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EXTENDED ANALYSIS OF SELECTED DEVIATIONS AND PRECISION OF GEARS MANUFACTURING AS A POSSIBILITY FOR REDUCTION OF GEARBOXES' VIBROACTIVITY USED IN MEANS OF TRANSPORT

Summary. The paper presents the results of deviations and accuracy manufacturing measurement of selected geometric parameters of pinions and gears made for the same nominal dimensions and the same accuracy class. The measurement was made on the coordinate measuring machine from Klingelnberg GmbH, which is commonly used, among others, to assess the accuracy of gears manufactured for air transport vehicles. Selected parameters of the tested pinions and gears were measured and analyzed, which have a significant impact on the emission of vibrations and noise of the operating gearbox. Vibroactivity of gearboxes in case of many means of transport is a very important research topic because vibrations and noise generated by drive systems of various means of transport affect passengers and are the source of environmental noise pollution. The analysis of the obtained results showed that despite adopting the same nominal dimensions and the same accuracy class, the tested gears are characterized by

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significant (often strong and exceeding the range of the adopted accuracy class) variability of specific, selected geometric parameters. The use of gears, even those made in the same precision class, in the case of gearboxes used in means of transport, whose quiet operation is an important operational aspect, should be extended by accurate measurement of selected geometric parameters.

Keywords: gears deviations, precision of gears manufacturing, gears class of accuracy, means of transport drive systems

1. INTRODUCTION

Gearboxes are commonly used in the transmission systems of many machines and devices. They are also widely used in the drive systems of various means of transport such as motor vehicles, rail vehicles, aircraft and ships. The key part of many drive transmission systems used in means of transport is the gearbox. In order to ensure the correct operation of the gearbox, high precision of the components and their assembly is required [1-3]. The precision of the gearbox components, including gears, is extremely important as it affects both the reliability of the gearbox and the vibrations and noise emitted during its operation [1-7]. In many research works, the recording and analysis of vibroacoustic signals is used to assess the technical condition of the operating gearbox [8-12].

a)

b)

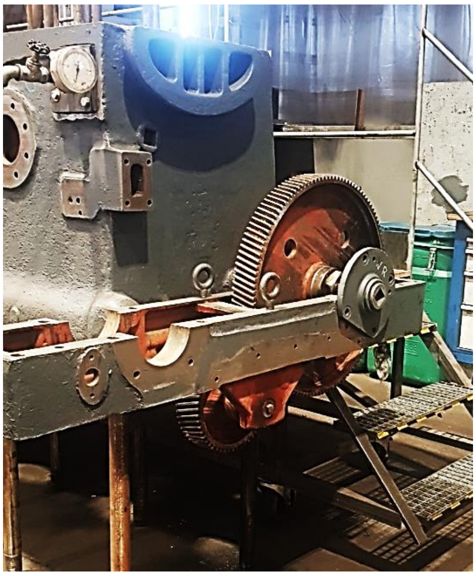

Fig. 1. Examples of gear applications in rail vehicles: a) fragment of the wheelset gearbox, b) example of gearbox used in the construction of locomotive engine

Irrespective of the means of transport type and the drive system used in its construction, solutions are sought that are characterized by the lowest possible emission of vibrations and noise. In the case of gearboxes used in various means of transport, the issue of vibroactivity is extremely important and current because vibrations and noise generated during gearbox operation affect the users of the means of transport, significantly affecting the comfort of use. Increased vibration emission can lead to accelerated wear of the vehicle's structural elements. This is confirmed by the research presented in numerous scientific papers aimed at finding possibilities of reducing the vibration activity of the gearboxes [13-18]. Furthermore, vibrations and the associated noise generated by means of transport also affect the environment in which the means of transport is used. Noise generated by means of transport is one of the dominant sources of environmental noise pollution [19, 20]. High noise levels in the area of the transport mean structure and its surroundings have a significant and negative impact on the health of passengers and people in the immediate surroundings [21].

One of the directions of research aimed at reducing vibrations of an operating gearbox is the modification of the internal structure of gears and attempts to use new (in the context of gears) materials and methods of their production. The patent [22] presents a modification of the internal structure of the gear in order to limit the propagation of vibrations from the meshing zone to the remaining gearbox elements. The effectiveness of this solution is confirmed by the research results presented in [23]. It is worth noting that in the case of the gear internal structure modification and the use of different construction materials, the accuracy of manufacturing is of great importance in the context of the operation of the gear. The papers [24-27] present, among others, research devoted to the production of gears using additive methods. The use of additive methods enables the use of new materials, as well as more free shaping of the internal structure of the gears in order to modify its mechanical properties and dynamic characteristics. In the case of gears made using this type of manufacturing method, the issue of gear manufacturing accuracy is often a priority research area [28-31].

The issue of the accuracy of gear manufacturing, both in the case of well-known machining methods and intensively developed additive methods, is a significant research problem. Despite the use of identical parameters during the gear manufacturing process, there is a probability of obtaining significant differences in selected geometric dimensions in relation to the adopted nominal dimensions, which affects the running-in period and the proper operation of the gearbox, even in the case of assigning the gear to a given manufacturing accuracy class. The continuous development of measurement techniques and methods allows for an in-depth assessment of deviations in the execution of selected geometric parameters of a given gear. This paper presents selected measurement results of geometric dimensions of 4 pinions and 4 gears that were subjected to running-in in the same gearbox. To measure the geometric dimensions of the gears, a stand from Klingelnberg GmbH was used together with the software provided by the manufacturer of the measuring machine. The analysis of the obtained test results showed significant differences in selected geometric dimensions of the tested gears manufactured for the same assumed nominal dimensions, exceeding the range of the manufacturing accuracy class to which they were assigned.

2. DESCRIPTION OF THE TEST STAND AND CONDUCTED RESEARCH

The production of gears, as in the case of many other machine parts, is burdened with inaccuracies resulting from, for example, the technological limitations of the production process or the quality of the tools and devices used. The mentioned gear deviations affect the operation of the gearbox. Their complete elimination of these deviations is difficult to achieve and highly unprofitable considering the manufacturing costs, especially in the case of mass production. In order to precisely describe a given gear, measurements of various deviations are made, the descriptions of which are included in the appropriate DIN standards. Based on them, it is possible to determine the accuracy class of the gear for many geometrical quantities describing the precision of the gear meshing shape. The DIN standards describing the deviations for gears with straight and helical teeth are listed in the table below.

Tab. 1

List of valid DIN standards for gears and gearboxes

Standard designation	**Description of DIN standard**
DIN 3960	Definitions and parameters for cylindrical gears and cylindrical pair with involute teeth
DIN 3961	Tolerances for cylindrical gear teeth
DIN 3962 part 1	Tolerances for cylindrical gear teeth; tolerances for deviations of individual parameters
DIN 3962 part 2	Tolerances for cylindrical gear teeth; tolerances for tooth trace deviations
DIN 3962 part 3	Tolerances for cylindrical gear teeth; tolerances for pitch-span deviations
DIN 3963	Tolerances for cylindrical gear teeth; tolerances for working deviations
DIN 3964	Centre distance allowances and shaft position tolerances of housing for cylindrical gear transmissions
DIN 3967	System of gear fits, backlash, tooth thickness allowances and tooth thickness tolerances; bases, calculation of tooth thickness allowances, conversion of allowances for the different measuring methods

To measure selected geometrical parameters of the tested pinions and gears specialist measuring equipment and software designed for testing the geometrical dimensions of gears from Klingelnberg GmbH, located in the laboratory of the Rzeszów University of Technology – Department of Machine Design, were used. The test stand enabled measurement of selected geometric parameters of the tested pinions and gears with an accuracy of 0.1 μm.

Fig. 2. Klingelnberg GmbH test stand used during measurement of selected geometrical parameters

The measurements were taken for 4 selected pinions and 4 gears, which were made using the same dimensions and nominal settings. Then the tested pinions and gears were run-in in the same gearbox. Selected parameters of the tested pinions and gears are presented in table 2.

Tab. 2

List of selected parameters of tested pinions and gears

Parameter	**Value of parameter**
Number of teeth z_1 - pinions	16
Number of teeth z_2 - gears	24
Module m_n	4,5 mm
Helix angle β	0°
Face width b	20 mm
Center distance a_w	91,5 mm
Profile shift coefficient - pinions	0,864
Profile shift coefficient - gears	-0,5

For each pinion and gear, the measurement of the same 3 teeth was performed, during which the right and left tooth face were tested, which means 18 different gears in terms of deviations in the production of the tooth sides. For each gear measurements were taken, in the case of the pinions - teeth numbers: 1, 7 and 12, and in the case of the gears - teeth numbers 1, 9, 17. An example measurement report is shown in figure 3.

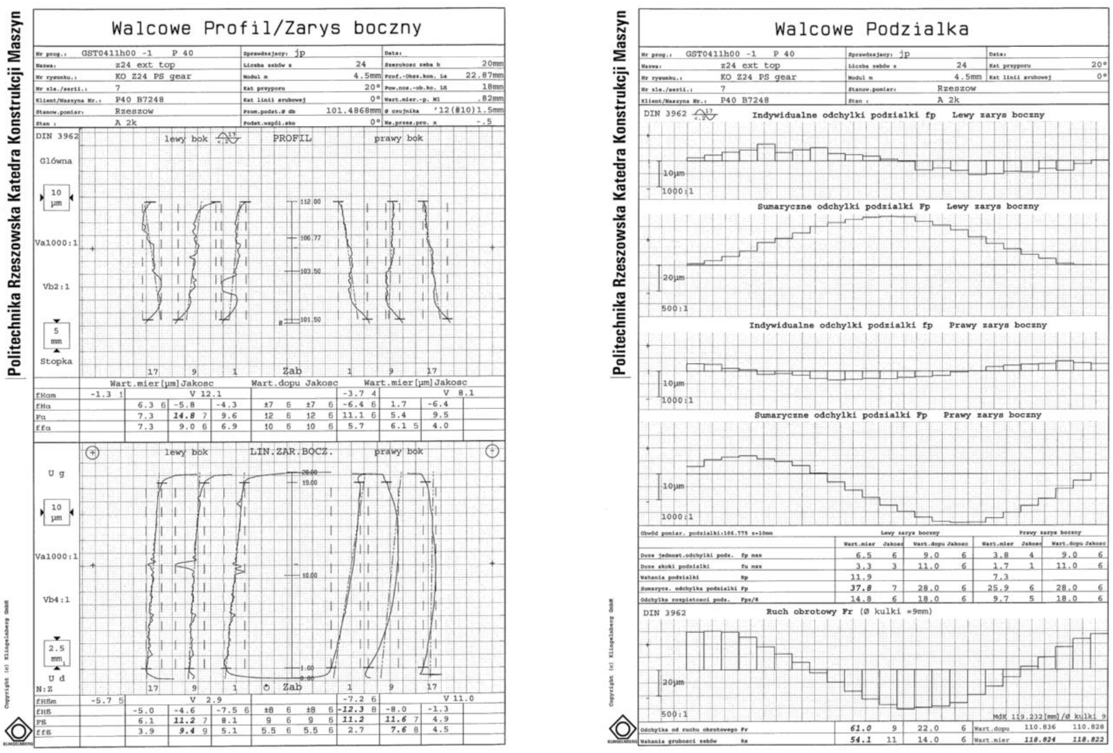

Fig. 3. An example measurement report obtained for gear number 1 (G_1)

During the measurements, the values of selected deviations were checked, which have a significant impact on the operation of the gearbox, and in particular the operation of the meshing, which is an important area from the point of view of vibrations and noise generated by the transmission. The measurement of geometric parameters of pinions and gears was performed according to the recommendations presented in the standards DIN 3960 – DIN 3964 and DIN 3967.

3. ANALYSIS AND DISCUSSION OF OBTAINED MEASUREMENT RESULTS

This chapter presents selected measurement results of geometric parameters of the tested pinions (P_1 – P_4) and gears (G_1 – G_4). The following parameters (in accordance with DIN 3960 – DIN 3964 and DIN 3967 standards) were selected for further analysis, as they have a significant impact on the operation and vibration generation of the gearbox:

- F_f - total profile deviation,
- F_β - tooth trace total deviation,
- F_p - total/cumulative pitch deviation,
- F_r - concentricity deviation,
- R_s - tooth thickness fluctuation.

For each analyzed parameter, its minimum value (*min.*), maximum value (*max.*), arithmetic mean ($\bar{X}$) and standard deviation (σ) were determined. Additionally, the coefficient of variation (*CV*) value was also calculated.

3.1. Analysis of F_f and F_β measurement results

The graphs in fig. 4 and 5 show the measured minimum and maximum values, as well as the calculated values of the arithmetic mean ($\bar{X}$) and standard deviation (σ) of the measurement results of the parameters F_f and F_β for tested pinions (fig. 4 and 5 – a), c), e), g)) and tested gears (fig. 4 i 5 – b), d), f), h)).

Additionally, the coefficient of variation (*CV*) of the measured parameters F_f and F_β was also calculated. The calculated coefficient of variation (*CV*) values are shown in fig. 6.

Based on the analysis of the measured minimum and maximum values presented in the graphs in Fig. 4 and 5, as well as the calculated values of the arithmetic mean ($\bar{X}$) and the standard deviation (σ) of the parameters F_f and F_β, it was demonstrated that both for the tested pinions and the tested gears there are significant changes in the above-mentioned parameters. The scale of changes was presented graphically as the area of a quadrangle whose vertices were created in the coordinate system based on the measured and calculated values of the above-mentioned parameters F_f and F_β.

In order to extend the analysis of the obtained results, the coefficient of variation was also calculated for each tested pinion and gear wheel, and the obtained values of the above-mentioned coefficient are presented in the graphs in Fig. 6. Based on the calculated values of the *CV* coefficient, it was shown that in the case of the tested pinions (P_1 – P_4), the highest variability of the measured parameter F_f was observed for pinion no. 3 (P_3; $CV\_ F_f$ = 23%), while the highest variability of the measured parameter F_β was observed for pinion no. 1 (P_1; $CV\_ F_\beta$ = 38%). In the case of the tested pinions, the range of changes in the $CV\_ F_f$ coefficient was 6 percentage points, and each calculated value was lower than 25%, which indicates a low variability of the parameter [32]. For the tested pinions and the F_β parameter, the range of changes in the CV_F_β coefficient was 26 percentage points, and for pinion no. 1 (P_1) it reached the value of 38%, which indicates an average variability of the parameter [32]. In the case of the tested gears (G_1 – G_4), the highest variability of the measured parameter F_f was observed for gear no. 3 (G_3; CV_F_f = 43%), while the highest variability of the measured parameter F_β was observed for gears no. 1 and 3 (G_1 and G_3; CV_F_β = 30%). The range of changes in the CV_F_f coefficient was 33 percentage points, and in the case of 3 tested gears (G_1, G_2, G_3) this value was higher than 25%, which indicates an average variability of the parameter [32]. However, in the case of the tested gears and the F_β parameter, the range of changes in the CV_F_β coefficient was 15 percentage points and also in the case of 3 tested gears (G_1, G_3, G_4) this value was higher than 25%, which indicates an average variability of the parameter [32]. For tested pinion P_1 and gears (G_1-G_4), the analysis of the results of the parameters F_f and F_β showed an average variability of these parameters. It is also worth noting that in the case of several tested pinions and gears, significant variability of one parameter is not associated with comparable variability of the second analyzed parameter (P_1, G_2, G_4) despite their assignment to the same manufacturing accuracy class.

3.2. Analysis of F_p, F_r and R_s measurement results

The graphs in Fig. 7, 8 and 9 show the measured values as well as the calculated values of the arithmetic mean ($\bar{X}$) and the standard deviation (σ) of the measurement results of the parameters F_p, F_r and R_s for the tested pinions and gears. Additionally, *CV* coefficient was also calculated for the analyzed parameters.

Based on the analysis of the measured values of the parameters F_p, F_r and R_s presented in the graphs in figs. 7-9, as well as the calculated values of the arithmetic mean ($\bar{X}$) and standard deviation (σ) of the mentioned parameters, it was shown that both for the tested pinions and the tested gears there are significant changes in the values of the above-mentioned parameters. In the case of the F_p parameter defining the cumulative pitch deviation and the measured pinions, the difference between the measured maximum and minimum values was 31.2 μm, while for the measured gears it was 66 μm. In these cases, the calculated values of the standard deviation (σ) were as high as 31 μm (pinions) and 29.24 μm (gears), and the calculated values of the *CV* coefficient were 91% and 98%, respectively. This means that the measured parameter F_p was characterized by strong variability [32]. This is particularly important due to the fact that pitch deviations significantly influence changes in the values of dynamic forces in the meshing, contributing to increased vibration emission from the gear meshing area.

Additionally, the measured values of the parameters F_r and R_s defining the concentricity deviation and tooth thickness fluctuation were analyzed. In the case of both of these parameters and the measured pinions and gears, high values of the standard deviation (σ) were obtained in relation to the calculated arithmetic mean value ($\bar{X}$) as shown in fig. 8 b) and fig. 9 b). Moreover, an extended analysis of the obtained values showed that the calculated *CV* coefficient values were as follows: for the tested pinions 90% and 82%, while for the tested gears 106% and 111% respectively. The presented calculated *CV* coefficient values indicate strong variability in the case of the tested pinions and very strong variability in the case of the tested gears [32].

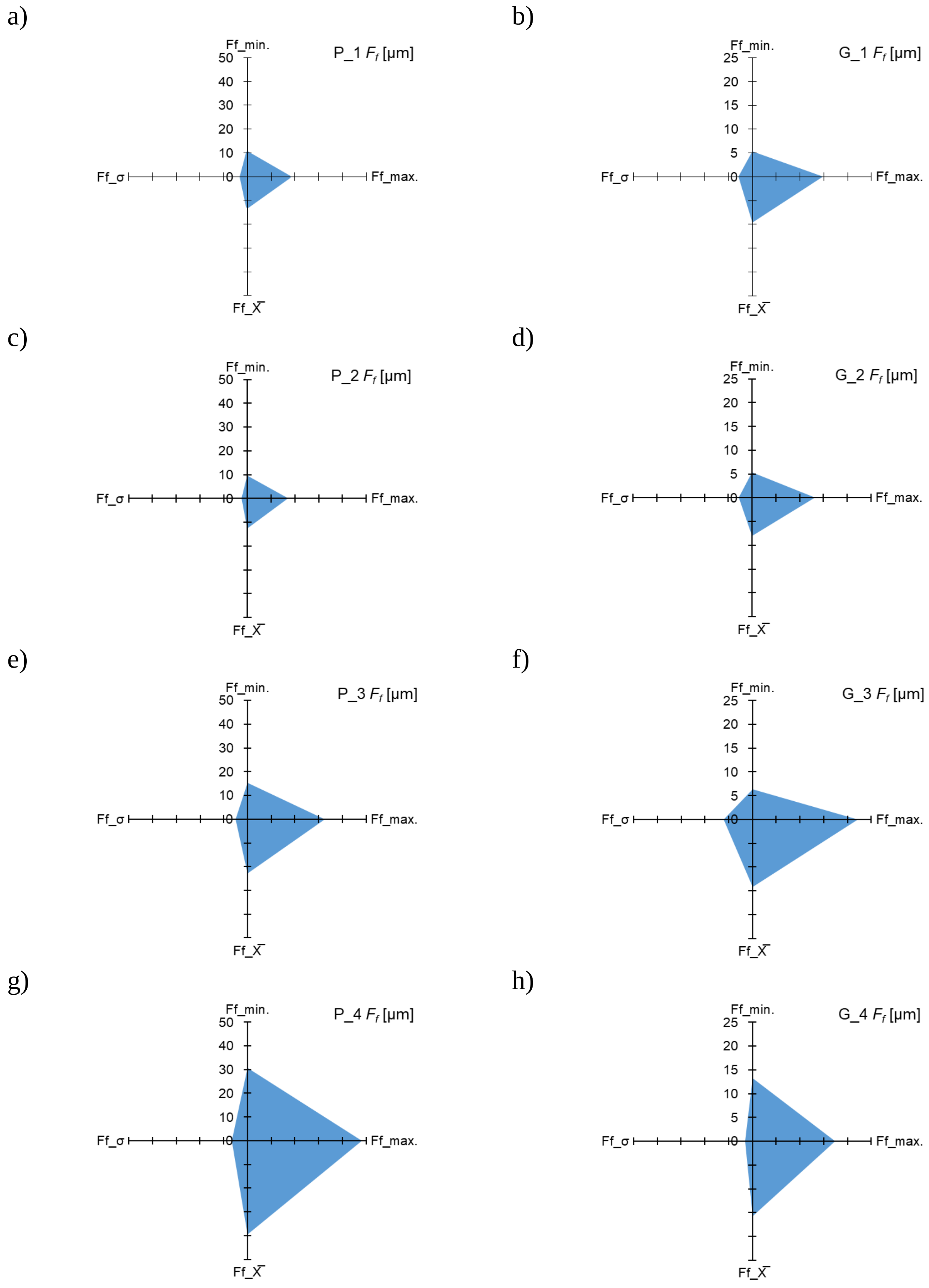

Fig. 4. Measured and calculated values of F_f parameter for: tested pinions – a), c), e), g); tested gears – b), d), f), h)

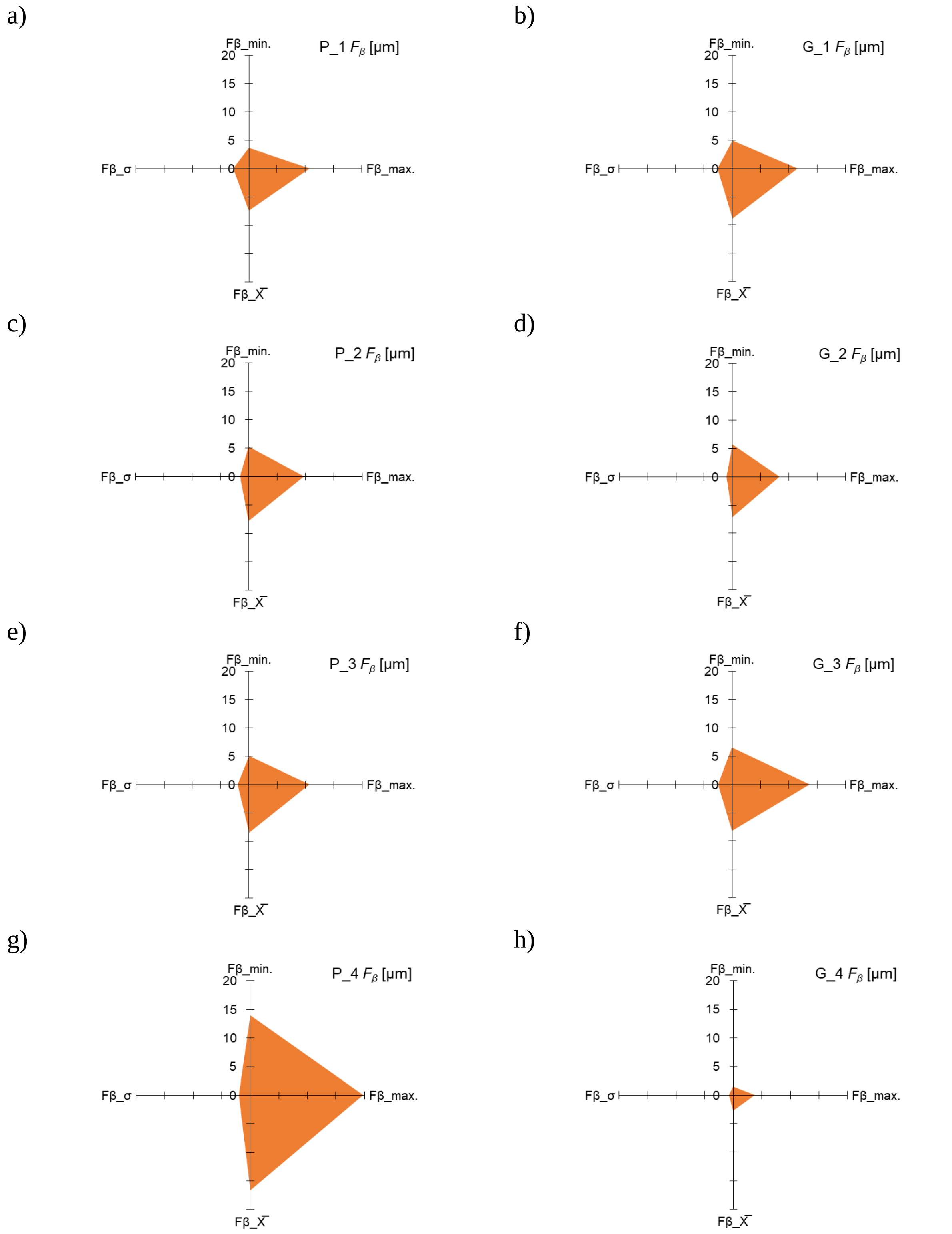

Fig. 5. Measured and calculated values of F_β parameter for tested pinions – a), c), e), g); tested gears – b), d), f), h)

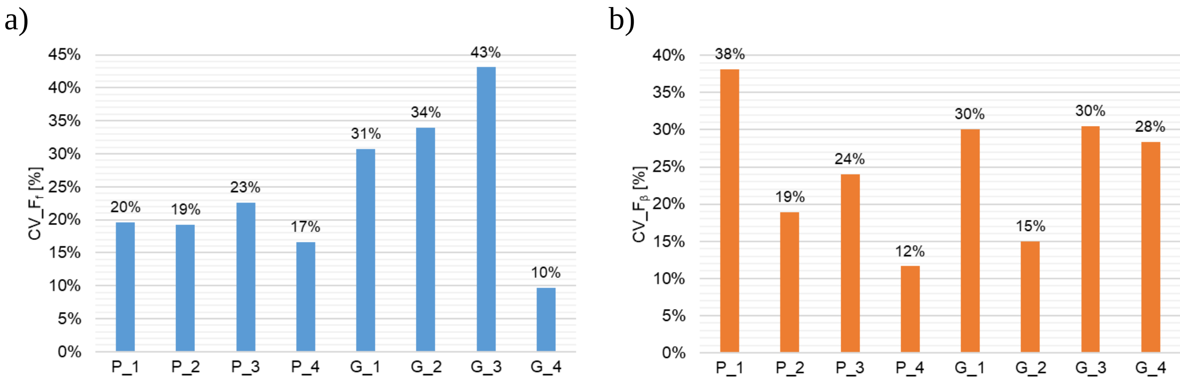

Fig. 6. Calculated values of *CV* parameter for all tested pinions and tested gears: a) in case of F_f parameter, b) a) in case of F_β parameter

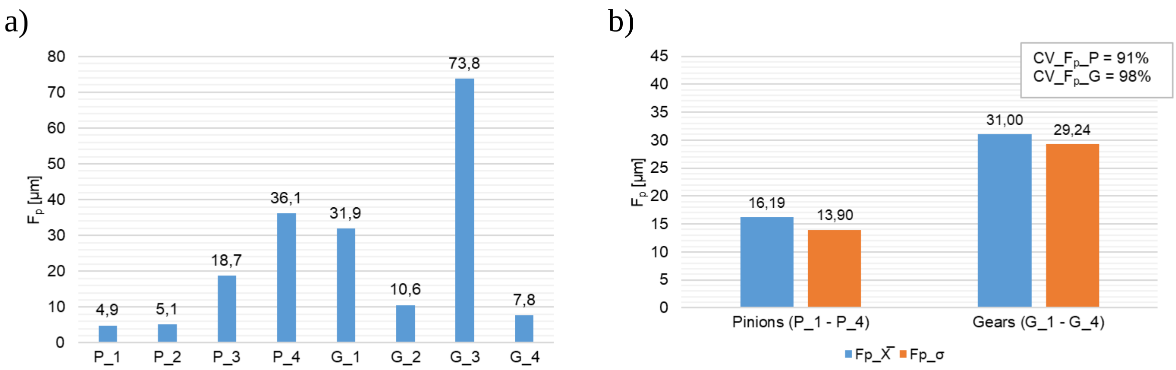

Fig. 7. Measured and calculated values of F_p parameter for the tested pinions and gears: a) measured values of F_p, b) calculated values of mean ($\bar{X}$), standard deviation (σ) and coefficient of variation (*CV*)

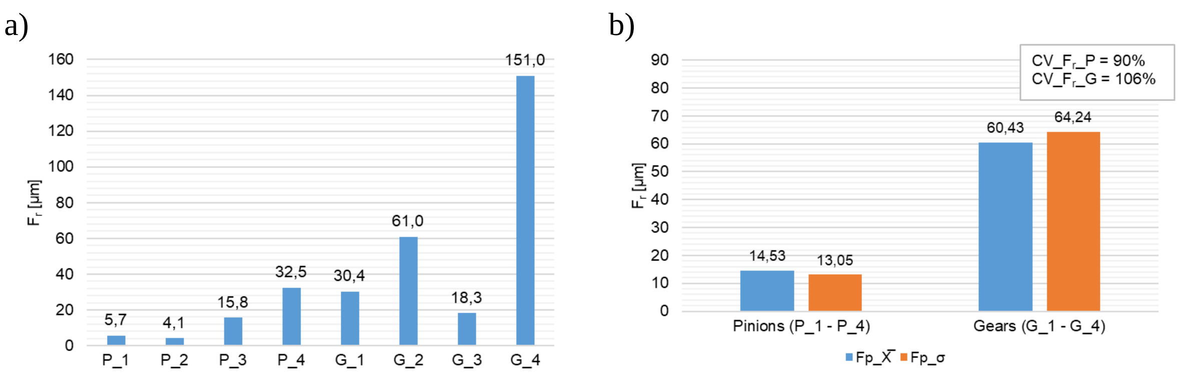

Fig. 8. Measured and calculated values of F_r parameter for the tested pinions and gears: a) measured values of F_r, b) calculated values of mean ($\bar{X}$), standard deviation (σ) and coefficient of variation (*CV*)

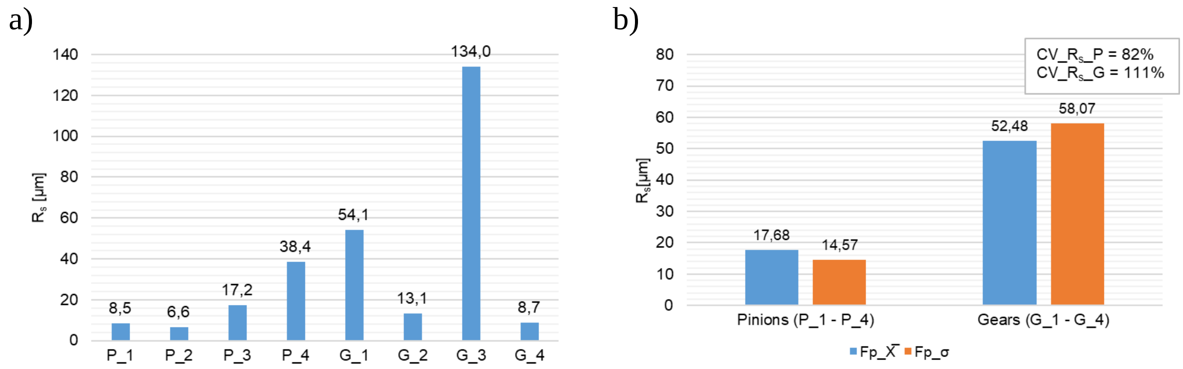

Fig. 9. Measured and calculated values of the R_s parameter for the tested pinions and gears: a) measured values of R_s, b) calculated values of mean ($\bar{X}$), standard deviation (σ) and coefficient of variation (CV)

4. CONCLUSION

The presented results and their analysis showed that in the case of gears production, maintaining similar geometric values of selected parameters despite adopting the same nominal dimensions is a complex issue. This phenomenon of significant variability of selected geometric parameters of gears is an additional factor influencing the emission of vibrations and noise of the operating gearbox. In the case of drive systems used in various means of transport, excessive variability (often exceeding the adopted manufacturing accuracy class) of the selected geometric parameter may significantly contribute to an undesirable increase in vibration and noise emissions affecting the entire structure of a given means of transport and its users.

In the case of the tested pinions, it was shown that despite the adoption of the same nominal dimensions, selected measured deviations in many of the analyzed cases showed significant differences. For the analysis of the measurement results of the F_β parameter, the highest value of the coefficient of variation CV was obtained for pinion no. 1 (P_1). In the case of the F_f parameter, the calculated values were similar. Significant differences in the tested group of pinions were noted for the parameters F_p, F_r and R_s. The obtained values of the coefficient of variation CV were 91%, 90% and 82%, respectively (fig. 7-9) and they indicate a strong variability of the above parameters.

In the case of the tested gears, it was shown that even despite adopting the same nominal dimensions, the selected manufacturing deviations of the measured gears in many of the analyzed cases showed significant differences. For the analysis of the measurement results of the F_f parameter, the highest coefficient of variation CV value was obtained for gear no. 3 (G_3), while the highest coefficient of variation CV values for the F_f parameter were calculated for gears no. 1 and 3 (G_1 and G_3). Significant differences in the tested group of gears were noted for the parameters F_p, F_r and R_s. The obtained values of the coefficient of variation CV were 98%, 106% and 11%, respectively (fig. 7-9) and indicate strong and very strong variability of the above-mentioned parameters.

The commonly used system for assessing the manufacturing accuracy of gears using manufacturing accuracy classes may not adequately reflect the actual deviations of a given gear. A gear specimen that has been assigned a general class of high manufacturing accuracy may be characterized by deviations in the context of selected parameters from a range of several classes worse than the above-mentioned assigned class. In such situation, some of the measured pinions and gears may be classified as so-called outlier cases. This phenomenon was observed, for example, for the tested pinion (P_3) and gears (G_3 and G_4). The use of such gears in a gearbox which is an element of the drive system of any means of transport may result in the generation of increased vibrations and noise. As a result, the reliability of the drive system used in the construction of a given means of transport may be reduced, and its service life may be shortened due to accelerated wear. In addition, increased vibration and noise emissions significantly reduce the comfort of using a given means of transport, affecting, among others, passengers and the immediate surroundings. In order to reduce vibrations and noise generated during the use of means of transport, it is recommended to carry out an extended analysis of selected manufacturing deviations of gears used in gearboxes intended for application in transport means drive systems.

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