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Influence of Gears and Oil Levels Upon Efficiency of Ravigneaux Gearset

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Abstract: Nowadays planetary gearsets have found their use primarily due to meeting of reasonable requirements for reduction of mass and overall dimensions of gearsets, as well as due to ability to set upgear ratio within very wide limits which fact gives freedom to mechanical design engineers when solving various problems of power transmission and movement. This paper presents results of experimental research of power losses and determination of efficiency of multi-stage planetary gearset for which calculation, design and construction were done for that purpose. The research was conducted in the Center for testing mechanical power gearsets at the Faculty of Engineering University of Kragujevac. The device was made for switching gears and blocking of certain elements of gearsets: planetary carrier, small sun gear and big sun gear. On the grounds of defined experiment plan we determined in our research efficiencies in certain gears with defined number of rotations, different oil levels and appropriate values of brake force. On the grounds of results we got we could conclude that decrease of power losses along with increase of efficiencies are achieved by switching of gears, i.e. by gearing down. The important conclusion we made was that power losses increased and efficiencies decreased with increase of oil level while keeping the same number of rotations.

Keywords: efficiency; gearbox; multi-stage planetary gearset; oil level; power losses

1 INTRODUCTION

Multi-stage planetary gearsets are getting more and more used due to tightening of requirements for power transmission systems of higher quality in terms of energy and environment efficiency. These gearsets have a significant influence upon reduction of noise and vibrations. They reduce environmental warming thus contributing to environmental protection. Multi-stage planetary gearsets represent complex mechanical components with strict requirements in terms of manufacturing precision, high-quality semi-finished products and relevant expertise in making of technical and technological documentation [1-7].

It presents a challenge to determine power losses and increase of efficiency in planetary gearsets as early as in the product development phase. Many researchers in this area analysed in their papers influence of various factors on power losses in planetary gearsets which was in majority of cases also verified by experimental test results.

Hildebrand and others presented in their study [8] the analysis of influence of various parameters during interaction of rotating mechanical elements with fluid inside gearboxes leading to the flow of fluids and power losses. Their analysis was conducted for three different geometries of gears, three different types of mineral oil with different viscosity levels and three different depths of gear immersing during four different values of circumferential speed.

Concli and others presented in their paper [9] specific models for prediction of power losses in planetary gearsets which have additional power losses in comparison to ordinary gearboxes caused by movements (churning) of oil. Experiments were conducted for various number of rotations within the range of n=250-1500 rpm, for various temperatures within the range of 20-85 °C and for various static levels of oil ranging from −20 mm in reference to gearbox axis up to the level of total fullness of gearbox housing. Analysis of test results indicates that power losses increase with higher number of rotations for each level of oil and temperature, whereas they decrease with rise of oil temperature because of decrease of thickness and viscosity of fluid. Increase of static oil levels causes increase of power losses.

Zhu and Dai [10] proposed a number of formulas for prediction of power losses for gears that function while partially immersed in oil. The presented model uses depth of immersing in real time instead of static depth of immersing. The theorethical results got in this way largely correspond to experimental research. The maximum number of rotations during experiment is n = 12000 rpm. The results obtained from experimental research showed that when the number of rotations is over 2000 rpm churning losses are less; still they cannot be ignored.

In their study [11], Mastrone and others monitored the oil flow through a transparent cover of gearbox housing in planetary gears using a high-speed recording camera. They analysed numbers of rotations ranging from n = 81-324 rpm for two levels of immersing in oil, lower level up to the value of 3 of normal module size and upper level which corresponds to the level of medium gear line. With lower number of rotations oil rings occur because oil stays inside during contact with rotating parts and this phenomenon causes circular traces of oil, whereas with higher number of rotations, oil mostly splashes towards gearbox housing due to high centrifugal effects and forms a ring around gearbox housing walls.

Stavytsky and others in their paper [12] described the development of modern generalized methodology for calculation of hydrodynamic losses of power in high-speed gears. For each gear, whether partially or fully immersed into the oil bath, the power consumed to overcome hydromechanical resistance could be presented as the sum of the following losses: loss due to the action of Coriolis force, viscosity friction losses at the periphery of the gear and the viscosity friction at the face of the gear. Change of hydrodynamic losses with switching of gears is practically subject to the cubic parabola law but only up to a certain number of rotations i.e. up to n = 4000 rpm. In case of significant number of rotations n = 5000-7000 rpm, oil quantity inside housing decreases and power losses get slightly decreased due to hydrodynamic losses.

Tamade and his associates presented in their paper [13] the approach to designing a multi-stage planetary gearset applied in automotive industry with simpler and improved characteristics of efficiency of mechanical flow of power by use of CAD CAM modelling. They concluded that gearboxes with five speeds had a higher efficiency than gearboxes with seven speeds.

Hussen and others analysed in their paper [14] the losses resulting from gear sliding friction. In their paper, they also made an overview of previous methods for calculation of efficiencies of planetary gearsets that could be classified in two main categories. Papers [15-19] belong to the first category because in them the calculation of efficiency depends on balance of the system torque, whereas the second category includes the papers which rely on the concept of potential power i.e. papers [20, 21], concept of latent power - paper [22] and concept of virtual power papers [23, 24].

The main contribution of this paper is in the fact that an experimental determination of power losses i.e. efficiency was conducted on a calculated, designed and constructed Ravigneaux planetary gearset. It was determined that decrease of gears/speed causes increase of efficiency i.e. decrease of power losses. Increase of oil level with the same number of rotations decreases efficiency due to increased power losses.

2 DESCRIPTION OF EQUIPMENT

We conducted experimental tests of efficiency of multi-stage planetary gearset on equipment AT200 [25], presented along with electrical installation set-up in Fig. 1.

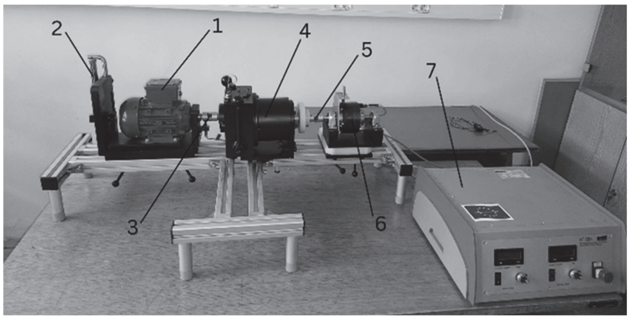

Figure 1 Equipment AT200 with electrical installation set-up

This equipment consists of electric motor (1), which has nominal power of 200 W and which rests with help of two bearings on the upper part of the stand and may be rotated around its longitudinal axis, dynamometer (2) used for measurement of input torque of electric motor, claw coupling connecting output shaft of electric motor and input shaft of gearset (3), tested multi-stage planetary gearset (4), claw coupling (5) connecting output shaft of gearset and shaft of electromagnetic brake (6) for setting brake force and control unit (7). Control unit may be used to adjust number of rotations of electric motor; values of brake force are defined by changing intensity of electric power in interval of 0-0.3 A, while the maximum brake torque that could be reached is10 Nm.

We did a calculation, design and construction of Ravigneaux gearset for the selected appropriate concept, as indicated in Fig. 2.

On the grounds of requirement for design, and in accordance with general equation of movement of Ravigneaux planetary gearset, we defined gear ratios of multi-stage planetary gearset as follows: $i_{PP1} = 3.909$; $i_{PP2} = 2.122$; $i_{PP3} = 1.891$ and $i_{PP4} = 1.344$. In accordance with the equipment available for performance of experimental research, we assumed a certain method of connecting the constructed planetary gearset and measuring equipment. One of the most important contributions of this constructive solution is the fact that we defined and built the device that will enable manual switching of gears and blocking of certain elements of planetary gearset (small sun gear, big sun gear and planetary carrier). Fig. 3 shows the case when the first gear is selected, whereas Fig. 4 shows blocked planetary carrier for the first gear.

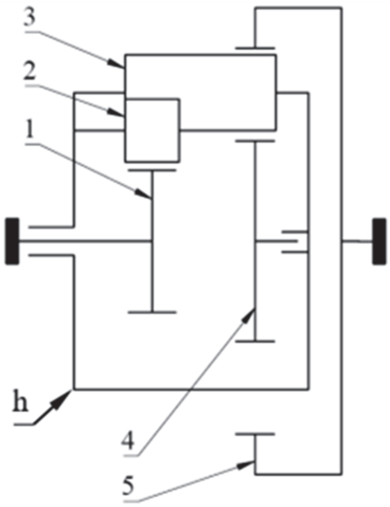

Figure 2 Schematic layout of Ravigneaux planetary gearset: 1) small sun gear, 2) planetary gear (satellite), 3) external planetary gear, 4) big sun gear, 5) sun gear with inner teeth, h) planetary gears carrier

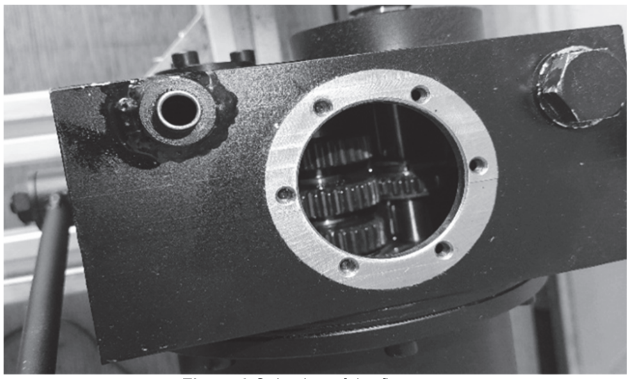

Figure 3 Selection of the first gear

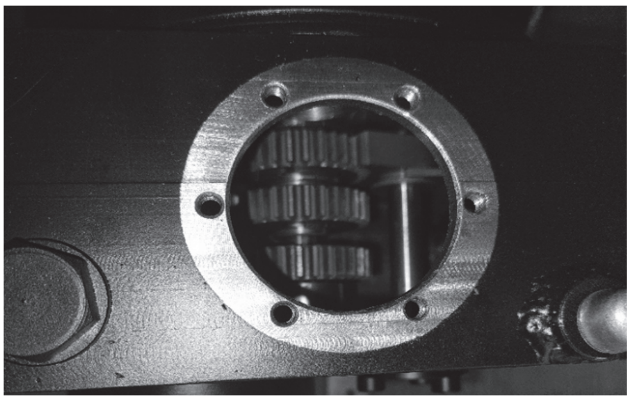

Figure 4 Blocking of planetary carrier for the first gear

Fig. 5 shows selection of the second gear, whereas Fig. 6 shows blocking of big sun gear for the second gear.

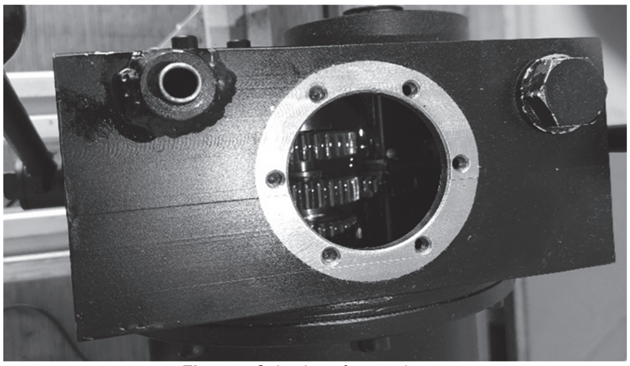

Figure 5 Selection of second gear

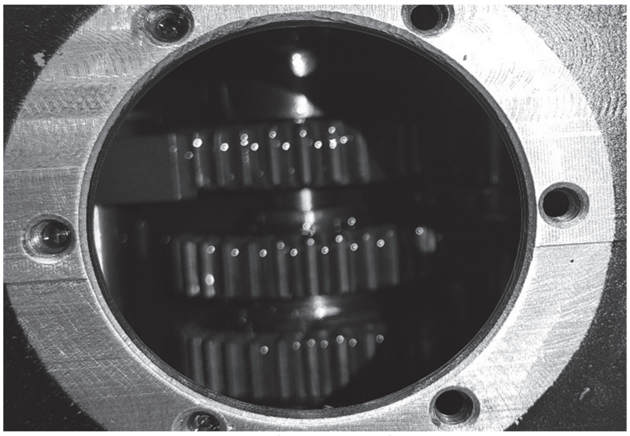

Figure 6 Blocking of big sun gear for second gear

Fig. 7 shows selection of the third gear, whereas Fig. 8 shows blocking of small sun gear for the third gear.

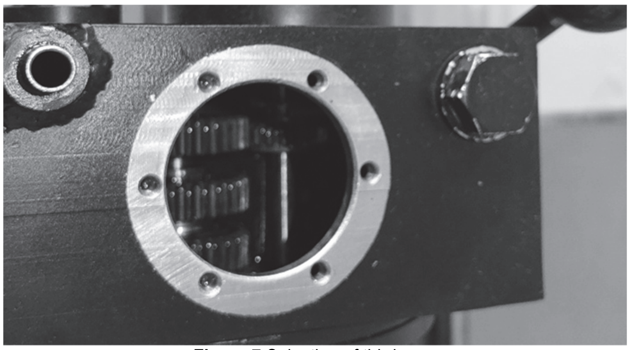

Figure 7 Selection of third gear

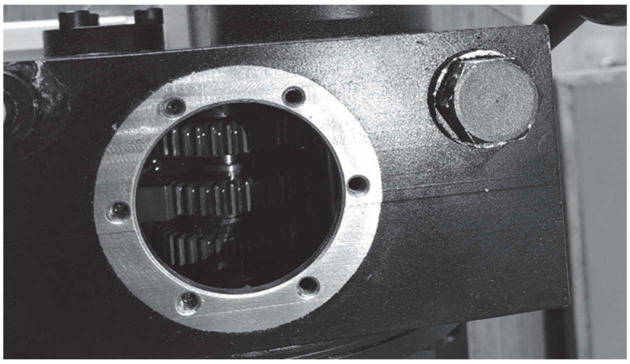

Figure 8 Blocking of small sun gear for third gear

Fig. 9 shows selection of the fourth gear, whereas Fig. 10 shows blocking of small sun gear for the fourth gear.

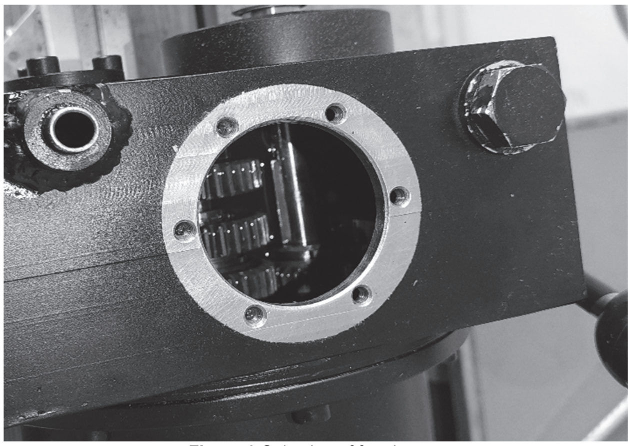

Figure 9 Selection of fourth gear

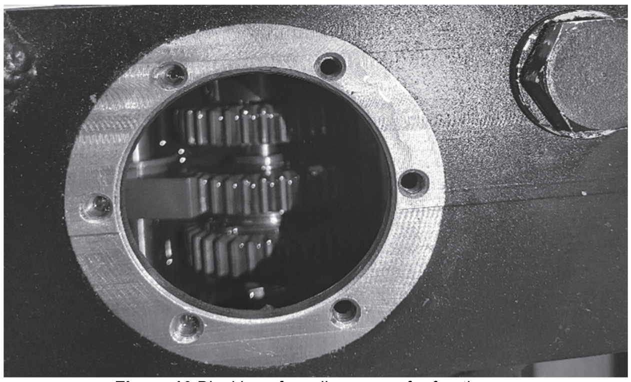

Figure 10 Blocking of small sun gear for fourth gear

3 EXPERIMENT PLAN

The experiment plan for determination of efficiencyof multi-stage planetary gearset has been made in accordance with the possibilities for pairing available equipment AT200 with developed gearset.

The experimental research plan for four gears/speeds was based upon variation of three different set values of circumferential speeds of gears, i.e. of input rotations: 500, 750 and 900 rpm, for three different values of output torque, i.e. brake forces on electromagnetic brake defined by changes in electrical power intensity on control unit: 0.05, 0.07 and 0.09 A. We conducted tests with all three different oil levels (minumum oil level −12 mm, medium oil level 0 mm and maximum oil level +12 mm measured by oil level meter) always with the same initial temperature conditions in all four gears/speeds.

4 EXPERIMENT RESULTS AND DISCUSSION

According to experiment plan we determine the value of efficiency on the grounds of the ratio between active power at output shaft and input power of gearset towards output:

$$\eta = \frac{P_2}{P_1} = \frac{T_2}{T_1 \cdot i} \tag{1}$$

Fig. 11 shows efficiency values in the first gear for all three oil levels with input rotation of 500 rpm. For minumum oil level 1, values of output torque were in the range of T_2 = 0.75-4.65 Nm, whereas efficiency was η =

0.15-0.64. For medium oil level 2, values of output torque were in the range of T_2 = 0.73-4.46 Nm, while efficiency was η = 0.14-0.61. For maximum oil level 3, values of output torque were in the range of T_2 = 0.55-4.37 Nm, whereas efficiency was η = 0.11-0.60. Change of efficiency is noticeable for values of output torque of T_2 = 1.5-3 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 6.59% for torque value of T_2 = 2.1 Nm.

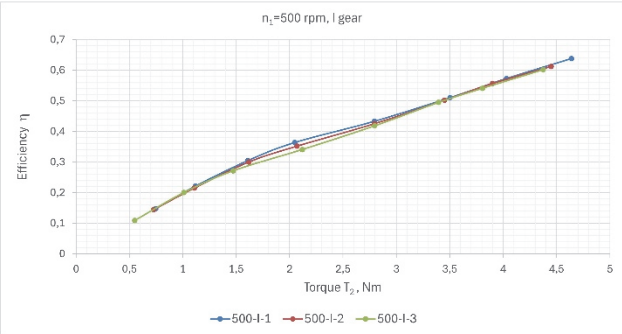

Figure 11 Values of efficiency with 500 rpm in the first gear for all three oil levels

Fig. 12 shows values of efficiency in the first gear for three oil levels with input number of rotations 750 rpm. For minimum oil level 1, values of output torque were in the range of T_2 = 0.88-4.46 Nm, and efficiency was η = 0.17-0.65. For medium oil level 2, values of output torque were in the range of T_2 = 0.80-4.66 Nm, and efficiency was η = 0.16-0.64. For maximum oil level 3, values of output torque were in the range of T_2 = 0.79-4.45 Nm, and efficiency was η = 0.15-0.62. Change of efficiency is noticeable for values of output torque T_2 = 1.5-4.5 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 6.54% for torque value T_2 = 2 Nm.

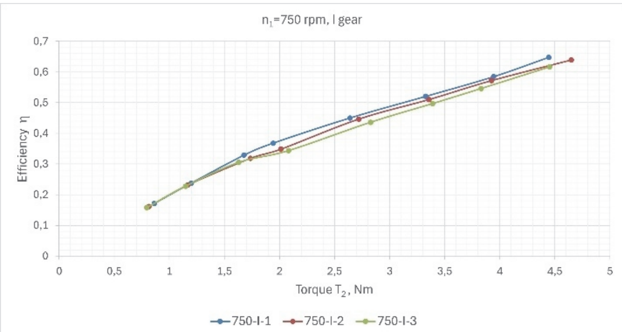

Figure 12 Value of efficiency with 750 rpm in the first gear for all three oil levels

Fig. 13 shows values of efficiency in the first gear for all three oil levels with input number of rotations of 900 min^{-1}. For minimum oil level 1, values of output torque were in the range of T_2 = 0.83-4.44 Nm, and efficiency was η = 0.19-0.66. For medium oil level 2, values of output torque were in the range of T_2 = 0.82-4.35 Nm, and efficiency was η = 0.17-0.64. For maximum oil level 3, values of output torque were in the range of T_2 = 0.80-4.56 Nm, and efficiency was η = 0.16-0.62. Change of efficiency is noticeable for values of output torque T_2 = 2-4.5 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 10% for torque value T_2 = 3.6 Nm.

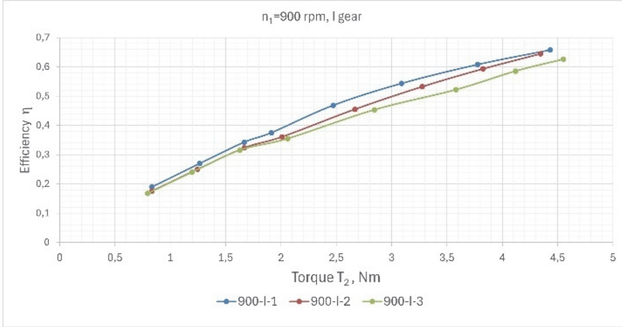

Figure 13 Value of efficiency with 900 rpm in the first gear for all three oil levels

Fig. 14 shows efficiency values in the second gear for three oil levels with input number of rotations 500 rpm. For minumum oil level 1, values of output torque were in the range of T_2 = 0.84-2.74 Nm, and efficiency was η = 0.27-0.74. For medium oil level 2, values of output torque were in the range of T_2 = 0.81-2.76 Nm, and efficiency was η = 0.26-0.73. For maximum oil level 3, values of output torque were in the range of T_2 = 0.90-2.72 Nm, and efficiency wasη = 0.25-0.72. Change of efficiency is noticeable for values of output torque T_2 = 0.8-1.8 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 9.3% for torque value T_2 = 1.25 Nm.

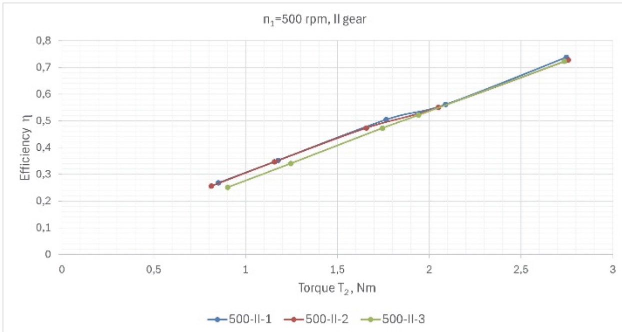

Figure 14 Values of efficiencies with 500 rpm in the second gear for all three oil levels

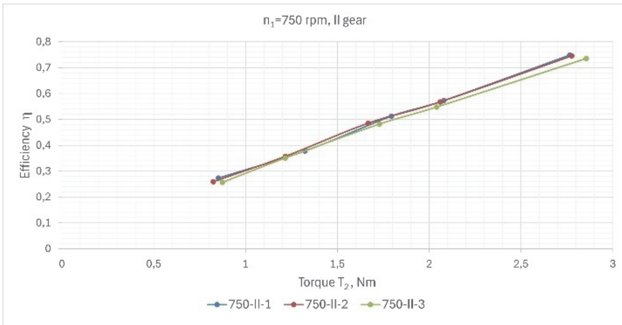

Figure 15 Value of efficiency with 750 rpm in the second gear for all three oil levels

Fig. 15 shows values of efficiency in the second gear for all three oil levels with input number of rotations of 750 rpm. For minimum oil level 1, values of output torque were in the range of T_2 = 0.85-2.77 Nm, and efficiency was η = 0.27-0.75. For medium oil level 2, values of output torque were in the range of T_2 = 0.82-2.78 Nm, and efficiency was η = 0.26-0.75. For maximum oil level 3, values of output torque were in the range of T_2 = 0.87-2.85 Nm, and efficiency was η = 0.26-0.73. Change of efficiency is noticeable for values of output torque T_2 = 1.7-2.75 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 4.7% for torque value T_2 = 2.75 Nm.

Fig. 16 shows efficiency values in second gear for all three oil levels with input rotation of 900 rpm. For minimum oil level 1, values of output torque were in the range of T_2 = 0.92-2.82 Nm, and efficiency was η = 0.28-0.76. For medium oil level 2, values of output torque were in the range of T_2 = 0.87-2.72 Nm, and efficiency was η = 0.26-0.73. For maximum oil level 3, values of output torque were in the range of T_2 = 0.86-2.74 Nm, and efficiency was η = 0.25-0.73. Change of efficiency is noticeable for values of output torque T_2 = 1.2-2.1 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 8.5% for torque value T_2 = 1.6 Nm.

Fig. 17 shows efficiency values in third gear for all three oil levels with input rotation of 500 rpm. For minimum oil level 1, values of output torque were in the range of T_2=0.83-2.05 Nm, and efficiency was η = 0.27-0.61. For medium oil level 2, values of output torque were in the range of T_2 = 0.88-2.09 Nm, and efficiency was η = 0.26-0.59. For maximum oil level 3, values of output torque were in the range of T_2 = 0.8-2.05 Nm, and efficiency was η = 0.25-0.58. Change of efficiency is noticeable for values of output torque T_2 = 0.9-2 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 10% for torque value T_2 = 1.2 Nm.

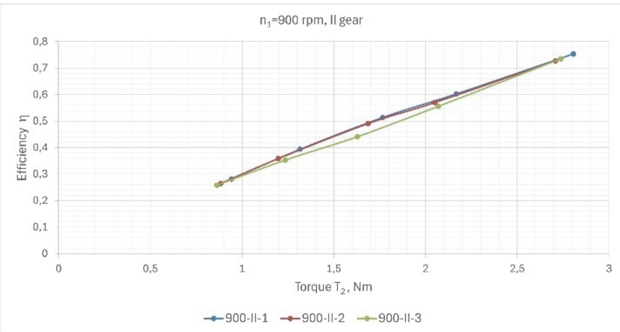

Figure 16 Value of efficiency with 900 rpm in second gear for all three oil levels

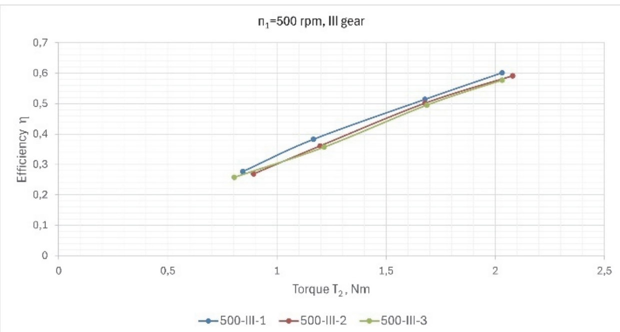

Figure 17 Values of efficiencies with 500 rpm in third gear for all three oil levels

Fig. 18 shows efficiency values in third gear for all three oil levels with input rotation of 750 rpm. For minimum oil level 1, values of output torque were in the range of T_2 = 0.80-2.1 Nm, and efficiency was η = 0.28-0.62. For medium oil level 2, values of output torque were in the range of T_2 = 0.87-2.05 Nm, and efficiency was η = 0.27-0.61. For maximum oil level 3, values of output torque were in the range of T_2 = 0.9-2.05 Nm, and efficiency was η = 0.27-0.58. Change of efficiency is noticeable for values of output torque T_2 = 1-2 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 11.1% for torque value T_2 = 1.7 Nm.

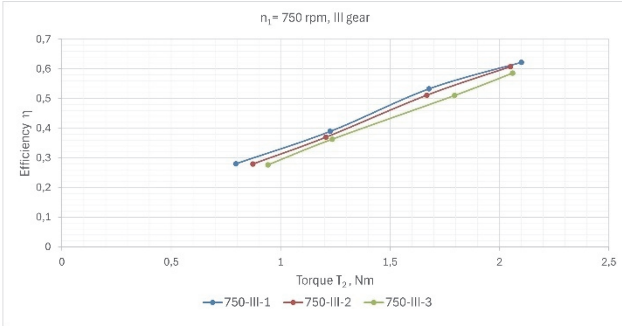

Figure 18 Value of efficiency with 750 rpm in third gear for all three oil levels

Fig. 19 shows efficiency values in third gear for all three oil levels with input rotation of 900 rpm. For minimum oil level 1, values of output torque were in the range of T_2 = 0.89-2.12 Nm, and efficiency was η = 0.28-0.63. For medium oil level 2, values of output torque were in the range of T_2 = 0.85-2.11 Nm, and efficiency was η = 0.26-0.62. For maximum oil level 3, values of output torque were in the range of T_2 = 0.92-2.04 Nm, and efficiency was η = 0.27-0.59. Change of efficiency is noticeable for values of output torque T_2 = 1-2 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 9.1% for torque value T_2 = 1.7 Nm.

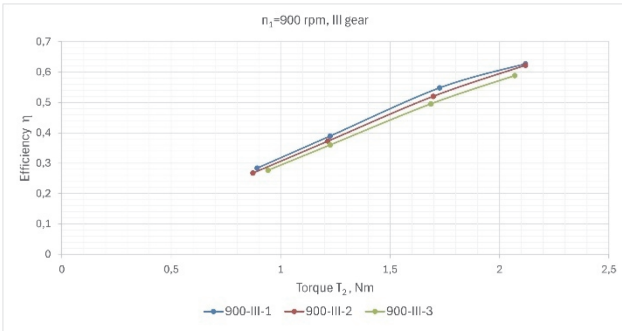

Figure 19 Value of efficiency with 900 rpm in third gear for all three oil levels

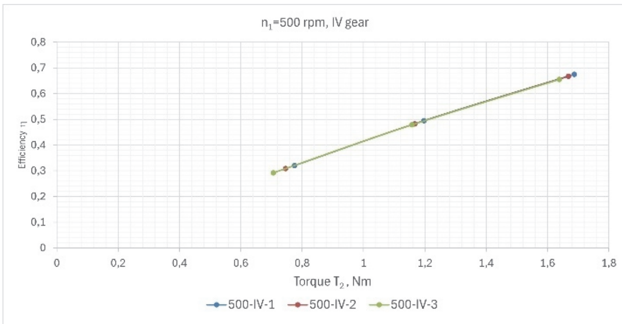

Figure 20 Values of efficiencies with 500 rpm in fourth gear for all three oil levels

Fig. 20 shows efficiency values in fourth gear for all three oil levels with input rotation of 500 rpm. For minimum oil level 1, values of output torque were in the range of T_2 = 0.78-1.69 Nm, and efficiency was η = 0.32 - 0.68. For medium oil level 2, values of output torque were in the range of T_2 = 0.75-1.67 Nm, and efficiency was η = 0.3-0.67. For maximum oil level 3, values of output torque were in the range of T_2 = 0.72-1.64 Nm, and efficiency was η = 0.29-0.66. Change of efficiency for all three oil levels in fourth gear with input number of rotations of 500 rpm was not noticeable, i.e. efficiencies were almost at the same level.

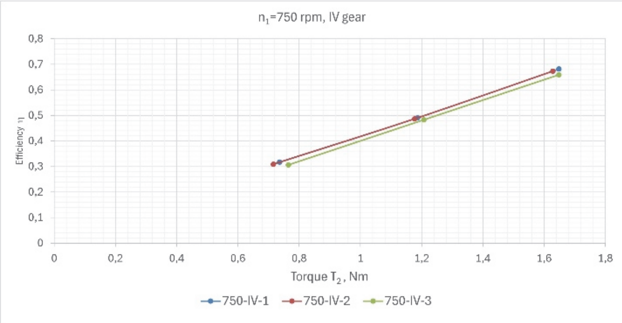

Figure 21 Value of efficiency with 750 rpm in fourth gear for all three oil levels

Fig.21 shows efficiency values in fourth gear for all three oil levels with input rotation of 750 rpm. For minimum oil level 1, values of output torque were in the range of T_2 = 0.74-1.65 Nm, and efficiency was η = 0.32-0.68. For medium oil level 2, values of output torque were in the range of T_2 = 0.73-1.62 Nm, and efficiency was η = 0.31-0.67. For maximum oil level 3, values of output torque were in the range of T_2 = 0.77-1.65 Nm, and efficiency was η = 0.31-0.66. Change of efficiency is evenly split and it is noticeable for values of output torque of T_2 = 0.7-1.7 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 4% for torque values T_2 = 1.2 Nm.

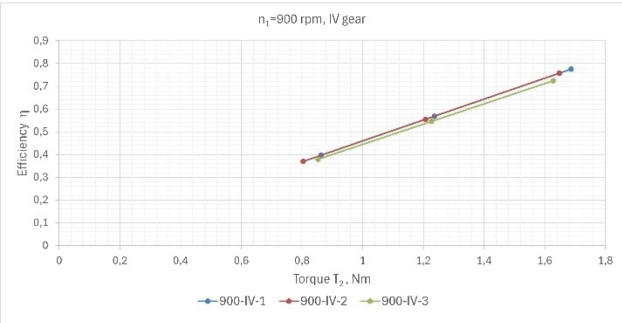

Figure 22 Value of efficiency with 900 rpm in fourth gear for all three oil levels

Fig. 22 shows efficiency values in fourth gear for all three oil levels with input rotation of 900 rpm. For minimum oil level 1, values of output torque were in the range of T_2 = 0.85-1.69 Nm, and efficiency was η = 0.39-0.77. For medium oil level 2, values of output torque were in the range of T_2 = 0.81-1.65 Nm, and efficiency was η = 0.37-0.76. For maximum oil level 3, values of output torque were in the range of T_2 = 0.86-1.64 Nm, and efficiency was η = 0.38-0.72. Change of efficiency is evenly split and it is noticeable for values of output torque of T_2 = 0.7-1.7 Nm, whereas the highest increase of efficiency is noticeable with oil level 1 in comparison to oil level 3 and it amounts to 4% for torque value T_2 = 1.6 Nm.

Correlation of efficiency for all four gears with input rotations of 500 rpm has been shown for three different oil levels (minimum oil level of −12 mm) indicated in Fig. 23, medium oil level of 0 mm indicated in Fig. 24 and maximum oil level of +12 mm indicated in Fig. 25. In these three figures one may see that we get the highest efficiencies in unchaged conditions when we have the least value of gear ratio, i.e. in the fourth gear/speed. Also, one may see that the trend is always the same and that efficiency increases when gear ratio value decreases, i.e. when gear/speed changes up.

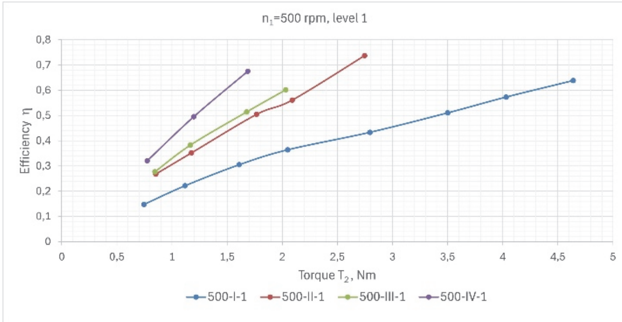

Figure 23 Value of efficiency with 500 rpm for all four gears and for minimum oil level (−12 mm)

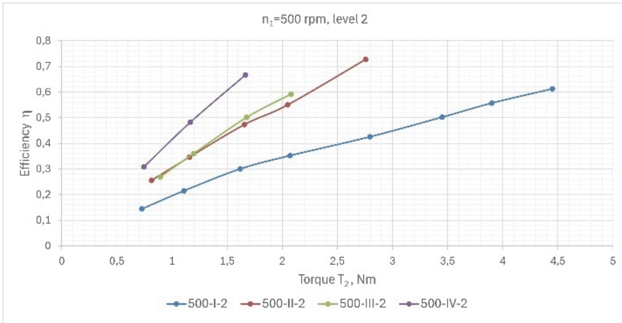

Figure 24 Value of efficiency with 500 rpm for all four gears and for medium oil level (0 mm)

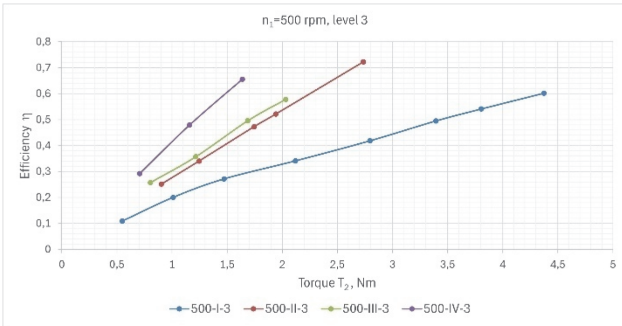

Figure 25 Value of efficiency with 500 rpm for all four gears and for maximum oil level (+12 mm)

Having analysed values of efficiencies for the value of output torque of T_2 = 1.5 Nm, for all three oil levels with input rotations of 500 rpm, we saw that efficiency with oil level 1 in comparison to oil level 3 was higher by 6.9% in the first, by 6.8% in the second and by 6.4% in the third and by 1.6% in the fourth gear.

Having analysed the results we got we saw that oil churning and increase of oil level caused additional power losses which further increased with increase of rotations, whereas, in case of the same number of rotations, power losses increased with increase of oil level, as indicated in paper [9]. Efficiency increases with increase of load and rotations following a very similar trend as the one presented in paper [25]. Efficiency can be achieved by decrease of values of gear modules, as presented in paper [5]. Gearset input power presents the most influential parameter relevant for power losses of planetary gearset teething, where increase of input power causes increase of efficiency [26]. Decrease of power losses and increase of efficiency of gearsets are achieved by decrease of working temperature of gearsets [26] and with higher viscosity of oil which induce lower values of friction coefficient due to better forming of oil film between meshed sides of gear teeth [25].

5 CONCLUSION

The presented experimental research unmistakeably points at the fact that determining of power losses in multi-stage planetary gearsets and increasing of efficiency are a new challenge in all areas of design and that in the phase of design of planetary gearsets it is necessary to have the appropriate models for predicting efficiencies with the help of which we could quantify power losses as early as in the phase of product development. In the first three gears/speeds, efficiency increase with oil level 1 in comparison to oil level 3 changes depending on the level of load, but it can be observed that the maximum value is around 11%. In the fourth gear/speed, this maximum value has a somewhat lower value which is around 4%.

The trends of growth of efficiencies for all three input numbers of rotations: 500, 750 and 900 rpm are the same and the highest efficiency is accomplished in the fourth gear/speed, i.e. with the least value of gear ratio i_{PP4} = 1.344, whereas the least efficiency is reached in the first gear/speed, i.e. with the highest value of gear ratio i_{PP1} = 3.909.

Value of efficiency in case of concrete value of output torque T_2 = 1.5 Nm, for all three oil levels with input rotations of 500 min^{-1} is the same with oil level 1 in comparison to oil level 3 for the first three gears/speeds i.e. 6.4-6.9, whereas the efficiency is 1.6% in the fourth gear/speed.

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