DOI: 10.46793/41DAS2025.019K

EXPERIMENTAL ANALYSIS OF HIGH-SPEED GEARBOXES

Nenad KOLAREVIĆ[1], Milosav OGNJANOVIĆ[2], Miloš STANKOVIĆ[3], Aleksandar DIMIĆ[4], Nikola DAVIDOVIĆ[5], Marko MILOŠ[6]

[1] 0000-0003-2836-7405, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia, E-mail: nkolarevic@mas.bg.ac.rs;

[2] 0000-0002-1118-0102, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia, E-mail: mognjanovic@mas.bg.ac.rs

[3] 0000-0002-1931-1170, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia, E-mail: mstankovic@mas.bg.ac.rs;

[4] 0000-0001-5495-0763, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia, E-mail: adimic@mas.bg.ac.rs;

[5] 0000-0002-0500-3388, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia, E-mail: ndavidovic@mas.bg.ac.rs;

[6] 0000-0002-1931-1170, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia, E-mail: mmilos@mas.bg.ac.rs;

1. Introduction

With the rise of rotation speed of the gears in the gearboxes several phenomena that can significantly affect the gearbox energy efficiency and reliability occur. A lot of experimental data is available in literature for peripheral speeds below 40-60 m/s. But above this value some load parameters are changing their trends so this value can be classified as a limit between low and high speed application. The main causes of power loss in gearboxes are tooth mesh losses, bearing losses, churning, windage, oil pocketing and gear drag [1]. Some literature shows that windage losses [2] which occur due to sliding friction of the high-speed gears in the oil-mist environment in the gearbox housing can be up to 30% or even more of the entire gear drive meshing losses. The phenomena of squeezing out the oil from the gear meshing area can also add more power losses in the system [3]. In the worst case when the backlash is very small, these phenomena can even create oil blockage. Some problems with hydrodynamic losses due oil retaining in some housing pockets can also lead to lower energy efficiency, Fig.1. All of the mentioned hydrodynamic losses are negligible in the low speed gearboxes, but in high speed gearboxes they can exceed basic gear teeth meshing losses and even become larger.

In the case of high speed gears, hydrodynamic losses represent a large portion of total power losses [4]. They can be approximately measured during gearbox operation at the maximum speed with no load. This means that these gearboxes have very low energy efficiency at the low load regimes because of high hydrodynamic losses. With power rise, the basic gear teeth meshing loss increases, while the increase in hydrodynamic losses is much less or negligible. The effect of this can be presented as an increase in energy efficiency of the high speed gearbox with the increase in load transmitted. Beside mentioned, some load parameters as dynamic factor lower their value, so power efficiency of high speed gearbox could reach even 0.99 value [5].

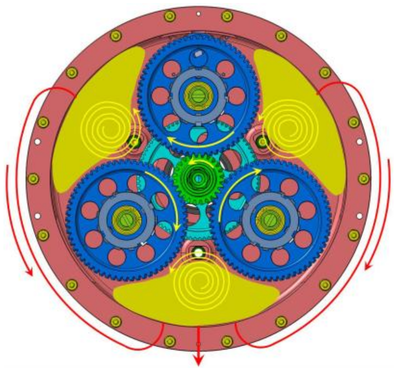

Fig. 1. Oil retaining pocket in gearbox housing [6]

For investigating the dependency of energy efficiency of the high speed gearbox with transmitted power increase, a special mechanical power circulation test rig [7] was developed at the EDePro company for testing its high speed gearboxes for aircraft application, i.e. for turbo shaft engines application. High speed gears can be found mostly in the aerospace industry. Every loss in power means lower thrust available for the aircraft. On the other hand, as all power losses are converted to heat, more mass, through the larger heat exchanger, is added to the aircraft, which is also highly undesirable. So the increase in energy efficiency of such gearboxes is of great importance for future exploitation and performances of aircraft.

In this paper, an experimental investigation of hydrodynamic losses and basic gear meshing losses are presented for two types of high speed gearboxes. Also, the objective of this paper is to present and compare two types of test rigs for experimental measuring of gearboxes parameters.

2. Case study

The case study are two gearboxes one for helicopter application and other one for aircraft application. The concept used is split path gearbox, with power dividing intro 3 branches, Fig.2. The peripheral speeds of gears are in the area of high speed application. The power is brought with input gear 1 (green) which is engaged with three gears 2 (blue). In this way power is divided into 3 branches. Gears 2 are directly connected to smaller gears 3 (red arrows) on each of the three branches of the gearbox. Then those gears 3 are geared with output gear 4 which transmits all power further to the coupling through the splined shaft. Both gearboxes are designed for the same gas generator with power of 200 kW which is also developed at the EDePro company from Belgrade.

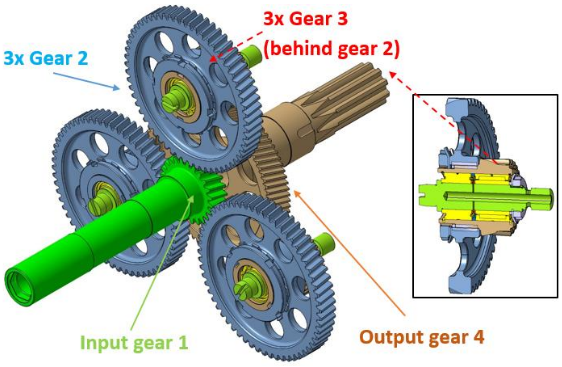

Fig. 2. Concept of the gearbox with power dividing into three branches [6]

The first gearbox, intended for helicopter application has a gear ratio of 6.67, see Fig.3. It reduces 40 000 rpm from the input shaft to 6 000 rpm of the output shaft. The peripheral speed of the first gear pair is around 100 m/s so it matches to high speed usage.

The second gearbox, intended for aircraft propeller drive has a ratio of 16, Fig.4. It reduces 40 000 rpm of input shaft rotation speed to 2 500 rpm of output shaft rotation speed. The peripheral speed of the first gear pair in this gearbox is around 76 m/s, which also matches to high speed usage.

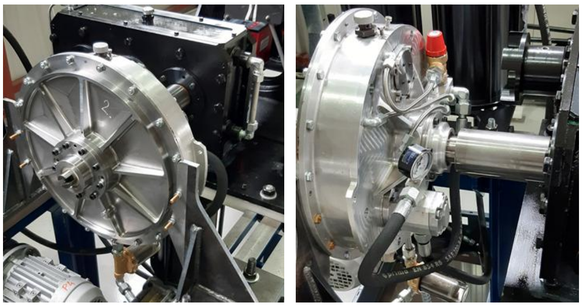

Fig. 3. High speed gearbox for helicopter application

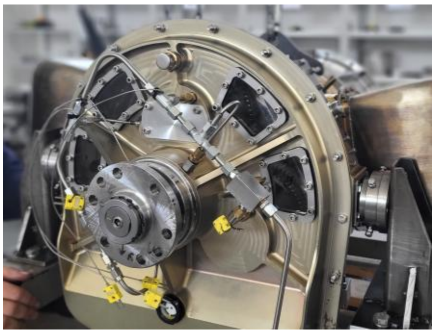

Fig. 4. High speed gearbox for propeller application

3. Test stand

The first one, helicopter gearbox, was experimentally tested on a test bench developed specially for the purpose of gears and gearboxes testing, Fig.5. A closed loop power circulation test rig, is developed as altered conventional one used only for gear experimental testing in order to accept two gearboxes facing each other. As it can be seen from Fig.5 in one branch of the device two high speed gearboxes (marked with numbers 6&7) are installed. They are placed in opposite position in order to connect the high speed shafts of each one together.

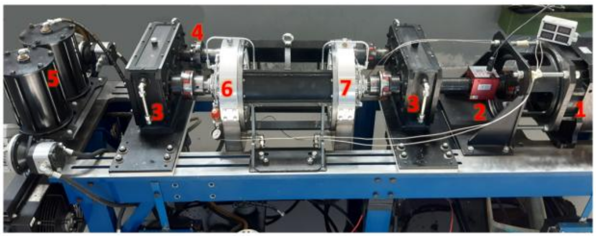

Fig. 5. Test stand with 2 gearboxes for helicopter application positioned opposite each other: (1) drive electromotor, (2) torque meter, (3) auxiliary gearboxes, (4) loading coupling, (5) oil supply system with pumps, (6&7) test articles – high speed gearboxes

From the right side in Fig.5, a drive electromotor (1) of 55 kW continual power is installed. This electromotor is used only to compensate for the power losses in the system which are assumed not to be larger than 5% per gearbox, auxiliary and test. The entire system is driven by the electromotor at 6 000 rpm, except for the part which connects the high speed input shafts of the gearboxes which runs at 40 000 rpm (between 6 and 7). In order to achieve high precision and to minimize the misalignment of these shafts, a black cylindrical part is installed, see Fig. 5. Two auxiliary gearboxes (3) from each side of the branches are installed in order to connect the two central branches-shafts by transmitting the power at a distance between their axes. One branch is used to install the test article – high speed gearboxes (6) and (7), while the other one (behind the one in Fig. 5.) is used to install the loading coupling (4). By this coupling, the torque is introduced in the system in a steady state, in order to simulate the power inside the system. The torque is applied by coupling specially designed so it can be connected in arbitrary position, twisted for the desired angular deformation by level system as in Fig.6. By running the system at some rotational velocity, the torque simulates full power, trapped in the system of 2 branches, 2 auxiliary gearboxes and 2 testing high speed gearboxes. Outside of them, for example on the branch where the torque meter is installed, there is no power generated due to level system. But there is a need to overcome the resistance to rotation in the system, power loss, due to friction in gearboxes and bearings which is converted to heat. So, there is a need for an external electromotor which has to compensate only for those power losses. Lubrication and heat exchanging subsystems are also required together with an acquisition system for monitoring the controlling parameters.

Fig. 6. Level system for applying the to flange of the specially designed coupling

The second gearbox is experimentally tested in an open loop power circulation system, where the electromotor is used to drive the system with all available power and an engine free turbine is used as a brake, Fig. 7. In order to create a load, an actual turbine is installed on the input shaft. So, the maximum available power is the power of the electromotor, i.e. 55kW, which is much lower than the maximum gearbox operating power of 200 kW, but it serves well enough for determining the hydrodynamic losses and losses at that power.

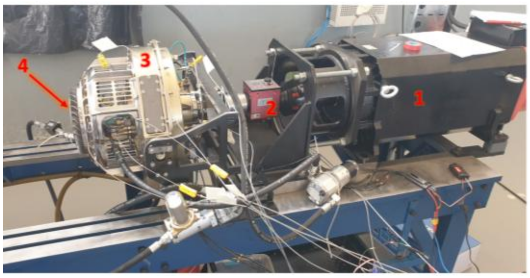

Fig. 7. Test stand with high speed gearbox for airplane application: (1) drive electromotor, (2) torque meter, (3) propeller gearbox, (4) free turbine

4. Experiments and results

The main advantage of the closed loop power circulating test rig is that it uses only the supply power equal to the power losses in the system. There is a need to differentiate between the power losses of the test rig, because it consists of two auxiliary gearboxes, and the power losses of the gearboxes which are tested. So, the first run is done on the required 6000 rpm with load and without the test articles – high speed gearboxes, in order to define the basic power losses of the test rig. The measured power losses of the empty system (without helicopter gearboxes) is 8.8 kW. This value represents the losses in the auxiliary gearboxes with the losses in the electromotor itself. Then during the test with the installed high speed gearboxes, as in Fig.5, the electromotor required the power of 23 kW in the first minute of operation. As time passes this power drops to 20.5 kW after a few minutes while it settled down on the value of 19 kW after more than 10 min. This is normal behavior due to phenomena of running in of the gears and bearings, oil temperature is raised to the balanced value of 70-80°C and with this the viscosity drops and consequent hydrodynamic losses and etc. Tests were done on 4 regimes, all at the same velocity of 6000 rpm. The first one is done without any load applied, the second one corresponds to 120 Nm (75kW), the third one is with 220 Nm (138kW) and the last one is with 320 Nm (200kW). Results for short tests of several minutes are shown in Table 1.

Table 1. Results of power measurement on torque meter

Case no.	T [Nm]	P [kW]	P_{tl} [kW]	P_{bl} [kW]	P_g [kW]	η [%]
1	0	0	17	5.2	5.90	-
2	120	75	19	6.6	6.20	0.92
3	220	138	21	7.7	6.65	0.95
4	320	200	23	8.8	7.10	0.97

In Table 1, T is the torque introduced to the system by coupling, P is the power simulated by the system, P_{tl} is the total power losses measured by the torque meter, P_{bl} is the basic power losses of the test rig (without test articles), P_g is the calculated averaged power losses per high speed gearbox and η is the energy efficiency of high speed gearboxes.

For the short tests when there is a need to define the settling temperature of input cooled, output heated oil or bearing operating temperatures, natural frequencies, noise or energy efficiency, the open-loop power circuit test rig is the better solution to obtain these results. There is a need for only one gearbox, and all power which is required to pass through the test rig and the gearbox itself should be compensated by the electromotor. The second high speed gearbox for aircraft propeller application is tested in this way. Firstly, a test without any load at the designed 2500 rpm of output shaft speed was conducted and the power required was 3.4 kW. This are the basic power losses during the operation without load. The high speed bearing housing system actually used for free turbine application, input bearing system for gearbox, was tested separately and shows the value of 2.5 kW at 40 000 rpm. This fact indicates that the losses of gear meshing without load, all other gearbox bearings and lubricating losses are only 0.9 kW. After this one test, a turbine is installed on the input shaft in order to provide the load (due to air resistance of turbine rotation through the ambient air). As the electromotor is of not enough power this test was done on the maximal load that corresponds to 55 kW. The power loss on this test was estimated to a value of 3.9 kW which gives the energy efficiency of 0.93.

5. Conclusion

Based on the above, the power of 23 kW is continuously required to drive the system at 6 000 rpm with a closed loop circulation test rig, with torque of 320 Nm inputted on the special clutch on the auxiliary branch in order to simulate the behavior of gears exposed to 200 kW of power. In this way, the power spent over time is almost 10 times lower than in the case of an open-loop power circuit test rig. This is an economically prevailing advantage in case of long-term gearbox testing.

The first test shows that energy efficiency of the high speed gearbox increases as the applied load increases. The worst case is with very low load applied and running the gears without load is not recommended due to low dynamic behavior which is even reflected by the sound produced. There are several reasons why energy efficiency is increasing. In the first place is the fact that dynamic load factor lowers its value by increasing the unit load per tooth width for high speed gearboxes that operate on supercritical speeds. The other one is the fact that the basic load due to windage effect, bearing friction, churning, oil pocketing and etc. remains more or less independent at the same rotational velocity with the load applied. As power is increased, mostly gear teeth mesh losses are increasing by a small percent. So, results show the trend of efficiency increase with load as in reference [7].

The second test shows that the most basic power losses (without load) occur in the area (on the parts) which are exposed to the high speed. The bearing housing subassembly of input high speed shaft takes 2.5 of the total 3.4 kW (74%) which goes to gear meshing (including high speed pair) and all others bearings.

Acknowledgments

The presented paper is a result of the researches supported by MPNTR RP according to the contracts 451-03-137/2025-03/ 200105 and 451-03-136/2025-03/200213 since 4th February 2025. The authors wish to acknowledge and thank the company EDePro for support and for encouragement in the project realization.

References

[1] Anderson, N. E., Loewenthal, S. H. Effect of geometry and operating conditions on spur gear system power loss, *Third International Power Transmission and Gearing Conference*, California, 18-22 August, 1980.

[2] Eastwick, C. N., Johnson, G. Gear Windage: A Review, *Journal of Mechanical Design*, 2008, 130(3):034001-1.

[3] Delgado, I., Hurell, M. The Jetting Phenomena in Meshed Spur Gears, A*HS International 74th Annual Forum & Technology Display*, Arizona, 14-17 May, 2018.

[4] Mizutani, H., Isikawa, Y., Towsend, D. P. Effects of Lubrication on the Performance of High- Speed Spur Gears, *Fifth International Power Transmission and Gearing Conference*, Illinois, 24-27 April, 1989.

[5] Anderson, N.E., Loewenthal, S.H., Black, J.D. An Analytical Method To Predict Efficiency of Aircraft Gearboxes, *ASME. J. Mech., Trans., and Automation.* September 1986; 108(3), 424–432.

[6] Ognjanović, M., Kolarević, N., Stanković, M., *Reduktori turbovratilnih motora*, Akademska misao: EDePro – Engine Development and Production, 2024.

[7] Lee, G.-H., Park, Y.-J., Nam, J.-S., Oh, J.-Y., Kim, J.-G. Design of a Mechanical Power Circulation Test Rig for a Wind Turbine Gearbox. *Appl. Sci*. 2020, 10(9): 3240.