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THE INFLUENCE OF LUBRICANT VISCOSITY ON THE EFFICIENCY OF WORM GEAR REDUCER

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Abstract: *The results of testing the influence of lubricant viscosity on the efficiency of the worm gear reducer are presented in this paper. The results are performed on the specialized testing device AT200 at the Center for testing power transmission at the Faculty of Engineering in Kragujevac, Serbia. The efficiency of worm gear reducer is determined for different values of input number of revolution, output torque and by variation of two types of oil. The lubricant of viscosity of 220 mm²/s and 680 mm²/s are used in the tests. The tests are performed according to the pre-defined experiment plan. The analysis of the results shows that the efficiency of the worm gear reducer increases with the increase of the number of revolutions of the input shaft, braking torque (current intensity of the brake), and the viscosity of the oil.*

Key words: *efficiency, worm gear, power.*

1. INTRODUCTION

Worm gears are widely used in technical systems both due to the possibility of achieving high speed ratios and due to the low cost of production. These gears generally have small dimensions, and they can also work as a reducer and as a multiplier. [1]

One of the main characteristics of the gear is the degree of efficiency. Despite the very low value of the degree of efficiency, the worm gears are widely applied. Numerous factors influence the degree of efficiency of warm gears, such as: the materials from which they are made, the viscosity and type of lubricants, the speed ratio, the gear type (reducer or multiplier), axial distance, operating conditions, temperatures, etc [2].

M.Turci et al. [1] were determining the degree of efficiency of worm gear reducer of the mutual distance of 50 mm, of the speed ratio of 49 and for the different types of lubricants they obtained the values of the degree of efficiency of $0.572 < \eta < 0.64$. Đ. Miltenović et al. [3] tested of the strength losses of the worm gear, in which there was a synthetic oil GH6-1500, at the value of the input number of revolutions of 5000 $\min^{-1}$ and different values of the output torque, and they obtained the value of degree of efficiency $0.52 < \eta < 0.71$. B.Magyar and B.Sauer [4] tested the values of the degree of efficiency at the lubricant temperature of 60^0C and output torque of $T_2 = 430$ Nm by which they obtained the degree of efficiency of $0.65 < \eta < 0.74$ for different values of input number of revolutions. H.Siebert [5] determined different types of lubricants on the degree of efficiency of the worm gear reducer, at the speed ratio of 39, the input number of revolutions of 350 $\min^{-1}$, and the output torque of $T_2 = 200$ Nm, and therefore he obtained the results of the degree of efficiency of $0.62 < \eta < 0.80$. According to the catalogue of the NORD Company [6], the value of the degree of efficiency of the worm gear reducers is within the range of $0.4 < \eta < 0.9$.

The influence of lubricant viscosity on the degree of efficiency of the worm gear reducer was analysed in this paper. Two types of lubricants were used in the testing, and the tests were performed for different types of values of input number of revolutions and output torque. The results show that the degree of efficiency of the worm gear reducer increases with the increase of the lubricant viscosity, input number of revolutions and output torque.

2. WORM GEARS

The worm gear pair or the worm gear is a type of gear whose axes pass by each other, mostly at the angle of 90°C. The worm gear consists of worm wheel and worm shown in the Figure 1. The angle at which the axes pass by each other can be greater and less than 90°C. If the driving part of the gear is a worm, than the reduction of the number of revolutions is done, and if the worm wheel is a driving part, than the multiplication of the number of revolutions is done. Since the values of the degree of efficiency are less than 0.5, the worm gear pair is rarely used as a multiplier [7].

It can be said that the worm gear pair is a sliding joint. One of the parts in the joint is made of a softer material (worm wheel), and the other part of the material of the greater hardness (worm), in order to achieve the function according to the principle of intensive sliding. So therefore, the worm gear is made of bronze, aluminum alloys, zinc alloys, pearlite grey and nodular cast, brass, and the worm is made of cemented steel with a hardness of up to 62 HRC as well as of induction and flame hardened steel which are used for high loads [7,8].

Figure 1. Worm wheel and worm

The basic characteristics and advantages of worm gears are:

- Very high speed ratio; In the case of reduction, the values of the speed ratio are $5 < i < 70$, and in the case of multiplication, they are $5 < i < 15$.
- Quieter operation and considerably lower dynamic shocks and vibrations that allow tooth on a tooth sliding.
- Long lifetime if the accuracy of the manufacture, assembly rules, good selection of materials and lubrication are respected.
- In comparison to other gears, they are usually smaller and cheaper.
- They could be a self-braking gears.
- The possibility of changing the direction of rotation of the worm wheel without structural changes so that the worm can be made with the right and left thread.
- It is possible to perform input and output power on the worm, as well as on the worm wheel from the both sides, which allows them to branch or distribute the energy by connecting a large number of worm gears [7,8,9].

The disadvantages of the worm gear are:

- Large amount of heat and energy loss due to high slide resistance.
- Relatively low degree of efficiency.

3. DEGREE OF EFFICIENCY OF WORM GEAR REDUCER

The ratio of invested and useful strength represents the degree of efficiency. In comparison to other types of gear reducers, the worm gear reducer has a lower value of the degree of efficiency. The reason for the deviation of the invested and useful strength are the strength losses occurring in the gear reducer.

If the strength on the worm is marked with P_1, and the strength on the worm gear is marked with P_2, in the case where the worm is a drive element, the efficiency can be expressed as [7,8]:

$$\eta = \frac{P_2}{P_1} = \frac{T_2\omega_2}{T_1\omega_1} = \frac{\omega_2}{\omega_1}\frac{F_{t2}\cdot d_2/2}{F_{t1}\cdot d_1/2} = = \frac{F_{t2}}{F_{t1}} tg\gamma_m = \frac{tg\gamma_m}{tg(\gamma_m+\rho)} \quad (1)$$

The equalities were taken into account, when expressing the equation:

$$i = \frac{d_2}{(d_1 tg\gamma_m)} \text{ and } F_{t2} = F_{a1} = \frac{F_{t1}}{tg(\gamma_m+\rho)} \quad (2)$$

The equivalent angle of friction and the lead angle on the middle cylinder of the worm follow from the equation:

$$tg\gamma_m = \frac{z_1}{q}; \ \rho = arctg\,\mu_z \quad (3)$$

where z_1 is a number of thread of the worm, q is a worm number and ρ is an equivalent angle of friction.

If assumed that $\rho \approx \gamma_m$, then the degree of efficiency can be expressed as following:

$$\eta = \frac{tg\gamma_m}{tg(\gamma_m+\rho)} = \frac{tg\rho}{tg2\rho} = \frac{1-tg^2\rho}{2}$$
$$\eta = \frac{tg\gamma_m}{tg(\gamma_m+\rho)} = \frac{tg\gamma_m}{tg2\gamma_m} = \frac{1-tg^2\gamma_m}{2} \quad (4)$$

The degree of efficiency increases with the increase of the lead angle to a certain maximum, and then it decreases. When the lead angle is $\gamma_m = 45^o$, the maximum value of the degree of efficiency of worm gear reducer is obtained. For the values of the lead angle $\gamma_m < 45^o$, the value of the degree of efficiency rapidly decreases, so it is recommended to use the higher angle values of the thread of the worm or to use the multi-start worms, but in doing so, the lower speed ratios are obtained [7,8].

A large number of parameters influence the degree of efficiency, among which there is one of the main types of materials, from which the worm and worm wheel are made. The extensive velocity is also an important factor that influences the degree of efficiency, because at higher extensive velocity, it is easier to create an oil film between the meshed flanks, which increases the degree of efficiency itself, as well as the worm type [8].

The total losses of energy or power occurring in the worm gear reducer consist of power losses due to the slide resistance of the worm gear pair during the movement P_{Gz}, the power loss occurring in the bearings P_{GL} and the power loss at idle motion P_{G0}. So that total power losses can be determined as following [7,8]:

$$P_G = P_{Gz} + P_{GL} + P_{G0} \quad (5)$$

If the power of the worm is marked as P_1 and the power on the worm wheel is marked with P_2, then the degree of efficiency of the worm gear, in case when the worm is drive element, can be expressed as following [7,8]:

$$\eta = \frac{P_1 - P_G}{P_1} = \frac{P_2}{P_2 + P_G} \tag{6}$$

The power lost in overcoming the slide resistance at mashing the worm gear pair, can be determined as following [7,8]:

$$P_{Gz} = F_N \cdot \mu_z \cdot v_k \tag{7}$$

where F_N - is a normal force on the tooth flanks, μ_z - a coefficient of friction of worm gear pair, v_k - sliding velocity which can determined by following equation:

$$v_k = \frac{\pi \cdot d_{m1} \cdot n_1}{60 \cdot \cos\gamma_m} \tag{8}$$

If the diameter of the middle cylinder is in meters and the number of revolutions of the worm is expressed in minutes.

The power loss of the worm gear reducer at idle motion can be determined as [7,8]:

$$P_{G0} = 10^{-7} \cdot a \cdot (\frac{n_1}{60})^{4/3} \cdot (\frac{v_{40}}{1.83} + 90) \tag{9}$$

where a [mm] – is a wheelbase, n_1 [$\min^{-1}$] – number of revolutions of the worm, v_{40} [$\mathrm{mm^2/s}$] - kinematic viscosity of oil on 40° C.

The following ratios are used for power loss in bearings depending on the bearing type used in the worm gear reducer [7,8]:

- $P_{GL} = P_1 \cdot (0.005...0.01)$ - if the roller bearings are built on the shaft of the worm and worm wheel.
- $P_{GL} = P_1 \cdot (0.02...0.03)$ - if the sliding bearing are built on the shaft of the worm and worm wheel.

4. DEVICE FOR TESTING THE DEGREE OF EFFICIENCY

The testing of the degree of efficiency was performed in the Center for testing power transmission at the Faculty of Engineering in Kragujevac, Serbia. Figure 2 shows the device AT200 on which the degree of efficiency was determined.

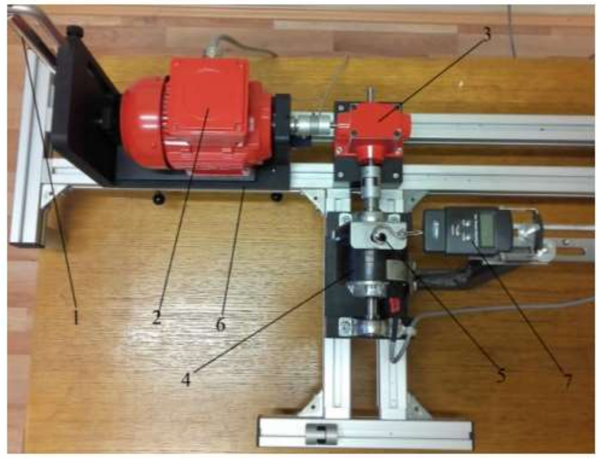

Fig.2: Device for testing the degree of efficiency - AT200

The device is used to determine the degree of efficiency of different gear transmissions and it contains the following parts (Figure 2):

1 - dynamometer at the input,

2 - motor,

3 - worm gear reducer,

4 - brake,

5 – brake lever,

6 - housing,

7 - dynamometer at the output.

The input torque of an electric motor is determined by using a 50 mm lever and a dynamometer. When the lever is placed in the horizontal position, and the force value on the dynamometer is read, with the help of the screw, the dynamometer remains locked at the given value. The electric motor is supported by two bearings. The tested worm gear reducer is connected to the electric motor via a claw coupling. The braking torque is calculated as the product of braking force and distance from the center of the brake to the place where the dynamometer is placed, and the length of this shaft is 100 mm. The brake consists of: the body of the brake and the shaft on which the brake is located. The brake is located on a multi-part stand, in order to allow the brakes to be connected to a different gear reducers. The entire device is placed on the frame.

The control unit (Figure 3) serves to adjust the input number of revolutions or the number of revolutions of the engine shaft as well as the braking force. The electric motor is powered from the control unit and the number of revolutions is adjusted by using a potentiometer. There is a sensor on the output shaft of the electric motor whose reading values are displayed on the control unit. The brake is also connected to the control unit and the braking force is regulated by the change of the current intensity.

Fig.3: Control unit

The degree of efficiency is calculated according to the following mathematical model [11]:
The input power is calculated according to:

$$P_1 = M_1 \cdot \omega_1$$

where:

$$M_1 = F_1 \cdot l_1$$

M_1 -is input torque EM [Nmm]; F_1 - balancing force [N]; l_1 - lever arm [mm];

ω_1 angular velocity [s^{-1}]:

$$\omega_1 = 2 \cdot \pi \cdot f_1$$

where:

$f_1 = \dfrac{n}{60}$ - is frequency.

Output power is calculated as:

$$P_2 = M_2 \cdot \omega_2$$

where:

$$M_2 = F_2 \cdot l_2$$

M_2 - output torque [Nmm] ; F_2 - balancing force [N]; l_2 - lever arm [mm]

ω_2 - angular velocity [s^{-1}]:

$\omega_2 = 2 \cdot \pi \cdot f_2$, where

$f_2 = \dfrac{n}{60}$ - is frequency.

The degree of efficiency is determined as the ratio between the output and the input power:

$$\eta = \frac{P_2}{P_1} \cdot 100, \%$$

5. TEST RESULTS

The degree of efficiency was determined on the previously described device for different values of the input number of revolutions and the output torque regulated by the current intensity on the control unit.
Table 1 and Table 2 show the values of the degree of efficiency of the worm gear reducer, for the viscosity of the lubricant 220 mm^2/s and 680 mm^2/s for the values of the input number of revolutions of 1500, 1750 and 2000, all with different values of output torque regulated by the current intensity on the control unit.

Table 1: Degree of efficiency of worm gear reducer for viscosity of lubricant ν=220 mm^2/s

	input number of revolutions [min^{-1}]		
current intensity [A]	**1500**	**1750**	**2000**
0.1	0.568	0.581	0.592
0.125	0.603	0.616	0.623
0.15	0.62	0.636	0.643
0.175	0.636	0.655	0.662
0.2	0.647	0.663	0.669

Table 2: Degree of efficiency of worm gear reducer for viscosity of lubricant ν=680 mm^2/s

	input number of revolutions [min^{-1}]		
current intensity [A]	**1500**	**1750**	**2000**
0.1	0.582	0.599	0.61
0.125	0.623	0.636	0.644
0.15	0.65	0.665	0.671
0.175	0.674	0.686	0.692
0.2	0.684	0.695	0.701

Figure 4 shows the values of the degree of efficiency of the worm gear reducer for the viscosity of the lubricant of 220 mm^2 / s and the difference that occurs when changing the output torque, regulated by the current intensity, on the control unit, can be easily noticed.

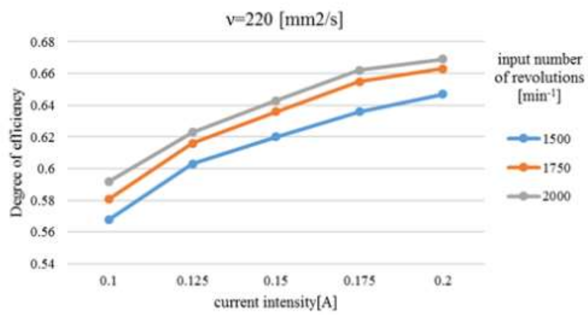

Fig.4: The value of degree of efficiency of worm gear reducer for viscosity of lubricants ν=220 mm^2/s

The values of the degree of efficiency of the worm gear reducer for the viscosity of the lubricant 680 mm^2/s are shown in Figure 5. It is also noticed that the difference occurs when changing the output torque, regulated by the current intensity, on the control unit.

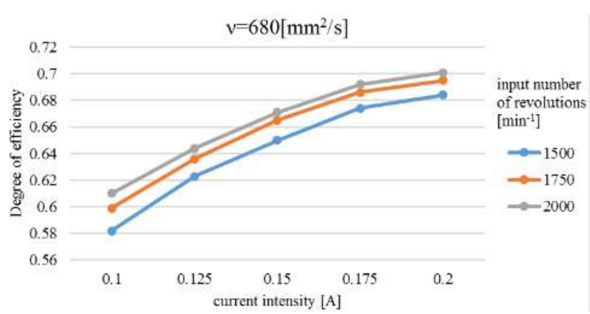

Fig.5: The value of degree of efficiency of worm gear reducer for viscosity of lubricants ν=680 mm^2/s

Figure 6 shows a comparative view of the values of the degree of efficiency for different viscosities depending on the input number of revolutions and current intensity, on the control unit.

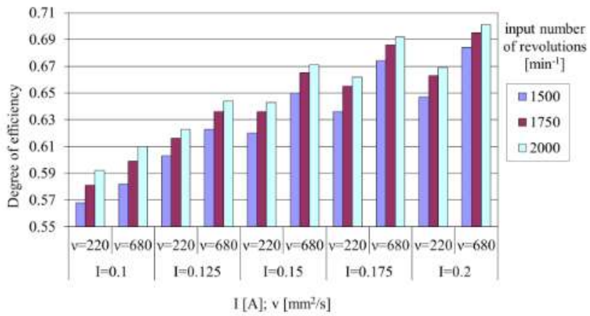

Fig.6: Comparative view of the values of degree of efficiency for different viscosities of lubricants

6. RESULT ANALYSIS

Table 1 and Figure 4 clearly show the proportional dependence of the value of the degree of efficiency from the output torque, regulated by the current intensity, on the control unit for the viscosity of the lubricant of 220mm^2/s. The value of the degree of efficiency increases with the increase of the value of current intensity or output torque. Table 2 and Figure 5 show that the degree of efficiency increases by using the lubricants of higher viscosity (680 mm^2/s) with the increase of the value of current intensity.

Likewise, it can be noticed that there is a difference in values of the degree of efficiency for a different values of the input number of revolutions. Figure 4 and Figure 5 clearly show that the degree of efficiency increases for the same currency intensity, or the output torque, with the increase of value of the input number of revolutions, for the tested worm gear reducer. The highest values of the degree of efficiency of the worm gear reducer are obtained for the value of the input number of revolutions of $2000\,\mathrm{min}^{-1}$, because the losses in the worm gear reducer decreases with the increase of number of revolutions.

The comparative view of the degree of efficiency for both types of lubricants is shown in the Figure 6 and it can be noticed that the degree of efficiency is always higher with the lubricants of higher viscosity than the one with lubricants of lower viscosity. The increase of the degree of efficiency for the both types of lubricants is noticed with the increase of the current intensity, and the highest degree of efficiency is obtained for the current intensity of 0.2 A, at the number of revolutions of $2000\,\mathrm{min}^{-1}$, and for the lubricant viscosity of 680 mm^2/s.

Also, the difference is clearly noticed in the trend of change of the degree of efficiency in relation to the current intensity for the lubricant viscosity of 220 mm^2/s, in relation to lubricant viscosity of 680 mm^2/s, because the lubricant viscosity of 220 mm^2/s is a mineral oil, while the lubricant viscosity of 680 mm^2/s is a synthetic grease.

The values of the degree of efficiency determined by the device AT200 are, for the most part, within the limits stated in the introduction of this paper. Somewhat higher values of the degree of efficiency occur due to the fact that the worm gear reducer is used for the purpose of testing, whose worm contains two threads. As shown in Figure 5, after the adjustment period, and if the worm contains two threads, the degree of efficiency is about 0.7, which are the values obtained by the experiment. Also, it is important to note that the slightly higher degree of efficiency is the consequence of the use of high viscosity lubricants.

7. CONCLUSION

Even though the worm gear reducers have the lower degree of efficiency than other reducers with the same speed ratio and sizes, they are still very interesting because they are simple and cheap.

The improvement of their degree of efficiency is done in pace with the continuous development of standard. If there is a tendency not to change the geometry of the worm gear reducer, the increase of the degree of efficiency can be made by the influence on the composition of the lubricant additive.

The tests have shown that the increase of the lubricants viscosity influence the increase of the degree of efficiency of the worm gear reducer. Also, the degree of efficiency increases with the increase of the number of revolutions of the input shaft and torque of the reducer output shaft. Make sure that the number of revolutions of the input shaft does not exceed $3000\,\mathrm{min}^{-1}$, because then, the degree of efficiency decreases due to the inability to form the lubricant layer

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