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INFLUENCE OF OPERATING CONDITIONS ON THE POWER LOSSES OF THE WORM GEARBOX

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Abstract: *The power losses of the worm gearbox, which are expressed through the efficiency, depend on various influencing factors, of which the operating conditions play a very important role. In order to analyze the influence of operating conditions on power losses, experimental tests of the efficiency of the single-stage worm gearbox on the AT200 device were performed. The experimental worm pair consists of a worm made of improved steel 42CrMo4 and a worm gear made of tin bronze CuSn12. The tests were carried out by varying two values of the rotational speed of 1500 min^{-1} and 2500 min^{-1} and five load levels (output torques), where mineral oil with a viscosity of 1000 mm^2/s was used as a lubricant. After the experimental tests, the power losses in the meshing of the gear teeth, as well as the power losses in the bearings and shaft seals, were calculated. Based on the obtained results, it is concluded that with the increase in the circumferential speed, the values of the efficiency increase between 3% and 5%. On the other hand, at a higher circumferential speed there is an increase in power losses in the gear meshing between 53% and 55% and an increase in power losses in the bearings between 47% and 58%, taking into account all test conditions.*

Keywords: *power losses, efficiency, worm gearbox, rotational speed, torque.*

1. INTRODUCTION

Geared power transmissions have a very wide field of application, starting from precise devices to huge machines, so they differ in their shape, construction and manufacturing method. Over 80% of the total transmitted mechanical energy is achieved through gear transmissions [1].

When gear pairs are connected, an accurate kinematic transmission ratio is achieved, which is their main advantage compared to other power transmissions. In addition, the advantages of gear pairs are small dimensions, high efficiency (except for hyperboloid gear pairs), great durability, durability in work, etc.

Worm gearboxes belong to the group of hyperboloid gear pairs where the axes of the shafts intersect at an angle of 90°. They are characterized by linear contact between meshed gear teeth, which is accompanied by high sliding friction, which leads to local high surface pressures. On the other hand, high sliding friction leads to considerable power losses, which causes lower values of the efficiency compared to other gear transmissions [2,3]. Such meshing conditions require that screw pairs be made of materials with high dynamic elasticity and high resistance to wear and pitting. In advanced constructions, worm gears are most often made of tin bronze, and the worms are made of hardened and ground steel. Depending on the mode of operation, gray cast iron, aluminum alloys, zinc alloys, plastics, etc. can be used for the production of worm gears [4-6].

During the operation of worm gearboxes, a combination of sliding and rolling occurs, and with larger reductions, sliding prevails. In order to reduce the losses due to sliding and consequently improve the performance of worm gearboxes, the correct choice of lubricant is extremely important. As worm gearboxes are applied for a wide range of possible working loads, speed and temperature, the lubricants used for their lubrication are exposed to very different operating conditions. For this reason, lubricants must have an extended service life, increased thermal stability, improved EP properties at high temperatures, as well as resistance to the influence of contaminants [7,8].

Modern worm gearboxes usually work under conditions of mixed and hydrodynamic lubrication. However, some transmissions work in difficult working conditions and are often exposed to shock loads, which can lead to an increase in the working temperature of the oil up to 100°C. As the working temperature of the oil increases, its viscosity decreases, which reduces the thickness of the oil film between the coupled gear teeth, which leads to an increase in the coefficient of friction [9,10]. On the other hand, with a decrease in viscosity, there is a decrease in hydraulic resistances that occur during the mixing and dispersion of oil during transmission operation. This has a direct impact on power losses and thus on the efficiency of the transmission as a whole.

The influence of operating conditions on the efficiency and power losses will be analyzed through different operating modes of the transmission, which are defined by the experimental research plan. With a change in the operating mode, the operating temperature of the oil changes, and the lubrication conditions change, which significantly affects the amount of losses and the efficiency of the transmission.

Considering that worm gearboxes in most cases operate in variable operating conditions where speed and load change frequently, it is very difficult to develop a simple and general approach for calculating power losses. Calculations are mainly based on existing analytical methods that are quite complex and generally require appropriate experimental data [11,12].

2. EQUIPMENT FOR EXPERIMENTAL TESTS

Experimental tests of the efficiency of the worm gearbox were carried out on the device AT200, which is shown in the Figure 1.

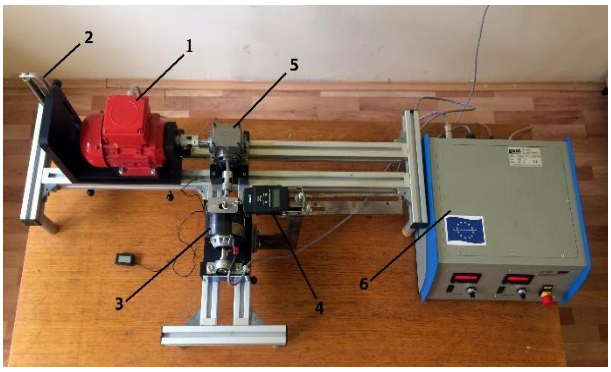

Figure 1. Efficiency testing device AT200 with complete installation

The device consists of the following basic parts: (1) electric motor, (2) dynamometer for measuring balancing force, (3) electromagnetic brake, (4) dynamometer for measuring braking force, (5) worm gearbox and (6) control unit. By changing the current on the control unit, it is possible to achieve a maximum torque of 10 Nm that can be taken over by the electromagnetic brake.

For the purposes of testing, a single-stage worm gear was constructed, the basic geometric characteristics of which are shown in the Table 1.

Table 1. Basic geometric characteristics of the worm pair

Parametar	Values
Worm gears type	ZI
Centre distance, a	31 mm
Transmission ratio, i	18
Number of teeth, z_1/z_2	1/18
Modul, m_x	2 mm
Lead angle, γ_m	4,76°

The worm is the driving element and is made of strengthening steel 42CrMo4, and the worm gear is made of tin bronze CuSn12. The test plan envisages that the values of the efficiency are determined at different operating conditions, which are achieved by changing the rotational speed and loads. By varying the current on the control unit in the interval from 0.1 A to 0.2 A, with a change of 0.025 A, there is a change in the load (output torque T_2) in five different levels. Changing the input rotational speed is also done using the potentiometer located on the control unit [13, 14]. Tests were performed at rotational speeds of 1500 min^{-1} and 2500 min^{-1}, where high viscosity mineral oil ν_{40} =1000 mm^2/s. is used for lubrication.

The efficiency is determined based on the known values of input P_1 and output power P_2 according to the following expression:

$$\eta = \frac{P_2}{P_1} \qquad (1)$$

The efficiency values are recorded every 5 minutes after the check and its average value is determined. Based on the obtained experimental results, power losses are calculated for different working modes of the worm gear.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The values of the efficiency are determined according to the expression (1) for different working conditions of the worm gearbox. Based on the obtained results, a diagram of the dependence of the efficiency and the output torque T_2 was constructed, which is shown in the Figure 2.

It can be seen from the diagram that the values of the efficiency increase with the increase of the load (output torque). The values of the output torque on this occasion range from 2.24 Nm to 5.56 Nm. On the other hand, the values of the efficiency increase with the increase of the input rotational speed (circumferential speed of the gears). These values range between 0.50 and 0.60 for an input rotational speed of 1500 min^{-1} and between 0.53 and 0.62 for an input rotational speed of 2500 min^{-1}. Therefore, with an increase in the circumferential speed, the values of the efficiency increase by 3% to 5% depending on the load level.

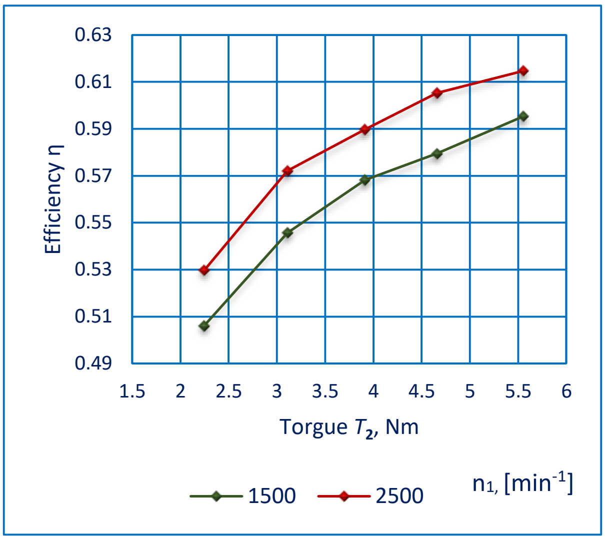

Figure 2. Values of the efficiency depending on rotational speed n_1 and output torque T_2.

Based on the experimental results, the total power losses of the worm gear were calculated, consisting of power losses in the gear meshing P_{GZ}, power losses in the bearings P_{GL} and power losses in the shaft seals P_{GD}. First, the calculation of power losses in the bearings and seals of the drive and driven shafts was performed.

Power losses in rolling bearings largely depend on the amount of friction. These losses are usually the second largest in total power loss. For the precise determination of these power losses, a mathematical calculation by the bearing manufacturer SKF was applied. According to this calculation, power losses in one bearing are determined according to the following expression [15]:

$$P_{GL1} = 1{,}05 \cdot 10^{-4} \cdot M \cdot n \, . \qquad (2)$$

where are:
M - total bearing friction torque, Nmm and
n - rotational speed, min^{-1}.

Based on the calculation results, a diagram of the dependence of power losses in bearings P_{GL} and output torque T_2 was constructed for the values of the input rotational speed of 1500 min^{-1} and 2500 min^{-1} (Figure 3).

Based on the diagram (Figure 3), it can be concluded that the power losses in the bearings increase with the increase in circumferential speed. Also, these losses increase with increasing load. Namely, at an input rotational speed of 1500 min^{-1} and different values of the output torque T_2, the power loss values in the bearings range from 2.9 W to 4 W. However, with an increase in the input rotational speed to 2500 min^{-1}, these losses increase significantly and range from 4.6 W to 6.3 W. Depending on the load level, these power losses are greater between 47% and 58% compared to the previous mode of operation of the worm gearbox.

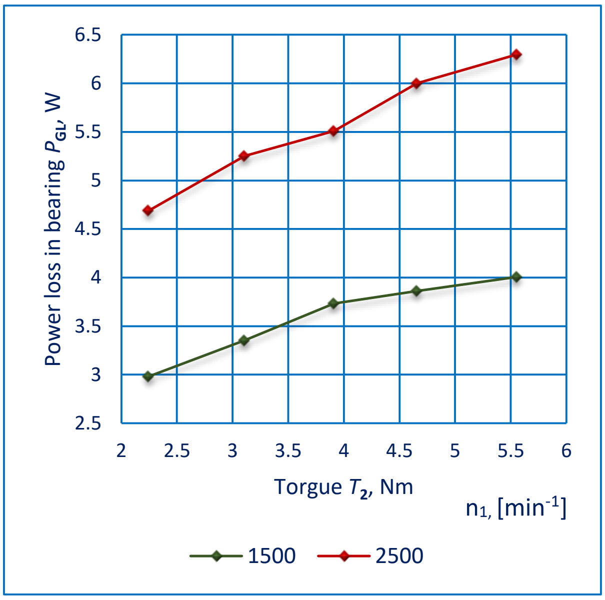

Figure 3. Addiction of power losses in bearings on the rotational speed n_1 and the output torque T_2

At higher circumferential speeds, more power is transmitted, which causes greater power losses in the bearings. As the circumferential speed increases, the operating temperature increases, and the viscosity of the oil decreases. As the viscosity of the oil decreases, the hydrodynamic resistance of the lubricant flow decreases, but the influence of inertial forces increases.

It should be noted that power losses differ in individual bearings, which largely depends on the operating mode of the transmission. Figure 4 shows the power losses in each bearing individually depending on the output torque T_2 for the input rotational speed 2500 min^{-1}.

Based on the diagram shown in Figure 4, it can be concluded that the greatest power losses occur in bearing B, and the smallest in bearing C. Bearing B is also the most loaded because axial and radial forces act in it, which resulted in the greatest power losses. The second largest are the power losses in bearing A, where only the radial force acts. Due to the lower rotational speed of the worm gear shaft, the power losses in bearings C and D are significantly lower than the power losses in the worm shaft bearings A and B.

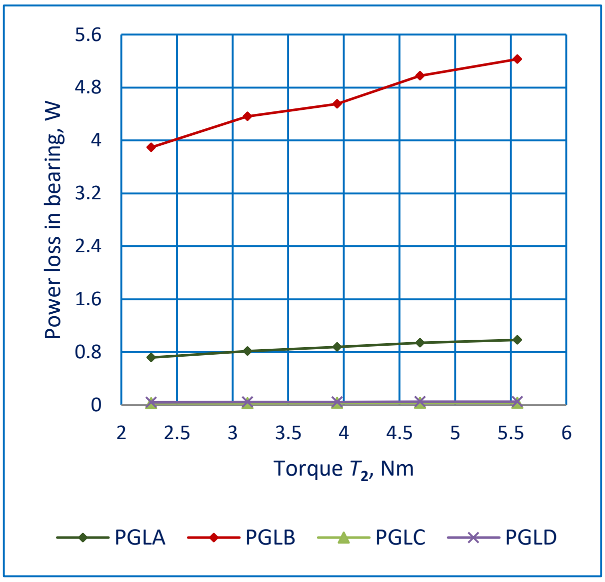

Figure 4. Power losses in bearings A, B, C and D for input rotational speed 2500 min^{-1}

Power losses in shaft seals represent the lowest power losses in a worm gear. These losses mainly depend on the rotational speed of the driving and driven shafts, as well as on the size of the diameter of the shaft at the place of the seal. The values of these losses are determined according to the following expression [12]:

$$P_{GD} = 7{,}9169 \cdot F_{D,\rho} \cdot \left(\frac{d_V}{1000}\right)^2 \cdot \frac{n}{60}. \qquad (3)$$

where are:

$F_{D,\rho}$ - factor that depends on the type of lubricants,

d_V - shaft diameter mm and

n - rotational speed, min^{-1}.

The biggest power losses in the worm gearbox occur due to friction in the gear meshing, especially at low circumferential speeds and high torques. These power losses are determined based on the known values of the efficiency η, the power losses in the bearings P_{GL} and the power losses in the seals, according to the following expression [12]:

$$P_{GZ} = P_1 \cdot (1-\eta) - (P_{GL} + P_{GD}). \qquad (4)$$

The results of the calculation of power losses in the gear meshing are shown in the Figure 5.

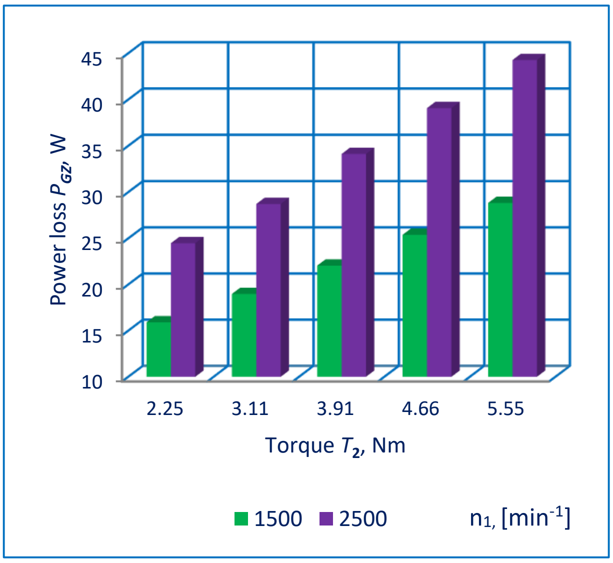

Figure 5. Power losses in the gear meshing for input rotational speed 1500 min^{-1} and 2500 min^{-1}

The diagram in Figure 5 shows the dependence of power losses and output torque for two different values of the rotational speed (1500 min^{-1} and 2500 min^{-1}). From the diagram, it can be seen that the power losses in the gear meshing increase with the increase in circumferential speed and load. With the increase in circumferential speed and load, the total transmitted power of the transmission also increases, and this leads to an increase in the working temperature of the oil. With a change in operating temperature, the viscosity of the lubricant changes and thus the thickness of the oil film between the meshing gear teeth, which has a direct impact on power losses. In this case, at a rotational speed of 1500 min^{-1}, power losses in the gear coupling range from 15 W to 29 W. However, when the rotational speed increases to 2500 min^{-1}, these power losses increase by 53% to 55%, taking into account all load levels. More precisely, with increasing circumferential speed, these power losses range from 24 W to 45 W.

Based on previously determined power losses, the distribution of the total supplied power P_1, which is supplied from the electric motor to the transmission, can be analyzed.

Figure 6 shows the percentage share of individual power losses for the last load level (average value of the input torque 5.56 Nm) and the rotational speed from 2500 min^{-1}.

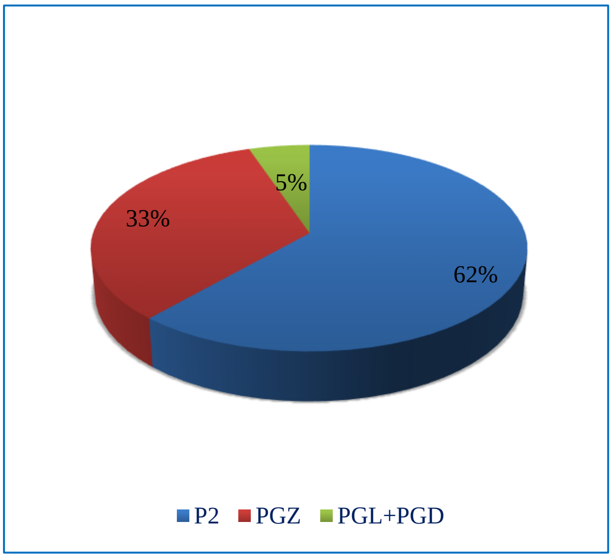

Figure 6. Power losses and useful power of the worm gear for the last load level

Based on the diagram shown in Figure 6, it can be concluded that the greatest power losses occur due to friction in the meshing between the worm teeth and the worm gear P_{GZ}, which amount to 33%. Power losses in the bearings and shaft seals (P_{GL}+P_{GD}) are considerably smaller in size, amounting to 5%, while the useful power on the output shaft of the P_2 transmission is 62%. These data indicate that more than a third of the total supplied power of electric motor P_1 is lost and converted into heat.

4. CONCLUSION

Based on the conducted research, it can be concluded that working conditions have a significant impact on power losses and the efficiency of the worm gearbox. The change in working conditions was achieved by varying two values of the input rotational speed numbers and five load levels.

Analyzing the obtained results, it can be seen that the values of the efficiency increase with the increase in volume speed and load. Namely, with an increase in the input rotational speed from 1500 min^{-1} to 2500 min^{-1}, the values of the efficiency increase between 3% and 5%, depending on the load level. The highest value of the efficiency was achieved at the input rotational speed of 2500 min^{-1} and the highest level of load (average value of the output torque 5.56 Nm). On that occasion, the efficiency values ranged from 0.50 to 0.62, taking into account all working conditions. On the other hand, at higher circumferential speeds and loads, more power is transmitted, which leads to greater power losses in the worm gear. Thus, with an increase in circumferential speed, the power losses in the gear coupling increase between 53% and 55%, while the power losses in the bearings increase between 47% and 58%, depending on the load level.

By analyzing the total power losses and useful power on the output shaft of the worm gear, the conclusion is drawn that more than a third of the total supplied power goes to losses and is converted into heat. More precisely, the greatest power losses occur in the meshing of gear teeth, which amount to 33%, followed by power losses in bearings and shaft seals, which amount to 5%, while the useful power on the output shaft is 62%.

Experimental results unequivocally show that through an adequate selection of lubricants, working conditions, materials and other factors, the power losses of the worm gear can be significantly influenced. This research is of great importance for engineering practice because it provides the opportunity to obtain all relevant information about the behavior of the transmission in operational conditions during the design phase of the worm gear.

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