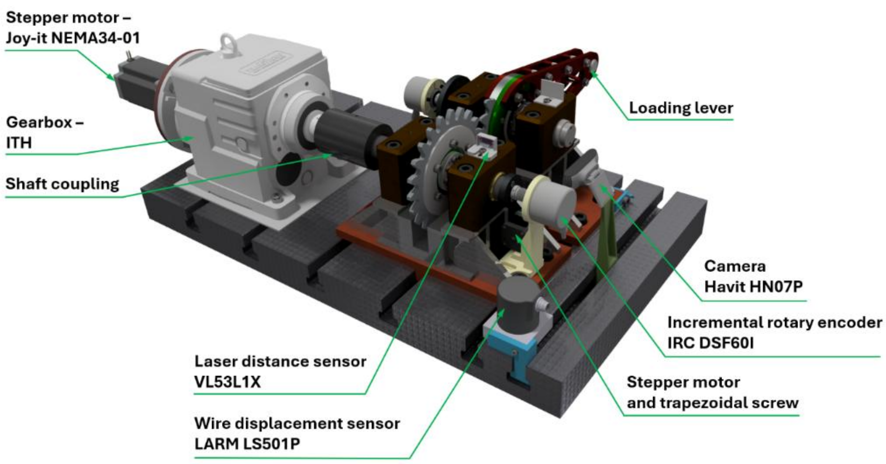

Fig. 1 Automated test rig workplace

The system incorporates several sensors essential for accurate data acquisition and control. Two incremental rotary encoders (IRC DFS60I) are utilized to precisely measure the angular displacement of both the driving gear (connected to the motor/gearbox) and the driven gear (connected to the loading lever). This enables accurate tracking of the relative angular position of the gears throughout the meshing process. For measuring the axial distance, two different sensor types were implemented: a VL53L1X laser distance sensor communicating via I2C and a LARM LS501P wire displacement sensor providing an analogue output. This dual approach offers flexibility and allows for exploration of different sensing principles. An end-stop microswitch is integrated to detect the lower limit position of the loading lever, serving as a safety feature and a crucial reference point for homing the system (Fig. 2). Additionally, a Havit HN07P camera is included to provide visual documentation of the meshing process during experiments. Power for the entire system is supplied by a LYONZG S-360-24 power supply.

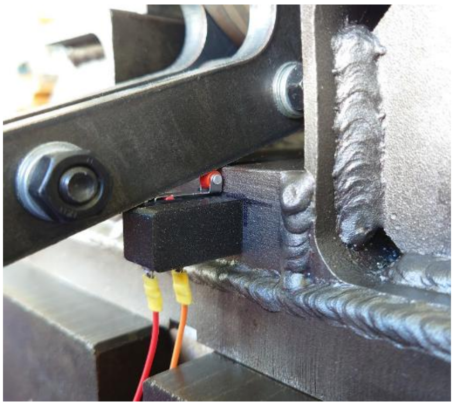

Fig. 2 End-Stop – safety feature and a reference for homing the system

The control and data acquisition core of the system is based on a combination of readily available open-source hardware components (see schematic Fig. 3). A Raspberry Pi minicomputer functions as the central processing unit, executing the main control software and hosting the graphical user interface (GUI). ESP32 microcontrollers serve as dedicated real-time processors responsible for reading high-resolution data from the IRC sensors and transmitting this processed data to the Raspberry Pi via serial communication. RS485 to TTL converters were used to interface the differential signals from the IRCs with the ESP32s. An Arduino UNO R4 microcontroller is specifically used for reading data from the distance sensors and forwarding it to the Raspberry Pi.

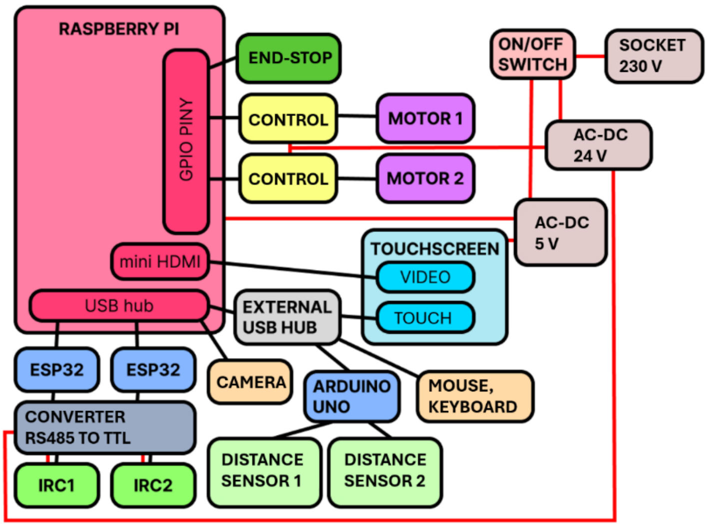

Fig. 3 System and control diagram

The system's software was developed primarily in Python, running on the Raspberry Pi. Key software components, include a dedicated Python class (Stepper_motor) for controlling the stepper motors by generating the necessary step, direction, and enable signals via GPIO pins. This class manages the calculation of steps required for desired angular movements or continuous rotation. Functions were developed for processing input related to the axial distance motor control, converting desired distance values into motor steps based on the lead screw parameters. An Endstop class manages the end-stop switch detection, triggering motor stops and resetting angular position references upon activation. SerialReader and DualSerialReader classes handle the reception and processing of data from the microcontrollers connected to the IRC and distance sensors via USB serial communication. Filtering algorithms, particularly for data from the laser sensor, were applied to improve accuracy. A graphical user interface (GUI), developed using the TKinter library in Python, serves as the primary user interface (Fig. 4).

Fig. 4 Graphical user interface

The GUI enables users to set measurement parameters, control motor movements (including automated sequences), view real-time sensor data (such as angular positions and axial distances), visualize results in graphs, manage data saving, and follow a built-in step-by-step guide for conducting measurements. The GUI's design was initially laid out using Figma and then converted to Python code, streamlining the development process. The GUI utilizes a touchscreen display for intuitive interaction, and a comprehensive help system is integrated to guide the user effectively through the measurement procedure.

This integrated system facilitates automated, precise, and repeatable measurement sequences, significantly reducing the time and effort previously required by the original manual methodology. The strategic utilization of readily available, low-cost open-source components makes this system highly replicable and adaptable for potential further research and development in the field.

3 Results of Functional Verification

Text Pilot measurements were conducted to verify the functionality of the proposed test rig innovations and the success of the software implementation. The measurements aimed to demonstrate the automated system's capability to perform the required measurement sequences and acquire relevant data for gear mesh stiffness analysis.

The pilot test was performed on a gear sample made of Extruded Plexiglas® XT (PMMA) with specified parameters. The axial distance was set to 180 mm, and a load corresponding to a total weight of 14.84 kg was applied via the loading lever, generating a specific torque.

The automated measurement sequence, controlled by the developed software, involved the controlled rotation of the gears while simultaneously acquiring angular position data from the two incremental rotary encoders (IRCs). The data acquired from the IRCs represent the total angular displacement of the driving and driven shafts during the gear meshing cycle, (Fig. 5).

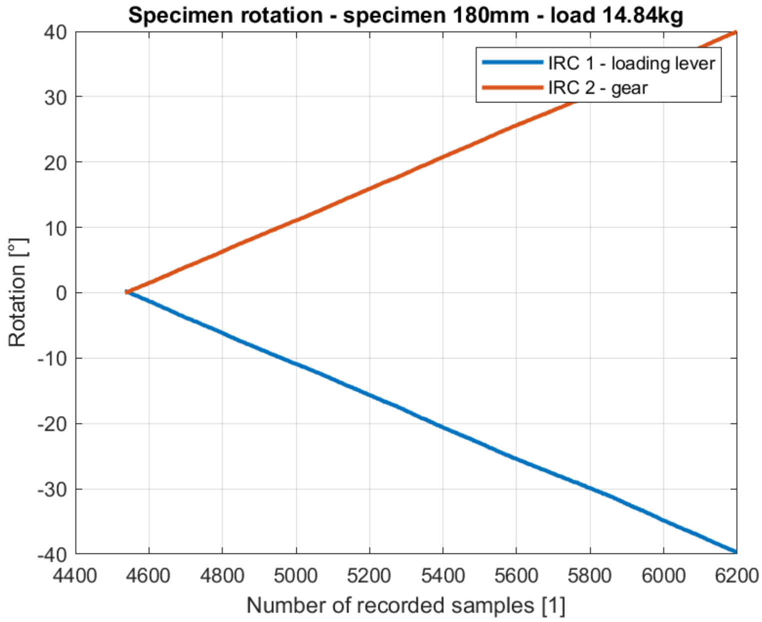

Fig. 5 Angular displacement of the driving and driven shafts

To isolate the angular deformation of the gear teeth from the overall rigid body rotation of the system, the measured raw data were processed. This involved determining a baseline representing the system's kinematic motion without tooth deformation. By subtracting this linearized baseline from the measured total displacement, the angular deformation solely attributable to the compliance of the gear mesh was obtained. The resulting differential angular deformation, representing the total elastic deformation within the gear mesh, was then analyzed. (Fig. 6).

The plot (Fig. 6) of the resulting deformation clearly shows the characteristic pattern of gear mesh stiffness variations during the meshing cycle, typically exhibiting higher stiffness during two-pair contact and lower stiffness during single-pair contact.

The pilot measurement successfully demonstrated the automated system's ability to:

- Control the precise angular movement of the gear samples using the integrated stepper motor and gearbox.
- Acquire synchronized high-resolution angular displacement data from both the driving and driven shafts using the IRCs and microcontrollers.
- Facilitate automated measurement sequences according to predefined angular ranges.

Generate raw data suitable for post-processing to determine gear tooth deformation.

Crucially, the observed deformation pattern and magnitude in the pilot measurement (Fig. 6) showed good agreement with results obtained using the original manual test rig (Fig. 7) and corresponded well with expected deformation characteristics for the tested PMMA gear sample. Specifically, the deformation observed during single-pair contact was approximately 0.22°, while during two-pair contact, it was around 0.15°, consistent with previous findings.

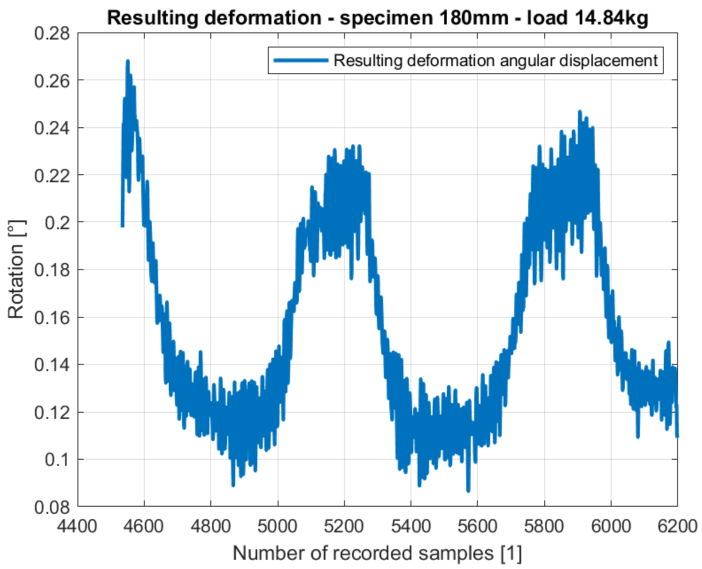

Fig. 6 Total elastic angular deformation within the gear mesh

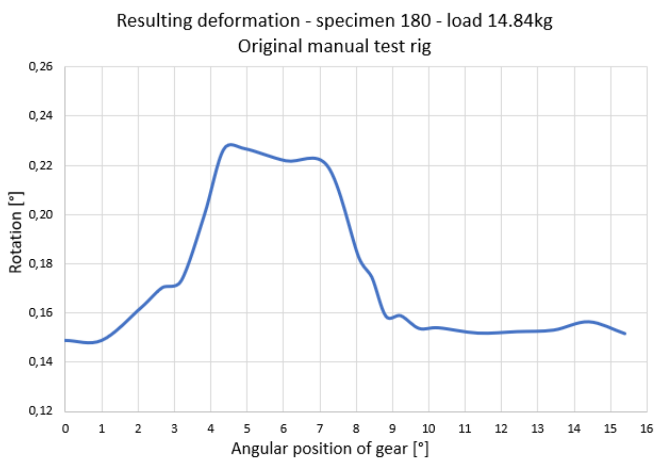

Fig. 7 Original data from a manual test rig for comparison with the new automated measurement

These pilot measurements definitively validate the functional verification of the automated test rig and the integrated hardware and software components for acquiring the necessary data for such calculations. The automated system proved reliable in executing measurement cycles and collecting consistent angular displacement data, which is the primary output required for mesh stiffness analysis.

CONCLUSION

The conducted work successfully addressed the primary objective of automating the static gear mesh stiffness measurement process on the existing test rig. By integrating a controlled stepper motor drive system and developing a comprehensive control and data acquisition system based on open-source hardware (Raspberry Pi, ESP32, Arduino) and software (Python, TKinter), the limitations of the original manual methodology were effectively overcome.

The original manual measurement procedure was characterized by its significant time consumption and dependence on operator skill, making extensive testing inefficient. The automated system noticeably reduces the time required for data acquisition during the meshing cycle, allowing for faster and more repeatable measurements. The graphical user interface simplifies the operation, guiding the user through the process and minimizing the potential for human error.

The pilot measurements verified the functional integrity of the developed system. The ability to precisely control the angular movement of the gears and simultaneously acquire synchronized data from both shafts is crucial for accurately determining gear tooth deformation. The obtained deformation patterns from the pilot test align well with previous measurements on the manual rig and theoretical expectations, confirming that the system is capable of capturing the relevant physical phenomenon. The open-source approach proved to be a viable and cost-effective alternative to traditional proprietary systems, such as those based on LabVIEW and associated National Instruments hardware, which would incur significantly higher costs for both hardware and software licenses. The total cost of the open-source solution was approximately 1 700 EUR (about 1 400 EUR for mechanical parts and 300 EUR for electronics), significantly lower than the estimated 6 000 EUR for a commercial solution with similar capabilities, which is dependent on licence fees. This makes this innovation accessible and easily replicable for other research groups or educational institutions. The system is also flexible for future upgrades due to universal communication protocols.

While the core objective of automation and functional verification was met, several areas for further improvement exist. Enhancements to the axial distance adjustment mechanism, potentially involving a more robust or dual-drive stepper motor system, could improve its reliability and precision. Automating the process of applying and removing weights, although requiring more significant mechanical redesign, would further reduce manual labor. Integrating the camera feed into the automated measurement sequence for synchronized video recording with sensor data could provide richer insights into gear behavior. Further refinement and modularization of the software code, along with enhanced error handling and self-check mechanisms, would improve the system's robustness and maintainability.

In conclusion, the developed automated test rig for gear mesh stiffness measurement represents a significant improvement over the previous manual method. The successful integration of open-source technologies for control and data acquisition provides a cost-effective, flexible, and replicable solution. The pilot measurements validate the system's functionality and its capability to deliver reliable data for gear mesh stiffness analysis. This work provides a solid foundation for future experimental research in gear design and analysis, demonstrating the potential of open-source solutions in complex engineering applications. The financial benefits of this approach make advanced experimental capabilities more accessible.

ACKNOWLEDGEMENT

This contribution was funded by Czech Technical University in Prague grant number SGS25/086/OHK2/2T/12.

REFERENCES

[1] Flek, J., Dub, M., Kolář, J., Lopot, F., Petr, K. "Determination of Mesh Stiffness of Gear –Analytical Approach vs. FEM Analysis", Applied Sciences 11(11), pp. 4960, **2021**. DOI: 10.3390/app11114960

[2] Ustynenko, O., Cherelev, S., Ondruška, J., Protasov, R., Yepifanov, V., Bondarenko, O., Andrienko S. "Optimal Design of Spur Gears with Increased Contact Ratio", Strojnícky časopis – Journal of Mechanical Engineering 75, pp. 163 – 172, **2025**. DOI: 10.2478/scjme-2025-0017

[3] Yu, W., Mechefske, C. K. "A New Model for the Single Mesh Stiffness Calculation of Helical Gears Using the Slicing Principle", Iranian Journal of Science and Technology, Transactions of Mechanical Engineering 43, pp. 503 – 515, **2019**. DOI: 10.1007/s40997-018-0173-x

[4] Karpat, F., Yuce, C., Doğan, O. "Experimental measurement and numerical validation of single tooth stiffness for involute spur gears", Measurement, 150, pp. 107043, **2020**. DOI: 10.1016/j.measurement.2019.107043

[5] Flek, J., Karas, T., Dub, M., Lopot, F., Ripa, V., Kolar, J. "Experimental Identification of Gear Mesh Stiffness and Verification by Theoretical Models", Manufacturing Technology 24 (4), pp. 552 – 566, **2024**. DOI: 10.21062/mft.2024.069

[6] Saxena, A., Chouksey, M., Parey, A. "Effect of mesh stiffness of healthy and cracked gear tooth on modal and frequency response characteristics of geared rotor system", Mechanism and Machine Theory 107, pp. 261 – 273, **2017**. DOI: 10.1016/j.mechmachtheory.2016.10.006

[7] Raghuwanshi, N. K., Parey, A. "Experimental measurement of mesh stiffness by laser displacement sensor technique", Measurement, 128, pp. 63 – 70, **2018**. https://doi.org/10.1016/j.measurement.2018.06.035.

[8] Raghuwanshi, N. K., Parey, A. "Mesh stiffness measurement of cracked spur gear by photoelasticity technique", Measurement 73, pp. 208 – 220, 2015. DOI: 10.1016/j.measurement.2015.05.022

[9] Raghuwanshi, N. K., Parey, A. "Experimental measurement of gear mesh stiffness of cracked spur gear by strain gauge technique", Measurement 86, pp. 266 – 275, **2016**. DOI: 10.1016/j.measurement.2016.03.001

[10] Wan, Z., Cao, H., Zi, Y., He, W., He, Z. "An improved time-varying mesh stiffness algorithm and dynamic modeling of gear-rotor system with tooth root crack", Engineering Failure Analysis 42, pp. 157 – 177, **2014**. DOI: 10.1016/j.engfailanal.2014.04.005

[11] Fang, G., Zongde, F. "Experimental and Theoretical Study of Gear Dynamical Transmission Characteristic Considering Measured Manufacturing Errors", Shock and Vibration 2018, pp. 266 – 275, **2018**. DOI: 10.1155/2018/9645453

[12] Danko, J., Nemec, T., Milesich, T., Magdolen, L. "Dynamic Stiffness Determination of the Rubber Bushing Fem Model with Viscoelastic Material Behaviour", Strojnícky časopis – Journal of Mechanical Engineering 72, pp. 121 – 128, **2022**. DOI: 10.2478/scjme-2022-0046

[13] Flek, J., Dub, M., Kadeřábek, P. "Experimentální stanoviště pro stanovení tuhosti ozubení", [Functional sample], **2024**.

[14] Flek, J., Dub, M., Kolář, J. "Návrh konstrukce experimentálního zařízení pro identifikaci tuhosti ozubení", In: 22. odborná konference z cyklu Integrované inženýrství v řízení průmyslových podniků, Praha, Czech Republic, pp. 25 – 33, **2022**.