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To cite this article: S Z Radosavljevi *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **393** 012050

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# Determination of power losses in worm gear reducer

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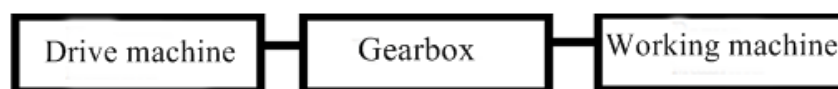
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**Abstract.** In this paper are presented the power losses and sources of their occurrence in worm gear reducer. These are the losses that occur in the coupling of worm teeth and worm gear, losses in bearings, seals and oil churning power losses in the transmission. Power losses are determined for the actual model of worm gear reducer, on the specialized testing device AT200 at the Center for testing power transmission at the Faculty of Engineering in Kragujevac, Serbia. The total losses are determined for different values of input number of revolution, output torque and by variation of types of oil, according to the pre-defined experiment plan. The aim of the paper is an experimental proof of theoretical assumptions of the influence of various factors on losses in the worm gear reducer.

## 1. Introduction

The transfer of mechanical energy (Figure 1) from the drive to the working machine is achieved by means of transmission shafts, couplings and gearboxes. In contrast to transmission shafts and couplings, gears can carry out transformations of the speed, torque, and sometimes direction of rotation [1].

The gearboxes transmit the movement and torque from one shaft to the other by means of a link made by a toothed gear. During this transfer, there is a certain transformation of the number of rpm and torque. The gear pairs are the simplest form of a gear boxes composed of two gears. One gear is drive, while other is driven. The drive gear transmits movement and torque to the driven. The gears forming a pair of gears are called coupled gears [2].



**Figure 1.** Scheme of mechanical energy transfer.

The worm pair or worm gearbox is a type of gearbox whose axis passes, most often at an angle of  $90^\circ$ . The worm gear unit consists of a worm gear (1) and a worm (2) shown in Figure 2. The angle at which the axes pass by can be greater or less than  $90^\circ$ . If the driving part of the gearbox is a worm then a reduction in the speed is performed, and if the worm gear is a drive part then the multiplication of the speed is performed. Since the efficiency of the multiplier is much smaller, worm gearboxes are most commonly used as reducer [2].





**Figure 2.** Worm gear and worm.

## 2. Efficiency of worm gearboxes

The ratio of output and input power is efficiency of gearboxes. Compared to other types of gearboxes, the worm gearbox has a lower value of the efficiency. The reason for the difference between the input and the output power is the power losses occurring in the gearbox. The efficiency of the worm gearbox is determined as the ratio of the output power to the input [2,3]:

$$\eta = \frac{P_{izl}}{P_{ul}} = \frac{P_{ul} - P_G}{P_{ul}} = 1 - \frac{P_G}{P_{ul}} < 1 \quad (1)$$

where :  $P_{ul}$  - input power [W],  $P_{izl}$  - output power [W],  $P_G$  - total losses of power [W];

From the previous expression, it can be concluded that the output power is equal to the difference in the input power and the power lost to various types of resistance, which is mostly converted into heat. The degree of loss is the relationship between the power that is lost and the input power, and it can be concluded from the previous expression that if this ratio is lower the efficiency is higher and vice versa. If  $P_1$  is power applied on worm, and  $P_2$  is power applied on worm gear, in the case where the worm is drive element, the efficiency can be expressed as [2,3]:

- In case where worm is drive element:

$$\eta = \frac{P_1 - P_G}{P_1} = \frac{P_2}{P_2 + P_G} \quad (2)$$

- In case where worm gear is drive element:

$$\eta = \frac{P_2 - P_G}{P_2} = \frac{P_1}{P_1 + P_G} \quad (3)$$

## 3. Power losses in worm gearbox

The total power losses occurring in the worm gearbox consist of the loss of power due to the slip resistance of the worm pair during movement  $P_{Gz}$ , the power loss occurring in the bearings  $P_{GL}$  and the loss of power during idling  $P_{G0}$ . So the total power losses can be determined as [2,3]:

$$P_G = P_{Gz} + P_{GL} + P_{G0} \quad (4)$$

The loss of power due to the slip resistance of the worm pair during movement, can be determined as [2,3]:

$$P_{Gz} = F_N \cdot \mu_z \cdot v_k \quad (5)$$

where are:  $F_N$  - normal force on the side of the tooth [N],  $\mu_z$  - coefficient of friction of worm gear pair,  $v_k$  - sliding speed [m/s], which can be determined by the following expression [2,3]:

$$v_k = \frac{\pi \cdot d_{m1} \cdot n_1}{60 \cdot \cos \gamma_m} \quad (6)$$

where:  $d_{m1}$  - is middle circle diameter [m],  $n_1$  - is rpm of worm [ $\text{min}^{-1}$ ],  $\gamma_m$  - is an angle of inclination of the coil.

The loss of power during idling can be determined by the following expression[2,3]:

$$P_{G0} = 10^{-7} \cdot a \cdot \left(\frac{n_1}{60}\right)^{4/3} \cdot \left(\frac{V_{40}}{1,83} + 90\right) \quad (7)$$

where:  $a$  - is a distance between the axes [mm],  $n_1$  - is rpm of worm [ $\text{min}^{-1}$ ],  $V_{40}$  - is a kinematic viscosity of oil on  $40^\circ$  [ $\text{mm}^2/\text{s}$ ].

The power loss occurring in the bearings can be determined by the following expression [2,3]:

$P_{GL} = P_1 \cdot (0,005 \dots 0,01)$  - if roller bearings are embedded on the shafts of worm and worm gear.

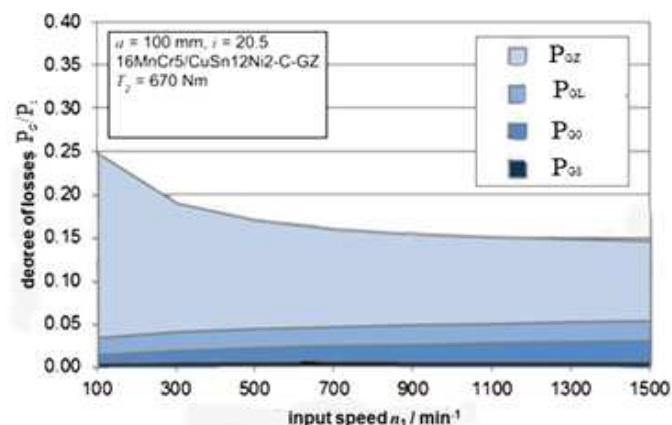
$P_{GL} = P_1 \cdot (0,02 \dots 0,03)$  - if sliding bearings are embedded on the shafts of worm and worm gear.

A number of authors have researched the influence of different factors on power losses in worm gearbox. Miltenovic et al. [4] have researched power losses in worm gear, in which there was synthetic oil GH6-1500, at the value of the input number of revolutions of  $5000 \text{ min}^{-1}$  and different values of the output torque. The measured efficiency values ranged in the interval of  $\eta = 0.52 \div 0.71$ , where the higher values were found at higher load.

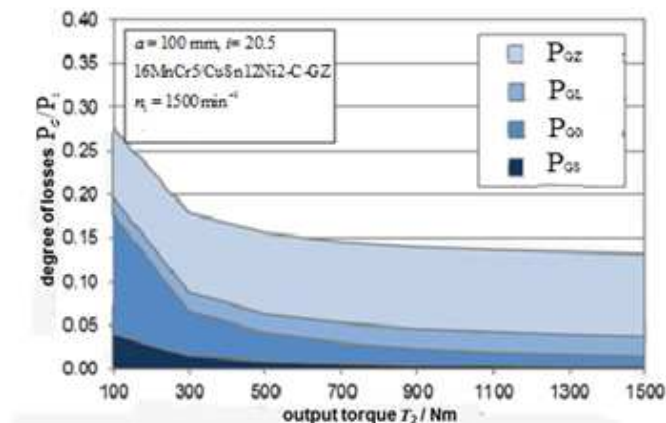
Stockman et al. [5] have tested the efficiencies of thirteen different gearboxes, using specially designed equipment, and found that at higher input torques and lower transmission ratios, the higher efficiency values are obtained. Mautner et al. [6] used FZG equipment to test the influence of viscosity and type of the oil on efficiency of a large sized worm gearing with center distance  $a=315\text{mm}$ . By using the high viscosity synthetic polyglycol oil (ISO VG 460) the measured efficiency values were higher compared to lower viscosity synthetic oil (ISO VG 220). Herman [7] and Muminovic et al. [8] have also emphasized the advantages of the usage of syntactic oils compared to mineral oils, where the higher efficiency values were obtained.

#### 4. Factors which affect the loss of power

In order to reduce the power losses occurring in the worm gearbox, it is necessary to choose the ideal combination of geometric parameters, lubrication, materials, working conditions, etc. It is therefore very important to know which parameter and how much it affects the losses of power in the worm gearbox [9]. Below are some of the parameters that affect the power loss of the worm gearbox. The influence of the input number of revolutions to the power losses are shown in figure 3.



**Figure 3.** The influence of the input number of revolutions to the power losses [10].

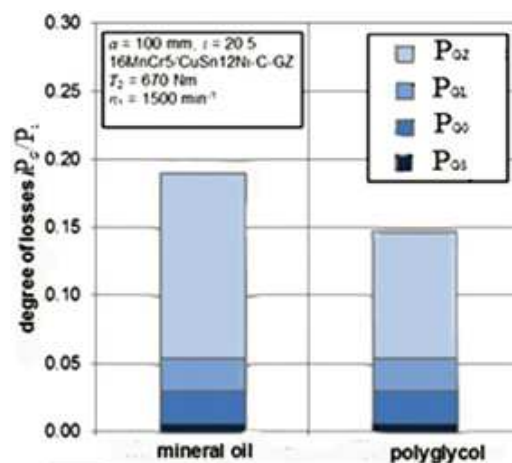


**Figure 4.** The influence of the output torque to the power losses [10].

In this regard, the lower value of the rotational speed leads to greater power losses. The part of the loss in the gearbox  $P_{GZ}$  increases with the reduction in the value of the input rotational speed, because the friction coefficient in the contact zone increases, when the number of rotations rises. The impact of loss in bearings and losses in idle mode is reduced with a decrease in the value of the speed, but none of these effects has such a large impact as the gearing losses [11]. As the value of the input speed affects the efficiency, the output torque also influences the efficiency of the worm gearbox. Usually lower values of the output torque affect the lower value of the efficiency. By examining the medium-sized worm gearboxes, in the work [12], the previous assertion was proved. Figure 4 shows the effect of the output torque to the power losses [11].

Regarding the influence of the viscosity of the lubricant on the efficiency, the viscosity lubricants 220 and 460 were tested under the same test conditions (input speed  $n_1 = 300 [\text{min}^{-1}]$  and output torque  $T_2 = 10 [\text{kNm}]$ ). It has been observed that a higher efficiency is obtained with higher oil viscosity values [11].

The influence of the lubricant type on the efficiency of the worm gearbox is high. Generally, synthetic lubricants lead to a reduced friction coefficient compared to mineral oils. Lower power losses and, therefore, a higher efficiency come with a lower friction coefficient [21]. The effect of the oil type is also described in DIN 3996 [10]. The worm gearbox, which has a mineral oil as a lubricant, has a higher value of power losses than those lubricated with polyglycol. Figure 5 schematically depicts the effect of the type of oil on the power losses of the worm gearbox [11].

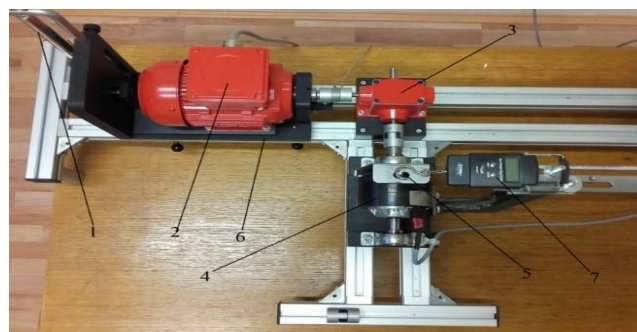


**Figure 5.** The influence of the oil type to the power losses [10].

Figure 5 clearly shows that the only effect of lubricant on the power losses is exactly the loss of the gearing. This is explained by the fact that the higher the friction coefficient is when the lubrication is carried out with mineral oil. Other effects are not influenced by the type of oil.

## 5. Results

Worm gear reducer was tested on the AT 200 device shown in Figure 6 a). The AT 200 is used for determining the efficiency of gears; the basic parts of the device are: 1-dynamometer at the input, 2-motor, 3-worm gear reducer, 4-brake, 5-brake lever, 6-chassis and 7-dynamometer at the output. This device is connected to the control unit (Figure 6b) at which the input number of revolutions is regulated, that is, the number of revolutions of the motor shaft, as well as the braking force of the brake also regulated on the control unit [13].



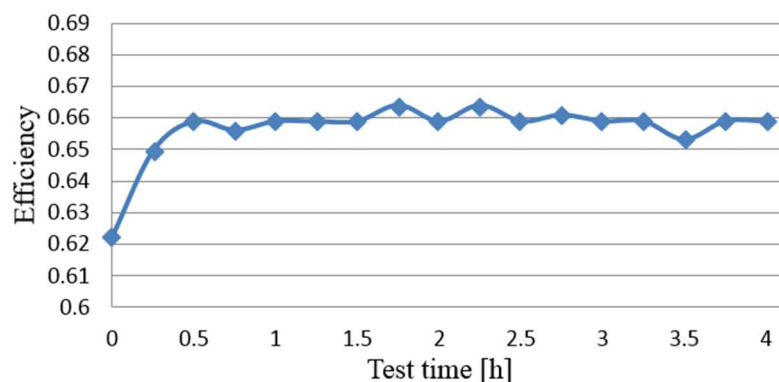
(a)



(b)

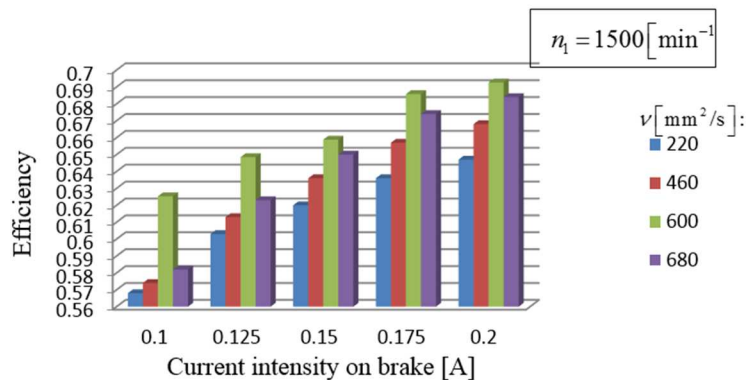
**Figure 6.** Device AT 200 (a) and control unit (b) [13].

The values of the current intensity on the brake, the input speed, and the type of lubricant were varied, i.e. lubricants with different viscosity values were used. Current intensity values vary from 0.1 [A] to 0.2 [A], with a change interval of 0.025 [A]. The values of the input speed were 1500 [min<sup>-1</sup>], 1750 [min<sup>-1</sup>], 2000 [min<sup>-1</sup>], while the lubricants used for testing had a viscosity value of 220 [mm<sup>2</sup>/s] 460 [mm<sup>2</sup>/s], 600 [mm<sup>2</sup>/s], and 680 [mm<sup>2</sup>/s].

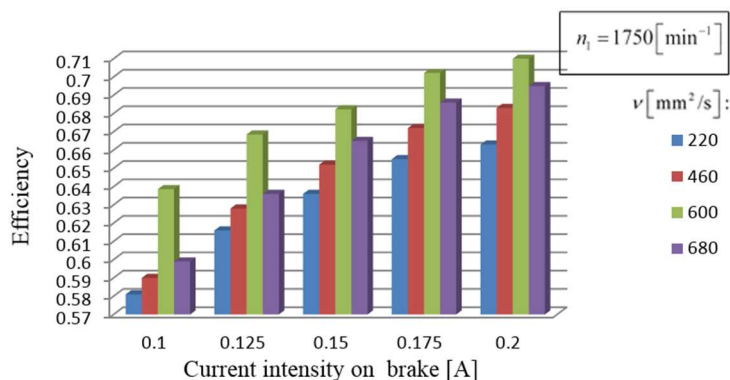


**Figure 7.** Efficiency depending on the test time.

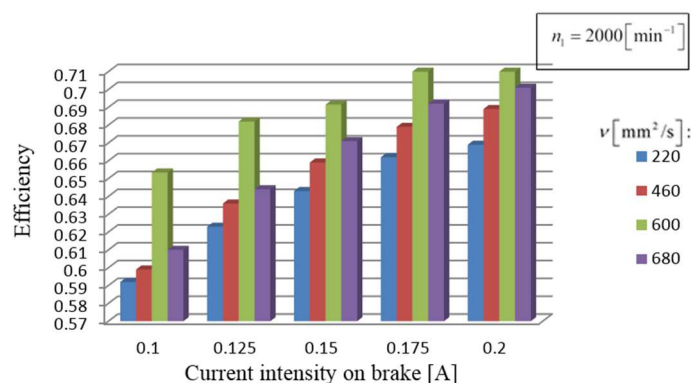
The test was carried out by changing the value of current intensity on the brake for one value of the oil, for the same values of the input speed, i.e., the value of the output torque. The value of the current intensity changed from 0.1 [A] to 0.2 [A], on every 1.5 hours by 0.025 [A], which is a total of eight hours for one type of lubricant and one value of the input speed. For a current intensity of 0.1 [A], the test lasted 2 hours, because worm gearbox needed 30 minutes to achieve the operating temperature and it is only then that the lubricant formed hydrodynamic layer (Figure 7). The reading of the results was carried out every 15 minutes. Figures 8, 9 and 10 show the influence of the lubricant viscosity value on the worm gearbox efficiency value for the different values of the input rotational speed.



**Figure 8.** Influence of the oil viscosity value on the efficiency of worm gear reducer for input rotational speed of 1500 [min<sup>-1</sup>].



**Figure 9.** Influence of the oil viscosity value on the efficiency of worm gear reducer for input rotational speed of 1750 [min<sup>-1</sup>].



**Figure 10.** Influence of the oil viscosity value on the efficiency of worm gear reducer for input rotational speed of 2000 [min<sup>-1</sup>].



## 6. Analysis of results

On all diagrams of the dependence of current intensity on brake on worm gearbox efficiency, at different values of the input speed and the viscosity of the lubricant, it can be seen that with the increase in the value of the output torque the efficiency of the worm gearbox also increases. This is explained by the fact that, when increasing the output torque, the losses that occur during the operation of the worm gear are drastically reduced in accordance with the literature [10] and [12]. In previous diagrams showing the efficiency for the same lubricant viscosity values but at different values of the input speed, it can be concluded from all diagrams that with the increase in the value of the speed, the efficiency of the worm gearbox also increases. A somewhat higher difference in the value of the utilization rate was observed between the value of the input speed 1500 [min<sup>-1</sup>] and 1750 [min<sup>-1</sup>], rather, between the value of the input speed 1750 [min<sup>-1</sup>] and 2000 [min<sup>-1</sup>], for all four values of the viscosity of the lubricant. With the increase in the value of the input speed, there is a reduction in the losses that occur in the worm gear. Losses in gears  $P_{GZ}$  have the greatest impact on the reduction, as with the increase in the speed, the friction coefficient in the contact zone and consequently losses are reduced. Also, as the number of rpm increases, the losses in bearings  $P_{GL}$  and losses in the empty stroke  $P_{GO}$  are reduced, but their influence is considerably lower, according to the literature [11].

In the previous diagrams showing the dependence of the viscosity of the lubricant on the efficiency of worm gearbox, for all three values of the input speed, it can be concluded that increasing the value of the viscosity increases the value of the efficiency. It is important to note that the increase in the value of the efficiency with the increase in viscosity for the lubricants of the manufacturer FAM (viscosity lubricants 220 [mm<sup>2</sup>/s], 460 [mm<sup>2</sup>/s] и 680 [mm<sup>2</sup>/s]), is clearly seen. Increasing the viscosity leads to an increase in power loss at idle speed, but less overall loss, as the lubricant film is better formed in the contact zone, so the losses are less, in accordance with the literature [11]. Also, there is a clear difference between the lubricants which value of viscosity are 220 [mm<sup>2</sup>/s], 460 [mm<sup>2</sup>/s] and 680 [mm<sup>2</sup>/s]) and lubricants which viscosity is 680 [mm<sup>2</sup>/s]), significantly higher values of efficiency were obtained for the lubricant which viscosity is 680 [mm<sup>2</sup>/s]), even for a lower value of output torque. It is important to note that larger differences are observed at lower values of the current intensity on the brake, i.e. the lower values of the output torque, but at higher values where this difference is significantly lower. The differences that occur are due to the types of lubricants, because the lubricants with viscosity value of 220 [mm<sup>2</sup>/s], 460 [mm<sup>2</sup>/s] and 680 [mm<sup>2</sup>/s]) are mineral oils, and the lubricant which viscosity is 680 [mm<sup>2</sup>/s]) is synthetic grease. Losses in gears are significantly higher in lubrication with mineral lubricants due to the higher friction coefficient in the contact zone. Other losses and their impact on total losses do not depend on the type of lubricants, in accordance with literature [11] and [10].

## 7. Conclusion

Power losses in gearbox vary from 0.5% to over 80%, therefore more attention is paid to ways for their reductions in order to increase the value of efficiency. Regardless of the fact that worm gears have a lower value of efficiency than other gears with the same transmission ratio and dimensions, they are still very interesting because they are simple and inexpensive. Improving their efficiency is in line with the continuous development of standards. Different working conditions of worm gear reducer lead to different values of efficiency. At higher input rotational speed and higher output torques, higher efficiency values were measured. The type and viscosity of the oil have a great influence on the efficiency of the worm gearbox. Numerous studies have shown that smaller losses, or higher efficiency, occur with the use of synthetic lubricants in relation to mineral, which has been proven in this work. Synthetic lubricants are more expensive but over time they pay due to a number of advantages over mineral. Since in practice it is impossible to achieve absolute efficiency (lossless operation), the main task of the constructor becomes that constructive solutions in terms of choosing geometry, materials, but more and the type and viscosity of lubricants to reduce power losses as much as possible. In this paper it is justified that the correct selection of input rotational speed, output torque, type of lubricants and viscosity can reduce losses and increase the efficiency.



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