Analysis of Dimensional Tolerances on Hydraulic and Acoustic Properties of a New Type of Prototypal Gear Pumps

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Received: 30 September 2020; Accepted: 24 November 2020; Published: 29 November 2020

Abstract: This study focuses on the construction of a prototype series of pumps. The technological capabilities of the entire series of gear pumps with a three-poly-involute outline were determined. We developed neural networks to analyze the dimensional tolerance and composition of the pump components and impact on the distribution for the constructed units. The most crucial dimensions to control were then determined—namely, dimensional and form tolerance were necessary—with a reduction in accuracy classification where it is less important. Measurements of acoustic quantities and of vibrations were also carried out. In conclusion, after positive verification, printed polyethylene wheels can be manufactured in greater, mass-produced quantities. Optimization techniques can then be applied, leading to reduced manufacturing costs and increased efficiency.

Keywords: prototype pumps; neural networks; optimization; acoustic tests; vibration measurements

1. Introduction

The development of modern pumping units is currently concerned with two trends: the overall efficiency, associated with the minimization of mass, durability, reliability, vibrations, and pump performance, as well as decreasing the noise emission. Working pressures in the hydrostatic system determine the pumping efficiency of the entire installation. In modern machines and devices with a hydrostatic drive, one can observe a tendency to increase the pressure of displacement at the expense of a reduced flow rate for the working medium. The flow rate significantly affects the hydraulic losses occurring in local ducts and at points of resistance.

Modern manufacturing technique gear pump designs have attained an efficiency of around 80–90% within a range of pressures up to 28 MPa. An important reason for such a wide range is the tolerance achieved by different production techniques [1–5]. Another important aspect is the pressure of pulsation and variable dynamic load, which are a main reason for the creation of sound-associated vibrations. The noise in hydrostatic drives is one of the most important issues determining the area of their application and the possibility for further improvement in regard to the reduction of consumable lubricants, etc. via the possibility of using new and innovative low-friction materials in hydrostatic drives. Where striving to minimize their use is aimed at improving the power-to-weight ratio. As a result, minimization and, then, through a process of optimization, small structures are achieved while maintaining optimal hydraulic parameters [6–8].
1.1. Development of Gear Unit Design

The development of a gear unit design tends to desire a reduction of performance pulsation, which may be the reason for: an improper operation of control elements, vibrations, and increased noise of machines and devices with hydrostatic drive. Ear units with an external toothing are characterized by a coefficient of unevenness in efficiency at an average level of approx. 18%. Compared to other positive displacement units, gear pumps have the highest pulsation rates. The most effective method of pulsation reduction is obtained as a result of using the active method, i.e., by mitigating the course of the instantaneous performance function and by reducing the amplitude of the pulsation of efficiency transmitted to the hydraulic system. The second important direction of gear pumps development is the minimization of energy losses and increase of transmitted power; thus, the tendency of any changes is aimed at increasing the energy efficiency of the generator even more.

The analysis of numerous patents, literary sources, and other currently manufactured gear units could indicate that technical methods have already been exhausted to ensure the optimal internal tightness with maximum operating pressures, minimum efficiency pulsation, and noise emissions [7-14]. The conducted tests and considerations prevent achieving peak operational parameters by comparisons to modern gear units.

Therefore, new tasks and goals have been set, one of which is presented and discussed in this article. Two basic goals set in this prototype gear pump research are: to present theoretical possibilities, as well as methods, to reduce performance pulsation and, then, to propose new design solutions to increase working pressures while ensuring high internal tightness. These tasks required solving several technological, design, and manufacturing problems. As a result, innovative design solutions were proposed to reduce the performance pulsation, increase the working pressure, and improve the volumetric and total efficiency, as well as reducing the noise emission to the environment. Eight patents, including copyrights, were filed during this research, with much time having also been devoted to the cognitive aspects. New mathematical models describing, among others, the bearing and gear wheel loads for new methods of compensation of clearance, the determination of presented stresses for compensating elements, relief of sealed space, shaping tooth contours, or performance pulsation modeling. The theoretical considerations carried out were verified by numerous acoustic and hydraulic tests.

There are many research efforts and production methods concerned with and regarding the design of pump profiles only to be used in gear units. It is instigated mainly by striving for better hydraulic and acoustic properties [15-19]. This is the next part of the article related to the identification of sensitive dimensions of the importance of measuring points. The tests were carried out for four pump prototype units: 1PWR, 2PWR, 3PWR, and 2PW-SEW. The results were compared with a conventional pump to determine the impact of the proposed innovative design solutions.

For example, in the work described in [19], the identification of sensitive control dimensions (value/tolerance) of examined pumps (3PWR-SE) was determined by means of the multi-valued logic trees.

In the present work, a neural network is used to analyze the dimensional tolerance and the impact of the performance of prototype 2PW-SE [15,20] gear pump components on the overall performance. Optimization then minimized the acoustic noise and vibration. In addition, the theoretical considerations and experimental results presented here open new possibilities for gear pumps.

1.2. Basics of Gear Pump Design

Considering the recommended sizes when designing a gear pump-specific performance, determined by Renard [17], the technology in manufacturing, the availability of manufacturing machinery, and the resulting restrictions are related to the standardization of machining tools, e.g., with a specific module, buttress angle, tooth height coefficient, and others. Tool cutting teeth are among the most complex and expensive. An important aspect is the correct selection of the cutting-edge contour, including the subsequent regeneration of this edge in the sharpening process. The
accuracy of machined wheels depends on this, which is the basic condition for the mass production of gears. At the design stage, in addition to the production technology, the design should assume the correct operating conditions. Newly designed units should be adapted to the working fluids used in typical hydraulic systems.

The original pump tested was a conventional unit, manufactured by the Wytwórni Pomp Hydraulicznych Sp. z o. o. located in Wrocław, Poland. The experimental pump was designed for the technological capabilities of WPH S.A., where this specific pump has been studied many times, and the results are published within the scientific literature [1,18,20].

The newly designed and realized prototype pump is a three-plate structure shown schematically in Figure 1. The front plate (1) is used for mounting the pump on the drive unit. The middle plate (2) contains gear wheels, slide bearing housings, and suction and forcing holes for connecting to a hydraulic system. The whole construction is closed with a rear plate (3).

![Three-plate design of a gear micropump with external meshing](image)

**Figure 1.** Three-plate design of a gear micropump with external meshing: (a) total view; (b)1—front (mounting) plate, 2—middle (rest) plate, 3—rear plate, 4—driving shaft.

The main meshing parameters for the pump with a unit delivery \( q = 40 \, \text{cm}^3 \) are listed in Table 1.

| Parameter              | Symbol | Unit | Value |
|------------------------|--------|------|-------|
| Number of teeth        | \( z \) | -    | 9     |
| Modulus                | \( m_0 \) | (mm) | 4.5   |
| Pressure angle         | \( \alpha \) | [°]  | 20    |
| Gear wheel width       | \( b \) | (mm) | 32.2  |

The original pump had gears for both active and passive rollers with an involute (or cycloid) outline, and wheels with or without side clearance were considered.
2. Optimization of the Technology of Poly-Involutedly Shaped Pump Construction

To obtain longevity in the accuracy of manufactured tolerances at the micrometer level, a whole series of errors should be continuously checked and compensated for, the kinematic and geometric errors caused by cutting forces of the accepted machining parameters. These errors can be significantly reduced, but they cannot be entirely eliminated. Currently, increasing the accuracy of machine tools is carried out by implementing new design and software solutions, applying error correction and compensation.

In the process of innovation, the involute profile was modified at its bottom by the so-called fillet. The modification was done by means of a cutting tool with protuberance or by the appropriate correction of teeth. This type of analysis was presented in a number of co-authored works, e.g., [1,18,20].

The improved pump model included two modifications:

The outline of the tooth was optimized using multi-valued logic trees. The optimization process was carried out considering five basic criteria: technology of the tool, minimum compression ratio, small changes in dynamic forces on the cavity, minimum efficiency of the pulsation coefficient, and high energy efficiency. From the viewpoint of the accepted criteria, a type X1 profile was selected among the several alternative combinations of the three-involute outlines. The profile selected through the optimization process was characterized by the occurrence of two ordinary involutes and one elongated involute. Such a procedure was described in the work described in [1,18,20]. The optimization of the contour of the polyevolvent tooth was made taking into account multi-valued logical trees. The main focus was on the values of the pressure angle between the pressure section and the tangent line to the rolling wheels at the rolling point as the most important evolvent parameter.

Taking into account the technological performance, it was assumed that the contour of the polyevolvent tooth will be made of three basic evolvents. With two ordinary evolvents and one elongated evolvent or three ordinary evolvents. The optimization process was performed in two stages. In the first step, multiple sets of profiles were analyzed, and then, five types of profiles were selected for the final step:

X1, X2, X3, X4, and X5, where for:

X1: Ordinary evolvent: $\alpha_1 > \alpha_2$ | Ordinary evolvent: $\alpha_2 = 20^\circ$ | Elongated evolvent
X2: Ordinary evolvent: $\alpha_1 < \alpha_2$ | Ordinary evolvent: $\alpha_2 = 20^\circ$ | Elongated evolvent
X3: Ordinary evolvent: $\alpha_1 > \alpha_2$ | Ordinary evolvent: $\alpha_2 = 20^\circ$ | Ordinary evolvent: $\alpha_1 < \alpha_2$
X4: Ordinary evolvent: $\alpha_1 < \alpha_2$ | Ordinary evolvent: $\alpha_2 = 20^\circ$ | Ordinary evolvent: $\alpha_1 > \alpha_2$
X5: Ordinary evolvent: $\alpha_1 < \alpha_2$ | Ordinary evolvent: $\alpha_2 = 20^\circ$ | Ordinary evolvent: $\alpha_1 < \alpha_2$

The determined effect can be obtained by rounding or chamfering the upper part of the outline (Figure 2). Such a solution is protected by a co-authoring patent. The upper ordinary involute in the polyevolvent contour is a modification of the vertex contour with respect to conventional constructions. The advantage of this solution is the maintenance of the same diameters inside the pump body. Figure 3 shows a polyevolvent outline cut with a trapezoidal rack.
Figure 2. Incision of an additional ordinary involute in the area of the apex: (a) front view and (b) axometric projection of the active gear: 1—active gear, 2—passive gear, and 3—additional upper ordinary involute [15].

Figure 3. Polyevolvent outline cut with a trapezoidal rack with the following curves: from W to P—ordinary involute, from P to T—elongated involute, from T to S-curve cut by the rounded edge of the tool [15].
The literary and patent analysis of existing solutions offered by gear pump manufacturers showed the absence of a design with three-involute, oblique outline cuts and made with a backlash-free technology. Therefore, the developed design was submitted to the Patent Office of the Republic of Poland to ensure the protection of the intellectual property.

Subsequently, the technology for making new outline gear teeth was developed. Before making the wheels, the kinematics of the optimized three-involute mesh was studied for gear wheels fabricated using 3D technology. The model gear wheels shown in Figure 4a were the equivalent of the group II pump with a unit output of $q = 8\text{cm}^3/\text{rpm}$. After positive verification of polyethylene-printed wheels, the fabrication process commenced in commercial industrial conditions, where the surface of the three-involute outline was manufactured by ground and chip technologies (Figure 4b).

![Figure 4.](image1)

**Figure 4.** (a) wheels manufactured in commercial industrial conditions; (b) tri-involute wheels fabricated using 3D printing technology [1,15,18,19].

The second modification was optimization of the machining technology for components affecting the overall efficiency of the newly designed unit (a topic discussed in this article). The dimensional analysis and shape tolerances of the fully realized gear wheels enabled the selection of the following groups of the control dimensions: critical, important, and non-important. This resulted in a rational narrowing for the tolerances of the manufactured shapes and dimensions where necessary by lowering of the required class of accuracy in spaces of less importance. Optimization of manufacturing technology helped to cut production costs and to increase productivity.

2.1. The Research Object

The research concerns the development of a prototype gear pump from the 2PW-SEW series belonging to group II. The pump was designed by a HYDROTOR S.A. Pumps prototype entirely executed by the company HYDROTOR S.A., Tuchola, Poland. All 10 tested pumps have the model number 2PW-SEW-08-28-2-776 and a serial number (from 1 to 10). The efficiency of each model pump is $8 \text{ cm}^3/\text{rev}$.

Figure 5 exploded the views of the 2PW-SEW prototype gear pump.
Ten pumps were studied (with serial numbers No.1–No.10). The hydraulic tests included:
- determination of the actual efficiency of the gear pump $Q_\text{rz} = f(p_t)$ and
- determination of the torque $M = f(p_t)$.

The following hydraulic measurements were determined: volumetric efficiency characteristic $\eta_{\text{vol}}$, total efficiency $\eta_c$, hydraulic-mechanical efficiency $\eta_{\text{hm}}$, and delivered power $N$.

Hydraulic tests were carried out for all ten pump units, while two 2PW-SEW-08-28-2-776 gear units (serial numbers: No. 2 and No. 4) were selected for comprehensive acoustic tests.

3. Measuring Rig

Static characteristics were determined on the test stand shown in Figure 6. In this system, the tested pump 1 is driven by a 100-kW DC motor 2 cooperating with the territorial control system. The DC motor Pxob-94a and the territorial control system type DSI-0360/MN-503 enable smooth changes of the pump speed in the range from 0 to 2000 rpm. Figure 7 shows a block diagram of the measuring path.
with electrical visual signaling; 13 and 14—manovacuometer; 15—pressure gauge; 16—flowmeter with microammeter; 17—measuring microphone; 18—sound chamber; 19—measuring shaft, and 20—tank; (b) view of the test rig.

**Figure 7.** A block diagram of a measurement path: (a) flow and (b) the torque on the shaft of the pump. BO—the test object: hydraulic gear pump, PT1—turbine flow meter type HO3/4x5/8-1,75-16 f-my Hoffer, PT2—turbine flow meter type HO3/4x5/8-2,5-29 f-my Hoffer, UL—universal counter MINItrol type E S730 DRT f-my KEP, MO—measuring shaftMT1000 Nm nr05/04 f-my SENSOR AT, and IN—interface BETA2000 nr05/03 f-my SENSOR AT.

Tables 2 and 3 present the values of total efficiency for model pumps 2PW-SEW-08-28-2-776 at the discharge pressure \( p_t \) [MPa] for the example rotational speed \( n = 500 \) (rev/min) and \( n = 2000 \) (rev/min) [20].

**Table 2.** Tested gear pumps for \( n = 500 \) (rev/min) [20]. \( P_t \): discharge pressure.

| No. | \( p_t \) (MPa) | \( n \) (min\(^{-1}\)) | 2PW No. 1 | 2PW No. 2 | 2PW No. 3 | 2PW No. 4 | 2PW No. 5 | 2PW No. 6 | 2PW No. 7 | 2PW No. 8 | 2PW No. 9 | 2PW No. 10 |
|-----|----------------|-------------------------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|
| 1   | 0              | 0                       | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0         | 0         |
| 2   | 2              | 92.0                    | 96.3     | 99.9     | 95.8     | 98.9     | 96.3     | 99.4     | 97.8     | 99.4     | 98.9      | 98.9      |
| 3   | 4              | 97.8                    | 96.9     | 98.1     | 96.2     | 96.8     | 97.6     | 96.4     | 95.0     | 95.4     | 96.6      | 96.6      |
| 4   | 6              | 94.8                    | 96.5     | 96.1     | 94.3     | 92.3     | 95.0     | 93.6     | 92.2     | 93.1     | 93.0      | 93.0      |
| 5   | 8              | 91.9                    | 93.3     | 92.8     | 89.2     | 90.8     | 90.3     | 92.6     | 89.0     | 84.8     | 89.3      | 89.3      |
| 6   | 10             | 91.4                    | 89.3     | 90.2     | 84.0     | 85.7     | 87.5     | 89.1     | 85.7     | 82.0     | 85.2      | 85.2      |
| 7   | 12             | 88.6                    | 88.7     | 89.7     | 79.1     | 83.8     | 84.1     | 86.0     | 82.8     | 80.8     | 83.6      | 83.6      |
| 8   | 14             | 89.2                    | 88.9     | 87.0     | 75.0     | 83.2     | 84.3     | 84.7     | 80.7     | 77.9     | 80.4      | 80.4      |
| 9   | 16             | 88.2                    | 86.6     | 84.4     | 72.3     | 80.3     | 81.1     | 83.8     | 79.1     | 76.7     | 77.0      | 77.0      |
| 10  | 18             | 85.8                    | 86.3     | 82.8     | 68.8     | 77.8     | 78.7     | 81.2     | 76.6     | 75.2     | 73.8      | 73.8      |
| 11  | 20             | 83.7                    | 84.3     | 80.2     | 66.4     | 74.3     | 75.3     | 77.9     | 73.8     | 73.9      | 69.4      | 69.4      |
| 12  | 22             | 81.0                    | 82.0     | 78.0     | 63.1     | 71.7     | 72.2     | 75.1     | 70.5     | 71.9      | 64.2      | 64.2      |
| 13  | 24             | 78.5                    | 78.8     | 74.3     | 59.3     | 67.3     | 68.4     | 72.3     | 66.8     | 69.5      | 58.3      | 58.3      |
| 14  | 26             | 71.8                    | 73.8     | 67.3     | 55.1     | 59.9     | 59.8     | 65.1     | 61.0     | 64.0      | 49.2      | 49.2      |
| 15  | 28             | 69.1                    | 74.3     | 64.8     | 54.2     | 54.1     | 54.0     | 63.4     | 58.1     | 62.6      | 40.0      | 40.0      |
| 16  | 30             | 61.5                    | 68.7     | 57.2     | 49.4     | 43.9     | 41.5     | 54.5     | 52.2     | 57.0      | 27.8      | 27.8      |
| 17  | 32             | 47.1                    | 60.6     | 49.1     | 45.6     | 29.0     | 24.2     | 41.9     | 41.9     | 50.2      | 0         | 0         |
Table 3. Tested gear pumps for \( n = 2000 \) (rev/min) [20].

| No. | \( p_t \) (MPa) | \( n \) (min\(^{-1}\)) | 2PW No. 1 | 2PW No. 2 | 2PW No. 3 | 2PW No. 4 | 2PW No. 5 | 2PW No. 6 | 2PW No. 7 | 2PW No. 8 | 2PW No. 9 | 2PW No. 10 |
|-----|----------------|-----------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 1   | 0              | 0               | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| 2   | 2              | 62.1            | 64.1     | 62.1     | 61.0     | 75.3     | 63.7     | 62.5     | 62.1     | 59.1     | 63.7     |
| 3   | 4              | 77.6            | 77.6     | 77.6     | 78.1     | 86.4     | 80.1     | 76.9     | 77.1     | 77.6     | 80.9     |
| 4   | 6              | 81.0            | 81.9     | 82.8     | 82.8     | 89.0     | 83.2     | 80.1     | 81.7     | 80.5     | 84.1     |
| 5   | 8              | 85.1            | 84.2     | 83.7     | 83.8     | 83.7     | 84.6     | 82.1     | 83.3     | 84.4     | 85.3     |
| 6   | 10             | 85.1            | 85.7     | 85.1     | 83.4     | 82.9     | 85.7     | 84.5     | 84.0     | 85.1     | 85.2     |
| 7   | 12             | 85.6            | 85.1     | 84.6     | 83.5     | 87.5     | 84.5     | 85.1     | 84.4     | 84.0     | 84.9     |
| 8   | 14             | 86.3            | 86.0     | 85.8     | 84.7     | 87.5     | 85.6     | 85.4     | 85.0     | 84.3     | 88.1     |
| 9   | 16             | 86.8            | 85.7     | 86.6     | 84.4     | 87.2     | 85.1     | 85.9     | 84.9     | 85.3     | 85.3     |
| 10  | 18             | 87.2            | 85.9     | 86.1     | 84.3     | 87.0     | 85.2     | 85.4     | 85.3     | 84.2     | 85.1     |
| 11  | 20             | 86.4            | 85.1     | 85.6     | 84.1     | 85.4     | 85.6     | 84.4     | 84.7     | 84.4     | 84.8     |
| 12  | 22             | 86.2            | 85.3     | 85.0     | 83.9     | 85.3     | 84.4     | 84.2     | 84.2     | 83.7     | 83.8     |
| 13  | 24             | 84.1            | 84.2     | 85.0     | 83.2     | 82.4     | 83.0     | 83.5     | 84.1     | 83.6     | 82.6     |
| 14  | 26             | 80.1            | 80.8     | 80.8     | 79.3     | 77.9     | 79.2     | 79.7     | 80.3     | 79.4     | 78.3     |
| 15  | 28             | 82.4            | 83.2     | 82.5     | 81.6     | 79.1     | 80.2     | 81.8     | 82.5     | 81.4     | 79.5     |
| 16  | 30             | 81.1            | 81.1     | 81.7     | 79.8     | 74.8     | 77.7     | 79.4     | 80.6     | 79.2     | 76.5     |
| 17  | 32             | 78.4            | 79.7     | 78.5     | 80.4     | 70.2     | 74.2     | 75.9     | 78.4     | 77.5     | 72.7     |

Figure 8 shows a comparison of the total efficiency of the ten gear pumps from Table 2 for a rotational speed of \( n = 500 \) (rev/min).

4. Determination of the Most Important Dimensional Tolerances for 2PW-SEW Pumps Using a Convolution Neural Network

Sensitivity analysis of gear pump control points was carried out as part of the Innovative Operational Program, Priority 1. Research and development of modern technologies, Measure 1.4 Support for targeted projects, project no. POIG.01.04.00-04-345/13. The difference in performance values of the tested pumps is related to the degree of sensitivity regarding the control dimensions.
Four components of the prototype pump were tested: body, active/passive gears, and the bearing set. For each part, an appropriate number of control points are generated corresponding to the control dimension (value/tolerance):

- for gears (active and passive): 17 points,
- for the body (housing): 22 points,
- for a bearing set: 39 points, and
- for the plate: 7 points.

Tables 4–8 show the selected measurement values for the test elements [20].
Table 4. Results of measurements of dimensional tolerance for the body—Kr [20].

| No. | Symbol/Tolerance | Dimension | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-----|------------------|-----------|------|------|------|------|------|------|------|------|------|------|
| 1   | KR1              | 55.7 (−0.03) | 55.7009 | 55.6728 | 55.6787 | 55.6774 | 55.6534 | 55.6638 | 55.6680 | 55.6745 | 55.6804 | 55.6902 |
| 2   | KR2              | 55.7 (−0.03) | 55.6985 | 55.6708 | 55.6793 | 55.6753 | 55.6544 | 55.6575 | 55.6671 | 55.6691 | 55.6785 | 55.6878 |
| 3   | KR3              | 55.7 (−0.03) | 55.7024 | 55.6747 | 55.6837 | 55.6788 | 55.6565 | 55.6636 | 55.6688 | 55.6738 | 55.6754 | 55.6862 |
| 4   | KR4              | 55.7 (−0.03) | 55.7006 | 55.6770 | 55.6830 | 55.6792 | 55.6566 | 55.6623 | 55.6614 | 55.6759 | 55.6742 | 55.6830 |
| 5   | KR5              | 55.7 (−0.03) | 55.7042 | 55.6740 | 55.6833 | 55.6816 | 55.6561 | 55.6625 | 55.6625 | 55.6745 | 55.6753 | 55.6829 |
| 6   | KR6              | 55.7 (−0.03) | 55.7033 | 55.6758 | 55.6827 | 55.6824 | 55.6545 | 55.6679 | 55.6631 | 55.6760 | 55.6746 | 55.6823 |
| 7   | KR7              | 55.7 (−0.03) | 55.7050 | 55.6743 | 55.6840 | 55.6850 | 55.6559 | 55.6665 | 55.6645 | 55.6674 | 55.6755 | 55.6834 |
| 8   | KR8              | 55.7 (−0.03) | 55.7052 | 55.6727 | 55.6832 | 55.6815 | 55.6569 | 55.6641 | 55.6708 | 55.6741 | 55.6808 | 55.6911 |
| 9   | KR9              | 55.7 (−0.03) | 55.6998 | 55.6707 | 55.6750 | 55.6702 | 55.6500 | 55.6589 | 55.6652 | 55.6705 | 55.6761 | 55.6849 |
| 10  | KR10             | 55.7 (−0.03) | 55.7007 | 55.6692 | 55.6760 | 55.6742 | 55.6508 | 55.6546 | 55.6650 | 55.6674 | 55.6762 | 55.6856 |

Pr.—perpendicularity.

Table 5. Measurement results of dimensional tolerance for the active gear—KzP [20].

| No. | Symbol/Tolerance | Dimension | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-----|------------------|-----------|------|------|------|------|------|------|------|------|------|------|
| 1   | Kzp1             | Ø18 (−0.025/0.030) | 17.9650 | 17.9660 | 17.9650 | 17.9650 | 17.9650 | 17.9655 | 17.9655 | 17.9655 | 17.9655 | 17.9650 |
| 2   | Kzp2             | Ø18 (−0.025/0.030) | 17.9640 | 17.9630 | 17.9630 | 17.9660 | 17.9660 | 17.9640 | 17.9640 | 17.9640 | 17.9660 | 17.9660 |
| 3   | Kzp3             | Ø24.8 (+/−0.2) | 24.8800 | 24.9400 | 24.8300 | 24.8300 | 24.8000 | 24.8200 | 24.8400 | 24.8400 | 24.8400 | 24.8400 |
| 4   | Kzp4             | Ø39 (−0.008/0.006) | 38.9380 | 38.9320 | 38.9300 | 38.9320 | 38.9300 | 38.9320 | 38.9320 | 38.9300 | 38.9320 | 38.9320 |
| 5   | Kzp5             | 11.7 (−0.01) | 11.7010 | 11.6980 | 11.6960 | 11.7010 | 11.7020 | 11.7010 | 11.7010 | 11.7000 | 11.6980 | 11.6960 |
| 6   | Kzp6             | 11.7 (−0.01) | 11.6980 | 11.6970 | 11.6950 | 11.7000 | 11.7000 | 11.7000 | 11.7000 | 11.6990 | 11.6970 | 11.6950 |
| 7   | Kzp7             | C (0.003) | 0.0032 | 0.0040 | 0.0037 | 0.0026 | 0.0034 | 0.0025 | 0.0024 | 0.0034 | 0.0039 | 0.0034 |
| 8   | Kzp8             | R (0.005) | 0.0050 | 0.0100 | 0.0025 | 0.0025 | 0.0050 | 0.0050 | 0.0075 | 0.0100 | 0.0050 | 0.0050 |
| 9   | Kzp9             | C (0.003) | 0.0041 | 0.0047 | 0.0083 | 0.0058 | 0.0041 | 0.0040 | 0.0038 | 0.0050 | 0.0047 | 0.0034 |
| 16  | Kzp16            | 14.602 | 14.5490 | 14.5540 | 14.5380 | 14.5500 | 14.5490 | 14.5560 | 14.5500 | 14.5480 | 14.5490 | 14.5600 |
| 17  | Kzp17            | R      | 0.0170 | 0.0110 | 0.0060 | 0.0120 | 0.0060 | 0.0060 | 0.0080 | 0.0180 | 0.0110 | 0.0080 |

W—cylindricity and R—run out.
Table 6. Measurement results of the dimensional tolerance for a passive gear—Kzpn [20].

| No. | Symbol/Tolerance | Dimension | Measurement Results—Kzpn |
|-----|------------------|-----------|-------------------------|
| 1   | Kzpn1            | Ø18 (+0.025/-0.035) | 17.968 17.967 17.964 17.964 17.964 17.964 17.956 17.966 17.966 17.968 |
| 2   | Kzpn2            | Ø18 (+0.025/-0.035) | 17.968 17.964 17.968 17.968 17.970 17.962 17.964 17.968 17.968 17.967 |
| 3   | Kzpn3            | Ø24.8 (+/-0.2)     | 24.800 24.970 24.970 24.930 24.740 24.930 24.980 24.980 24.900 24.780 |
| 4   | Kzpn4            | Ø39 (+0.08/-0.06)  | 38.920 38.918 38.920 38.918 38.924 38.918 38.916 38.920 38.916 38.922 |
| 5   | Kzpn5            | 11.7 (-0.01)       | 11.697 11.699 11.692 11.697 11.705 11.702 11.698 11.694 11.694 11.692 |
| 6   | Kzpn6            | 11.7 (-0.01)       | 11.696 11.693 11.690 11.698 11.700 11.700 11.698 11.694 11.694 11.690 |
| 7   | Kzpn7            | W (0.003)          | 0.006 0.007 0.003 0.003 0.007 0.006 0.005 0.003 0.003 0.005 |
| 8   | Kzpn8            | R (0.005)          | 0.005 0.003 0.005 0.005 0.005 0.003 0.005 0.005 0.005 0.000 |
| 9   | Kzpn9            | R (0.003)          | 0.006 0.005 0.004 0.005 0.005 0.007 0.007 0.007 0.003 0.007 |
| 16  | Kzpn16           | 14.602            | 14.536 14.576 14.540 14.498 14.498 14.521 14.540 14.500 14.536 14.488 |
| 17  | Kzpn17           | R                 | 0.004 0.006 0.011 0.012 0.007 0.006 0.011 0.006 0.006 0.009 |

Pr.—perpendicularity.

Table 7. Measurement results of the dimensional tolerance for the plate—Pt [20].

| No. | Symbol/Tolerance | Dimension | Measurement Results—Pt |
|-----|------------------|-----------|------------------------|
| 1   | Pt1              | F (0.02)  | 0.0354 0.0435 0.0391 0.0239 0.0220 0.0372 0.0437 0.0407 0.0351 0.0291 |
| 2   | Pt2              | P (0.03)  | 0.0296 0.0199 0.0299 0.0267 0.0386 0.0213 0.0187 0.0199 0.0255 0.0217 |
| 3   | Pt3              | 19 (+/-0.2) | 18.9989 19.0165 18.9837 18.9177 18.9311 18.9898 18.9686 19.0073 19.0161 19.0066 |
| 4   | Pt4              | 19 (+/-0.2) | 19.0049 19.0258 18.9908 18.9265 18.9183 18.9954 18.9830 19.0205 19.0152 19.0159 |
| 5   | Pt5              | 19 (+/-0.2) | 18.9791 19.0059 18.9772 18.9036 18.9124 18.9742 18.9656 19.0045 18.9662 18.9985 |
| 6   | Pt6              | 19 (+/-0.2) | 19.0087 19.0234 19.0071 18.9303 18.9511 18.9948 18.9844 19.0244 19.0217 19.0202 |
| 7   | Pt7              | 19 (+/-0.2) | 18.9901 19.0250 18.9951 18.9170 18.9188 18.9878 18.9752 19.0107 19.0183 19.0059 |

F.—flatness and P.—parallelism.

Table 8. Measurement results of the dimensional tolerance for a set of bearings—Kl [20].

| No. | Symbol/Tolerance | Dimension | Measurement Results—Kl |
|-----|------------------|-----------|------------------------|
| 1   | Kl1              | 22 (+0.08/-0.09) | 21.9077 21.9078 21.9103 21.9057 21.9030 21.9047 21.9041 21.9021 21.9031 21.9059 |
| 2   | Kl2              | 22 (+0.08/-0.09) | 21.9078 21.9113 21.9073 21.9059 21.9034 21.9081 21.9083 21.9118 21.9123 21.9141 |
| 3   | Kl3              | 22 (+0.08/-0.09) | 21.9075 21.9082 21.9057 21.9076 21.8999 21.9072 21.9071 21.9078 21.9116 21.9190 |
| 4   | Kl4              | 22 (+0.08/-0.09) | 21.9177 21.9096 21.9097 21.9276 21.9034 21.9083 21.9105 21.9108 21.9100 21.9091 |
|    | K15 | 22 (±0.08,−0.09) | 21.9063 | 21.9096 | 21.9092 | 21.9072 | 21.9053 | 21.9087 | 21.9186 | 21.9021 | 21.9025 | 21.9031 |
|----|-----|-------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 6  | K16 | 22 (±0.08,−0.09) | 21.9031 | 21.9058 | 21.9013 | 21.9050 | 21.9011 | 21.9042 | 21.9120 | 21.9060 | 21.9044 | 21.9058 |
| 7  | K17 | 22 (±0.08,−0.09) | 21.9039 | 21.9048 | 21.9026 | 21.9053 | 21.8990 | 21.9032 | 21.9093 | 21.9068 | 21.9064 | 21.9095 |
| 8  | K18 | P (0.004) | 0.0146  | 0.0065  | 0.0090  | 0.0026  | 0.0062  | 0.0055  | 0.0145  | 0.0010  | 0.0098  | 0.0159  |
| 9  | K19 | F (0.003) | 0.0083  | 0.0128  | 0.0087  | 0.0115  | 0.0086  | 0.0108  | 0.0104  | 0.0138  | 0.0164  | 0.0180  |
| 10 | K10 | 71.5 (±0.05) | 71.4897 | 71.4891 | 71.4620 | 71.4753 | 71.4905 | 71.4919 | 71.5106 | 71.5005 | 71.5027 | 71.4826 |
| 38 | K138| Pr. (0.01) | 0.0002  | 0.0008  | 0.0022  | 0.0028  | 0.0107  | 0.0037  | 0.0024  | 0.0029  | 0.0037  | 0.0001  |
| 39 | K139| Pr. (0.01) | 0.0001  | 0.0064  | 0.0040  | 0.0040  | 0.0007  | 0.0019  | 0.0105  | 0.0132  | 0.0171  | 0.0035  |

F—flatness, P—parallelism, and Pr.—perpendicularity.
4.1. Application of Neural Network in Extracting Measurement Points

The two main software applications used for the analysis were:

1. AitechSPHINX artificial intelligence software (program with a license purchased for the Faculty of Production Engineering and Logistics, Opole University of Technology, Opole, Poland). The Neuronix module was used for creation of the neural network.

2. The second, commercially available software used was MATLAB, Opole, Poland [21–23].

The following types of files were used: training file.lrn, test file.tst, weight file.wgt, knowledge-based file.bw, data file.vts, representation file.pre, multi-task learning system.aut, and chart.vtc.

The training file was created for the results of the control measurements (values/tolerances) for the prototype series gear pumps. The measurements included the following elements: body, active gear, passive gear, and plate and set of bearings (Tables 4–8).

The data elements were assumed to be vectors containing any finite number of coordinates. In contrast, the data on which the learning accuracy of the network was examined was the test set. All measurement points were included [24–28].

The set contained 1080 data points. The analysis was done for different training/test ratios: 50/50, 60/40, 70/30, 80/20, and 90/10 for three and four layers with one and two hidden layers, respectively. To calculate the accuracy, in addition, 5- and 10-part cross-validations were performed. The last step is the selection of the best performing model. That model is chosen based on the accuracy of the analysis for all cases, counting the overall average and selecting the model closest to that average.

The final size of the training set was 90%, whereas the test set size was 10%.

The other parameters of the neural network are:
- learning process parameters: learning rate: 0.9, torque factor 0.7, and learning cycle size: 1.
- conditions for completing the learning process: testing tolerance: 0.25 and Epsilon: 0.01.

The mean square error was used as a measure of error on the output neurons.

\[
\epsilon_{ms} = \sum_{i=1}^{i=n_{vl}} \sum_{j=1}^{j=n_{nl}} (E_{ij} - O_{ij})^2
\]

where

\(\epsilon_{ms}\) — mean square error,

\(i\) — the number of all learner vectors (in the training sequence),

\(E_{ij}\) — the expected value at the output of the \(j\) neuron for the learning vector \(V_i\),

\(O_{ij}\) — output of the \(j\) neuron in layer \(i\), and

\(n_{vl}\) — number of neural network layers.

Fragment of the source code:

```c
/ * * * * Generation of the weight values ****/
for(i=1;i<LW;i++)
for(j=0;j<n(i);j++)
for(k=0;k<=n(i-1);k++)
{W(i)(j)(k) = (((rand() % 1000000L) / 1700.0) - 9.8)*0.0015;
if(W(i)(j)(k) == 0.0) W(i)(j)(k) = 0.01492;}
/*****************************/
```

Listing 1. Generating the weight values.
Listing 2. Network input signal processing.

```c
/* * Single processing */
for(i=1;i<LW;i++)
for(j=0;j<n(i);j++)
{I(i)(j) = 0.0;
for(k=0;k<n(i-1);k++)
I(i)(j) += O(i-1)(k) * W(i)(j)(k);
O(i)(j) = 1.0 / (1.0 + exp(beta*(-I(i)(j))));}
/***********************************/
for(j=0;j<n(LW-1);j++)
B(LW-1)(j) = Wy(wu)(j) - O(LW-1)(j);
/***********************************/
```

Listing 3. Errors on network outputs.

```c
for(j=0;j<n(LW-1);j++)
B(LW-1)(j) = Wy(wu)(j) - O(LW-1)(j);
/***********************************/
```

Listing 4. Calculating errors on every neuron in the network (back-propagation).

```c
for(i=1;i<LW;i++)
for(j=0;j<n(i);j++)
for(k=0;k<n(i-1);k++)
{
W2(i)(j)(k) = W(i)(j)(k),
W(i)(j)(k) += eta * E(i)(j) * O(i-1)(k) + alfa*(W(i)(j)(k) - W1(i)(j)(k)),
W1(i)(j)(k) = W2(i)(j)(k);
}
/***********************************/
```

Listing 5. Adjustment of weights.

```c
/********** Adjustment of weights **********/
for(i=1;i<LW;i++)
for(j=0;j<n(i);j++)
for(k=0;k<n(i-1);k++)
{
W2(i)(j)(k) = W(i)(j)(k),
W(i)(j)(k) += eta * E(i)(j) * O(i-1)(k) + alfa*(W(i)(j)(k) - W1(i)(j)(k)),
W1(i)(j)(k) = W2(i)(j)(k);
}
/***********************************/
```

Listing 6. Calculating a network ERMS (Error Root Mean Square) error for a single epoch.
/ ***** Calculating network error *****/
for(j=0;j<n(LW-1);j++)
RMS += (Wy(wu)(j) - O(LW-1)(j))*(Wy(wu)(j) - O(LW-1)(j));
ERMS = sqrt(RMS/(double)(ile_wek*n(LW-1)));
/*************************/

Designations adopted in listings—meaning of individual variables:
lw—the number of layers in the network
n(i)—the number of neurons in layer i
i—layer number
j—single neuron number
k—weight number
w (i)(j)(k)—current weight k at j neuron in layer i
w1(i)(j)(k)—previous weight k at neuron j in layer i
i(i)(j)—input of neuron j in layer i
o(i)(j)—output of neuron j in layer i
e(i)(j)—delta (sigma) of neuron j in layer i
b(lw-1)(j)—error on jth neuron output
wy(wu)(j)—the expected value on jth neuron output for the learner vector wu
ile_wek—the number of all learner vectors (in the training sequence)
alfa—momentum factor
beta—activation curve factor
eta—learning rate
erms—network error

The loops start from the initial value of 0 (not from 1), so the index denoting the output layer of lw is (lw-1).

This procedure is repeated until the error generated by the network is smaller than the asserted value. Then, another input vector is fed to the network input, and the process is repeated. After the entire learning sequence is processed (this is called an epoch), an error for the epoch is calculated.

The entire cycle was repeated until the error falls below the acceptable margin.

The regression graphs in Figures 9–11 represent the network output data with respect to the learning goal, validation, and test sets. To get a perfect match, the data should lie along a line with a 45-degree positive-angle slope, i.e., where the network outputs are equal to the targets (patterns).
Figure 9. Plot of the output with linear approximation.

Figure 10. The network output with respect to the learning goal.
In our analysis, the qualitative approximation agrees very reasonably with the fitted data for all sets, with values of $R$ in each case being 0.93 or higher. The neural network classified the following parameters as the most important:

parameters=$(19, 20, 21, 22, 30, 31, 38, 39, 40, 41, 42, 44, 45, 46, 48, 57, 58, 59, 60, 61, 62, 65, 73, 74, 101, 102, 104, 111, 112, 113, 140, 141, 142, 143)$

which correspond to the measured points:

KR19, KR20, KR21, KR22, PKr1, PKr2, Kzp7, Kzp8, Kzp9, Kzp10, Kzp11, Kzp13, Kzp14, Kzp15, Kzp17, Kzp19, Kzp10, Kzp11, Kzp14, Kzp17, Kla8, Kla9, Kla37, Kla36, Kla37, Kla39, KI7, KI8, KI9, KI36, KI37, KI38, and KI39.

Figure 12 presents the dimensions and critical deviations: (1) the beating of plugs and the lateral surface of the toothed rim and (2) the perpendicularity of the side surface of the tooth to the pivots (wheel rotation axis) for the details of the gears speeding.
Figure 12. The dimensions and critical deviations: (a) the beating of plugs and the lateral surface of the toothed rim—perpendicularity of the side surface of the tooth to the pivots (wheel rotation axis) for the detail of the gears speeding and running, (b) the perpendicularity of the sump to the pump head for detail: pump corpus, and (c) fastening the plain bearing body to the CNC (Computerized Numerical Control) machine table.

The identification of the impact of the manufacturing technology for the model units showed that the important dimensions affecting the efficiency of the pumps are generally repeated in all details, regardless of the analyzed group.

Table 9 shows the results of the hydraulic measurements for the original pump and Table 10 for the improved unit.

| n (rpm) | p_t (MPa) | Q_{rz} (l/min) | M (Nm) | N_h (kW) | N_m (kW) | n_v (%) | n_{hm} (%) | n_c (%) |
|--------|-----------|----------------|--------|----------|----------|---------|-----------|---------|
| 500    | 15.1      | 2.0            | 0.00   | 0.10     | 94.4     | 0.0     | 0.0       | 0.0     |
|        | 13.1      | 25.5           | 1.08   | 1.34     | 81.7     | 99.5    | 81.2      |         |
|        | 11.4      | 52.5           | 1.89   | 2.75     | 71.2     | 96.8    | 68.9      |         |
| 5      | 10.0      | 81.0           | 2.50   | 4.24     | 62.5     | 94.2    | 58.9      |         |
| 10     | 9.5       | 110.0          | 3.17   | 5.76     | 59.6     | 92.5    | 55.1      |         |
| 20     | 9.4       | 139.0          | 3.89   | 7.28     | 58.4     | 91.5    | 53.5      |         |
| 24     | 8.6       | 172.0          | 4.30   | 9.01     | 53.8     | 88.8    | 47.7      |         |
| 30     | 31.7      | 2.2            | 0.00   | 0.23     | 99.2     | 0.0     | 0.0       |         |
| 5      | 30.4      | 25.5           | 2.53   | 2.67     | 95.1     | 99.5    | 94.6      |         |
| 10     | 28.8      | 53.0           | 4.79   | 5.55     | 89.9     | 95.9    | 86.2      |         |
| 1000   | 15.1      | 2.0            | 0.00   | 0.10     | 94.4     | 0.0     | 0.0       | 0.0     |
|        | 13.1      | 25.5           | 1.08   | 1.34     | 81.7     | 99.5    | 81.2      |         |
|        | 11.4      | 52.5           | 1.89   | 2.75     | 71.2     | 96.8    | 68.9      |         |
| 5      | 10.0      | 81.0           | 2.50   | 4.24     | 62.5     | 94.2    | 58.9      |         |
| 10     | 9.5       | 110.0          | 3.17   | 5.76     | 59.6     | 92.5    | 55.1      |         |
| 20     | 9.4       | 139.0          | 3.89   | 7.28     | 58.4     | 91.5    | 53.5      |         |
| 24     | 8.6       | 172.0          | 4.30   | 9.01     | 53.8     | 88.8    | 47.7      |         |
| 30     | 31.7      | 2.2            | 0.00   | 0.23     | 99.2     | 0.0     | 0.0       |         |
| 5      | 30.4      | 25.5           | 2.53   | 2.67     | 95.1     | 99.5    | 94.6      |         |
| 10     | 28.8      | 53.0           | 4.79   | 5.55     | 89.9     | 95.9    | 86.2      |         |
| 1500   | 15.1      | 2.0            | 0.00   | 0.10     | 94.4     | 0.0     | 0.0       | 0.0     |
|        | 13.1      | 25.5           | 1.08   | 1.34     | 81.7     | 99.5    | 81.2      |         |
|        | 11.4      | 52.5           | 1.89   | 2.75     | 71.2     | 96.8    | 68.9      |         |
| 5      | 10.0      | 81.0           | 2.50   | 4.24     | 62.5     | 94.2    | 58.9      |         |
| 10     | 9.5       | 110.0          | 3.17   | 5.76     | 59.6     | 92.5    | 55.1      |         |
| 20     | 9.4       | 139.0          | 3.89   | 7.28     | 58.4     | 91.5    | 53.5      |         |
| 24     | 8.6       | 172.0          | 4.30   | 9.01     | 53.8     | 88.8    | 47.7      |         |
| 30     | 31.7      | 2.2            | 0.00   | 0.23     | 99.2     | 0.0     | 0.0       |         |
| 5      | 30.4      | 25.5           | 2.53   | 2.67     | 95.1     | 99.5    | 94.6      |         |
| 10     | 28.8      | 53.0           | 4.79   | 5.55     | 89.9     | 95.9    | 86.2      |         |
| 2000   | 15.1      | 2.0            | 0.00   | 0.10     | 94.4     | 0.0     | 0.0       | 0.0     |
|        | 13.1      | 25.5           | 1.08   | 1.34     | 81.7     | 99.5    | 81.2      |         |
|        | 11.4      | 52.5           | 1.89   | 2.75     | 71.2     | 96.8    | 68.9      |         |
| 5      | 10.0      | 81.0           | 2.50   | 4.24     | 62.5     | 94.2    | 58.9      |         |
| 10     | 9.5       | 110.0          | 3.17   | 5.76     | 59.6     | 92.5    | 55.1      |         |
| 20     | 9.4       | 139.0          | 3.89   | 7.28     | 58.4     | 91.5    | 53.5      |         |
| 24     | 8.6       | 172.0          | 4.30   | 9.01     | 53.8     | 88.8    | 47.7      |         |
| 30     | 31.7      | 2.2            | 0.00   | 0.23     | 99.2     | 0.0     | 0.0       |         |
| 5      | 30.4      | 25.5           | 2.53   | 2.67     | 95.1     | 99.5    | 94.6      |         |
| 10     | 28.8      | 53.0           | 4.79   | 5.55     | 89.9     | 95.9    | 86.2      |         |

Table 9. Results of the hydraulic measurements for the original pump [15], where: n—rotation speed, p_t—discharge pressure, Q_{rz}—flow rate, M—torque, N_h—hydraulic power, N_m—mechanical power, n_v—volumetric efficiency, n_{hm}—hydraulic and mechanical efficiency, n_c—total efficiency.
Table 10. Results of the hydraulic measurements for improved pump [15].

| n (rpm) | p_{\text{t}} (MPa) | Q_{\text{t}} (/min) | M (Nm) | N_{\text{h}} (kW) | n_{\text{e}} (%) | n_{\text{h}} (%) | n_{\text{c}} (%) |
|---------|-------------------|---------------------|--------|-------------------|-----------------|-----------------|----------------|
| 500     | 15.6              | 0.0                | 0.03   | 100.0            | 0.0             | 0.0             | 0.0            |
| 20      | 15.6              | 0.5                | 0.03   | 100.0            | 0.0             | 0.0             | 0.0            |
| 30      | 15.6              | 10.0               | 2.34   | 90.4             | 88.4            | 79.9            | 79.9           |
| 1000    | 15.6              | 20.0               | 4.79   | 92.3             | 90.1            | 83.2            | 83.2           |
| 24      | 15.6              | 40.0               | 7.19   | 92.3             | 87.5            | 80.8            | 80.8           |
| 30      | 15.6              | 60.0               | 10.0   | 99.1             | 80.6            | 79.1            | 79.1           |
| 1500    | 15.6              | 80.0               | 12.0   | 99.8             | 85.1            | 84.9            | 84.9           |
| 20      | 15.6              | 100.0              | 14.1   | 99.8             | 88.2            | 86.7            | 86.7           |
| 30      | 15.6              | 120.0              | 16.2   | 99.8             | 90.9            | 90.1            | 90.1           |
| 2000    | 15.6              | 140.0              | 18.3   | 99.8             | 80.9            | 80.7            | 80.7           |
| 30      | 15.6              | 160.0              | 20.4   | 99.8             | 86.4            | 86.0            | 86.0           |

Other selected hydraulic (and acoustic) results for selected pumps were presented, e.g., in works [15,17]. The comparison of the hydraulic performance for the pumps before modification show that the total efficiency of the currently produced gear pumps ranges from 74% to 88%. These values are lower than the efficiency of the prototype units by 4% to 18%. The increase in energy efficiency of the prototype units is mainly due to the relatively high internal tightness. The slightly higher efficiency of a unit with a fitting angle of $c = 130$ is due to the low hydraulic-mechanical torque loss. Even greater differences in the overall performance favor prototype pumps that are observed at low rotational speeds. This is due to a high drop in the volumetric efficiency of conventional pumps at speeds below $n = 800$ rpm. The volumetric efficiency of the conventional units did not exceed 60% for the nominal pressures, and rotational speed $n = 500$ rpm. The relatively high internal tightness of the prototype pumps ensures that the volumetric efficiency is maintained at a minimum of 90% throughout the pressure range, regardless of the rotational speed.

5. Acoustic Measurements of Prototype Pumps

Acoustic measurements were carried out in a reverberation chamber at the Department of Hydraulic Drives and Automation, Wroclaw University of Science and Technology. In rooms of this type, there is a perfectly dispersed field characterized by the fact that all acoustic energy reflected
from the walls returns towards the source, such that the sound intensity at each point in this field is equal [27]. This property is achieved by lining the ceiling and floor walls with hard and smooth elements that perfectly reflect sound waves. To prevent standing waves, opposite walls are made at an angle to each other. The reverberation chamber shown in Figure 13 has a volume of \( V = 102 \text{ m}^3 \). The room meets the requirements of ANSI S1.21-1972 and PN-85/N-01334 and provides the possibility of testing machines and devices for vibration and noise. The chamber’s sound insulation in relation to external interference is within the 20–20,000 Hz frequency range of 50 dB. Such insulation ensures the elimination of interference from the propulsion system and the hydraulic system supplying the tested unit.

![Block diagram of gear pump noise measurement](image)

**Figure 13.** Block diagram of gear pump noise measurement: KA—calibrator, MC—eight free sound field microphones, MU—multiplexer, WP—instrumentation amplifier, AF—two-channel frequency analyzer, PC—computer, PZ—gear pump, and KO—chamber [15,17].

The chamber was made of two similar irregular polyhedrons located “one in the other”. The uniformity of the sound field distribution in the chamber is within acceptable limits, starting from
the center frequency for an octave of 125 Hz. Eight fixed measuring points were determined within
the chamber based on the sound field distribution tests [17]. The microphones were set in accordance
with the recommendations of the abovementioned standards at a height of 1.3 m from the floor,
where this height corresponded to the position of the drive shaft axis.

The measuring microphones were spaced at eight points, from which the sound pressure level
was read and then averaged. Measuring microphones were selected when reading data using a
multiplexer and the level together with the spectrum was stored in the memory of a two-channel
analyzer. The data was edited on a PC in the BeK program type 5306.

Acoustic measurements of an experimental version of the pump, respectively, for the value of
the discharge pressure pt: 0, 2, 4, ..., 30 MPa and the frequency f: 25±20kHz were obtained in the
analysis. Table 11 shows the exemplary acoustic measurements of a gear pump after tooth root
undercutting for pt = 12 MPa.

| f (Hz) | Microphone Numbers | Thirds Octaves | Lmj | Smj | KAj | LAj |
|-------|-------------------|----------------|-----|-----|-----|-----|
|       |                   |                 |     |     |     |     |
| 25    | 84.1              | 1.48            | 82.4| 78.1| 80.1| 44.7|
| 31.5  | 62.3              | -0.15           | 56.8| 60.3| 60.1| 39.3|
| 40    | 58.9              | -0.20           | 50.0| 60.0| 59.6| 20.8|
| 50    | 70.8              | 0.33            | 46.4| 63.0| 71.1| 36.0|
| 63    | 71.7              | 0.16            | 73.0| 66.0| 73.4| 40.9|
| 80    | 75.4              | -0.26           | 60.9| 66.0| 74.4| 48.2|
| 100   | 69.9              | 0.42            | 61.9| 66.0| 71.5| 50.9|
| 125   | 74.6              | 0.77            | 54.9| 66.0| 71.2| 50.0|
| 160   | 69.8              | -0.10           | 69.5| 66.0| 67.3| 38.4|
| 200   | 81.8              | 0.38            | 74.0| 69.4| 67.1| 13.4|
| 250   | 83.0              | -10.9           | 76.3| 74.0| 70.5| 65.4|
| 315   | 77.1              | 6.5            | 70.6| 72.6| 74.0| 65.7|
| 400   | 83.4              | -8.6           | 80.2| 75.9| 78.4| 69.8|
| 500   | 84.2              | 73.4            | 79.6| 73.2| 74.2| 81.2|
| 630   | 65.4              | 3.5            | 71.2| 69.7| 74.4| 66.6|
| 800   | 60.7              | -6.6           | 61.9| 69.5| 71.5| 68.6|
| 1k    | 61.8              | 3.8            | 63.1| 65.8| 66.4| 68.2|
| 1.25k | 68.8              | 0.6            | 65.5| 66.6| 68.4| 69.0|
| 1.6k  | 72.5              | 1.9            | 68.1| 67.1| 65.4| 70.3|
| 2k    | 73.2              | 1.2            | 70.8| 67.1| 65.4| 72.7|
| 2.5k  | 70.2              | 0.9            | 70.8| 67.1| 65.4| 72.7|
| 3.15k | 66.2              | 1.3            | 68.3| 67.1| 65.4| 72.7|
| 4k    | 69.4              | 1.1            | 69.3| 67.1| 65.4| 72.7|
| 5k    | 67.5              | 0.5            | 69.3| 67.1| 65.4| 72.7|
| 6.3k  | 67.7              | 0.1            | 69.3| 67.1| 65.4| 72.7|
| 8k    | 68.6              | 1.1            | 69.3| 67.1| 65.4| 72.7|
| 10k   | 65.5              | 0.9            | 69.3| 67.1| 65.4| 72.7|
| 12.5k | 66.1              | 1.1            | 69.3| 67.1| 65.4| 72.7|
| 16k   | 59.6              | 1.4            | 69.3| 67.1| 65.4| 72.7|
| 20k   | 53.2              | 1.6            | 69.3| 67.1| 65.4| 72.7|

As part of the research, the following measurements were performed: the sound pressure level
Lp, the A-weighted sound pressure level LA, the sound power level LW, and the A-weighted sound
power level LWA. The average value of the sound pressure level Lp was calculated according to the
following formula:
\[ L_p = 10 \log \left( \frac{1}{n} \sum_{i=1}^{n} 10^{\frac{1}{10}L_{pi}} \right) \]  

\[ L_{pi} \] — sound pressure level at the ith measuring point and 

\[ n \] — total number of measuring points.

The mean value of the A-weighted sound level was determined in the same manner:

\[ L_A = 10 \log \left( \frac{1}{n} \sum_{i=1}^{n} 10^{\frac{1}{10}L_{ai}} \right) \]  

\[ L_{ai} \] — sound pressure level at the i-th measuring point and 

\[ n \] — total number of measuring points.

The value of the A-weighted sound level was determined on the basis of the measured sound pressure level \( L_{ai} \) in the j-th band and after the correction \( K_j^i \) resulting from the characteristics of the weighted curve using the following formula:

\[ L_j^i = L_{pi}^i + K_j^i \]  

\( L_{pi}^i \) — sound pressure level in the j-th frequency band, 

\( L_j^i \) — A-weighted sound level in the j-th frequency band, and 

\( K_j^i \) — correction according to the A characteristic for the j-th frequency band.

Figure 14 presents the value of the acoustic pressure level \( L_m \), corrected acoustic pressure level \( L_{A} \), acoustic power level \( L_p \), and corrected acoustic power level \( L_{pA} \) in the function of the discharge pressure \( p_t \) at a constant rotational speed of a pump shaft \( n = 1500 \) rpm.

Figure 14. The noise of the gear pump after tooth root undercutting for the nominal rpm [15,17].
Figures 15 and 16 present a tertian and an octave spectrum of the gear pump after tooth root undercutting for the nominal discharge pressure and nominal rotational speed.

![Figure 15](image1.png)

**Figure 15.** The tertian spectrum of an experimental unit for the nominal pressure and rotational speed [15,17].

![Figure 16](image2.png)

**Figure 16.** The octave spectrum of an experimental unit for the nominal pressure and rotational speed [15,17].
The measurement of the RMS vibration acceleration was located on the rear cover of the gear pump in the axis of the driving wheel shaft. The choice of the measurement point resulted from the previous tests with the use of the acoustic probe. The distribution of sound intensity on the surface of the pump body, determined by the energy method, showed a local increase in sound vibrations. This fact proves the transmission of sound-generating vibrations mainly from the pump drive.

Comparing the acoustic characteristics of the prototype pumps with the basic units, it turned out that the solution with a polyevolvent outline is characterized by 3 to 5-dB lower noise emission to the environment. The beneficial effect of noise reduction was observed in the range from 0 to 20 MPa. In the extreme case, for 8 MPa, the sound level A was reduced to 5 dB.

Acoustic tests of model pumps with dimensional optimization and comparable units without modification showed similar noise emission parameters at low operating pressures. In the case of an increase in working pressure, units with the optimization of production technology are more favorable (Table 12).

| Parameter                              | Commercial Pump | Model Pump |
|----------------------------------------|-----------------|------------|
| Sound level A (dB)                     | 83–84           | 79         |
| Total efficiency (%)                   | 73–76           | 87.0       |
| Coefficient of performance unevenness (%) | 19.0–21.0* | 19.9       |
| Sound vibration level (effective acceleration value) (m/s²) | 0.058–0.074 | 0.049     |
| Power to weight parameter (kW/kg)     | 3.2–3.5**       | 4.5***     |
| Energy efficiency q/V                 | 0.27–0.29*      | 0.31       |
| Sealed space compression ratio Vmax/Vmin | 1.1–1.2*       | 1.0        |

* values estimated based on the tooth geometry measurement,
** the parameter was determined for the pump operating with the highest available power, and
*** the parameter was determined for the pump working with the highest available power in group II with a cover and plate made of PA9.

After optimizing the technology of the prototype pumps, a smaller dispersion is observed in the results of the efficiency course. The characteristics are more grouped. Comparing the acoustic characteristics of the prototype pumps (Figure 17), it turned out that the solution with ground wheels has a 3 to 5-dB reduction in noise emitted to the environment.

![Figure 17. Example of acoustic characteristics of a prototype pump with shaved wheels.](image-url)
The advantage of shaved pumps is a higher overall efficiency due to low hydraulic-mechanical losses. A higher relative hydraulic and mechanical efficiency is mainly associated with surface roughness. The use of carburizing and hardening of the teeth reduces the total height of the roughness profile (St). After stripping, the parameter St is at the level of 14 pm, decreasing after a treatment of carbonizing and hardening to the value of about 8 pm. The phenomenon of lowering the roughness can be explained by the high carburizing and hardening temperatures conducive with oxidation of a sharp surface roughness. Low values of the tooth profile roughness parameters help to improve the lubrication conditions of mating teeth.

6. Conclusions

The objective of this research was the construction of a model and prototype pumps. The final analysis of the dimensional and geometric tolerances allowed for the selection of dimensions critical, important, and not important to the control. This resulted in a rational narrowing of dimensional and geometric tolerances where necessary and a reduction in the accuracy classification in areas of little importance. Optimizing the production technology contributed to lowering the production cost and increasing its efficiency. The results obtained for both modeled and prototype pumps were referenced against other constructions manufactured by the implemented entity or by other leading gear pump manufacturers. Due to the large number of units tested, this monograph presents only selected aspects in a fragmentary way. In addition, during testing, the impact of the environment on the measuring system is negligible. Uniform measurement conditions were ensured, i.e., tests were carried out with the same apparatus while maintaining a constant temperature and humidity. This approach significantly simplifies the interpretation of results that are used for comparative purposes, i.e., they allow direct determination of the differences in measured physical quantities between the tested objects. The patent and analysis of the structures offered by gear pump manufacturers show a lack of solutions with a poly-involute outline.

At the design stage, in addition to selecting the tooth geometry, the designer should assume the correct operating conditions and consider the technological capabilities of the developed structure. In connection with the above, the research presents technological and operational conditions that should be met by newly designed constructions. The adopted construction, technological parameters, and operating conditions decide, amongst other factors, the efficiency, durability, reliability, and noise emission to the environment. There is a possibility of further generalizations and modifications with a detailed presentation of the technological method of making tooth shapes, referring, for example, to publications [29,30].

Author Contributions: A.D. was involved in the conception and design of the study, drafted the manuscript, with support from P.O., compiled all the results. P.O. prepared data from hydraulic and acoustic tests and supervised the tests with a cooperating company. M.A.P. prepared data from hydraulic and acoustic tests, and supervised the tests with a cooperating company. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Deptula, A.; Osiński, P. The optimization of three-involute tooth outline with taking into consideration multi-valued logic trees. In RESRB-2016 Proceedings of the 13th International Scientific Conference; Rusiński E., Pietrusiak D., Eds.; Lecture Notes in Mechanical Engineering; Springer: Cham, Switzerland, 2017; pp. 99–107.
2. Del Campo, D.; Castilla, R.; Raush, G.A.; Gamez Montero, P.J.; Codina, E. Numerical Analysis of External Gear Pumps Including Cavitation. ASME J. Fluids Eng. 2012, 134, 081105, doi:10.1115/1.4007106.
3. Ertürk, N.; Vernet, A.; Castilla, R.; Gamez-Montero, P.J.; Ferré, J.A. Experimental Analysis of the Flow Dynamics in the Suction Chamber of an External Gear Pump. Int. J. Mech. Sci. 2008, 53, 135–144.
4. Rundo, M. Models for Flow Rate Simulation in Gear Pumps: A Review. Energies 2017, 10, 1261.
5. Zhang, H.X. Analysis on Flow Pulse and Property of Double Helical Gear Pump. *Mach. Tool Hydraul.* 2011, 39, 8081–8084.
6. Battarra, M.; Mucchi, E. A method for variable pressure load estimation in spur and helical gear pumps. *Mech. Syst. Signal Process.* 2016, 76–77, 265–282.
7. Baltes, H.; Goebels, K.; Groben, M.; Post, M.; Weber, N. Primary and secondary measures to reduce the noise of hydraulic fluid power system. In *3rd International Fluid Power Conference*, Shaker: Aachen, Germany, 2002.
8. Dhar, S.; Vacca, A. A fluid—structure interaction model to analyze axial balance in external gearmachines. In *Proceedings of the 8th International Fluid Power Conference*, Dresden, Germany, 26–28 March 2012.
9. Feldhaus, F.M. *The Technology of Prehistoric Times, Historical Times and Primitive Peoples*; Verlag von W. Engelmann: Leipzig, Germany; Berlin, Germany, 1914.
10. Fröme, I. Loss Analysis on Gear Pumps, Theoretical and Experimental. Dissertation, Univ. Stuttgart, Germany, 1971.
11. Hübsch, H-G. Investigation of the noise behavior and design options for noise reduction in gear pumps that are not pressure compensated. Dissertation, Univ. Stuttgart, Germany, 1969.
12. Kerres, K. Gear melt pump in extrusion: Process analysis and options for computerized. Dissertation RWTH Aachen, Auslegung, Germany, 1993.
13. Kollek, W. Optimization of the efficiency of gear pumps and motors. *Konstruktion* 4/83.
14. Willekens, F.A.M. Instantaneous delivery volume, geometric stroke volume and degree of irregularity of gear pumps. *Industrie-Anzeiger* no 26, 1971.
15. Osiński, P. *High Pressure and Low Pulsation Gear Pumps with External Meshing*; Publishing House of the Wroclaw University of Technology: Wroclaw, Poland, 2013.
16. Śliwiński, P. Flow of liquid in flat gaps of the satellite motor working mechanism. *Pol. Marit. Res.* 2014, 21, 50–57.
17. Osiński, P.; Kollek, W. Assessment of energetistic measuring techniques and their application to diagnosis of acoustic condition of hydraulic machinery and equipment. *Arch. Civ. Mech. Eng.* 2013, 13, 313–321.
18. Osiński, P.; Deptula, A.; Partyka, M.A. Discrete optimization of a gear pump after tooth root undercutting by means of multi-valued logic trees. *Arch. Civ. Mech. Eng.* 2013, 13, 422–431.
19. Deptula, A.; Osiński, Partyka, M.A. Identification of Influence of Part Tolerances of 3PWR-SE Pump on its Total Efficiency Taking into Consideration Multi-Valued Logic Trees. *Pol. Marit. Res.* 2017, 24, 47–59.
20. Osiński, P.; Deptula, A. Optimization of the polyvalent tooth profile including multi-valued logical structures. In *Reports of the Faculty of Mechanical Engineering of the Wroclaw University of Technology*; Springer: Wroclaw, Poland, 2015.
21. LeCun, Y.; Yoshua, B. Convolutional networks for images, speech, and time series. In *the Handbook of Brain Theory and Neural Networks*; MIT Press: Cambridge, MA, USA, 1995.
22. Hubel, D.H.; Torsten, N.W. Receptive fields, binocular interaction and functional architecture in the cat’s visual cortex. *J. Physiol.* 1962, 160, 106–154.
23. Ciregan, D.; Ueli, M.; Schmidhuber, J. Multi-column deep neural networks for image classification. In *Proceedings of the Computer Vision and Pattern Recognition (CVPR) 2012*, IEEE Conference on IEEE, Providence, RI, USA, 2012.
24. Krizhevsky, A.; Sutskever, I.; Hinton, G.E. Imagenet classification with deep convolutional neural networks. In *Proceedings of the Twenty-sixth Annual Conference on Neural Information Processing Systems (NIPS)*, Lake Tahoe, NV, USA, 3–8 December 2012; pp. 1106–1114.
25. Ultsch, A. Self-organising neural networks for visualisation and classifi-cation. In *Information and Classification*, Opitz, O., Lausen, B., Klar, R. Eds.; Springer: Verlag, Berlin, 1993; pp. 864–867.
26. Xiaochuan, F.; Kang, Z.; Yuewei, L.; Song, W. Combining local appearance and holistic view: Dual-source deep neural networks for human pose estimation. In *Proceedings of the Computer Vision and Pattern Recognition (cs.CV)*, Boston, MA, USA, 7–12 June 2015.
27. Pigoli, D.; Pantelis, Z.H.; Coleman, J.S.; Aston, J.A. The statistical analysis of acoustic phonetic data: Exploring differences between spoken Romance languages. *Appl. Statist.* 2018, 67, 1103–1145.
28. Hosokawa, K.; Ogawa, M.; Hashimoto, M.; Inohara, H. Statistical Analysis of the Reliability of Acoustic and Electroglottographic Perturbation Parameters for the Detection of Vocal Roughness. *J. Voice* 2014, 28, 263.e9–263.e16.
29. Bo, P.; González, H.; Calleja, A.; de Lacalle, L.N.L.; Bartoň, M. 5-axis double-flank CNC machining of spiral bevel gears via custom-shaped milling tools—Part I: Modeling and simulation. *Precis. Eng.* **2020**, *62*, 204–212.

30. Fu, Y.; Zhuo, Y.; Zhou, X.; Wan, B.; Lv, H.; Wang, Z. Theoretical and Experimental Study on Contact Characteristics of Spiral Bevel Gears under Quasi-Static and Large Loading Conditions. *Appl. Sci.* **2020**, *10*, 5109. 

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