Assessment of the energy balance on test bench with open power flow and closed power flow for testing of planetary gears

M Herda¹, L Kučera¹, T Gajdošík¹ and M Benko¹
¹University of Žilina, Faculty of Mechanical Engineering, Department of Design and Machine Elements, Univerzitná 1, 010 26 Žilina, Slovakia

E-mail: Michal.Herda@fstroj.uniza.sk

Abstract: The article deals with the design of the deployment of components and the creation of kinematic bonds of the test bench for planetary gearbox. The source of the drive on test benches is an electric motor. In article is described creation of kinematic bonds for test bench with an open flow of mechanical power, the part of which is in addition to the electric motor also a dynamometer. It is also described a assembly procedure of kinematic bonds for test bench with an closed flow of mechanical power, in which only an electric motor is used, while this electric motor is the same for both test benches. The kinematics of test benches is modelled and calculated in programs KissSys and KissSoft. As a result, the article deals with comparing the energy balance of the individual test benches, especially by comparing the energy balance of the electric motor.

1. Introduction
Testing designed gearboxes is still very important for the whole construction process. Even though nowadays when there are highly developed simulation programs for virtual testing [1]. For physical testing of transmissions with high transmitted power, there is a high energy consumption in test benches. This is especially with test benches with open power flow.

Therefore, the main objective of the article is to calculate and assessed the energy balance of the two test benches by focusing on the energy balance of the engine. It will be compare to test bench with an open flow of mechanical power and test bench with a closed flow of mechanical power. The drive unit will be the same. At present, it is important to pay attention to energy consumption, because in long-term testing it is one of the decisive economic factors. Of course, if they do not decide on other more important factors.

For both test benches, double stage planetary gearbox A 2000 are used and the power source is a two-pole asynchronous motor with a output power of 50 kW.

2. Design of an test bench with an open flow of mechanical power
The design of the kinematic scheme was based on basic knowledge of testing transmission systems and tests which were already carried out at the University of Žilina [2-5].

The test bench with an open flow of mechanical power, consists of a drive that provides a two-pole asynchronous electric motor with a 50 kW output power controlled by a phase transducer, two planetary gearboxes A 2000 and a dynamometer.
Planetary gear units are connected in series but in a mirror position. So that the same values as the input are measured at the output. Of course, we must not forget the losses that occur through the passage of power through connected planetary gearboxes. After calculating output power and transmission losses on the planetary gearboxes, we get input power. A dynamometer is connected at the end of the test bench. Dynamo produces electricity from the output power by recuperation and returns it to the electricity grid.

All elements of the test bench with an open flow of mechanical power are connected by cardan shafts. Losses that arise on joints of cardan shafts are not included in the calculation of losses, because they are negligible for calculation. The design of the kinematic scheme is shown in the Figure 1.

![Figure 1. Kinematic scheme of the test bench with an open flow of mechanical power](image)

1- EM- Electric motor; 2, 3- A2000- Planetary gearbox A 2000; 4- DYN- Dynamometer; 5- Kinematic connection; arrowhead show power flow.

3. Modeling and calculation the test bench with an open flow of mechanical power in KissSys

To calculate the effectiveness of the test bench with an open flow of mechanical power, Swiss modeling and calculation program KissSoft / KissSys was used. Its features enable extremely accurate modeling and calculation of transmission systems. The planetary gearbox after modeling in KissSys was saved as a template. Then a new project was launched in KissSys and two planetary gearboxes were added.

They were connected to the series but in mirror position so that the output carriers could be connected. After placement, direct connection between planetary gearboxes was made. The bond coupled the carriers, thus transmission system with a kinematic transmission ratio \( i = 1 \) was created. After creating a connection between planetary gearboxes, boundary conditions have been added. Then the input and output have been added, braking torques have also been added to the ring element. Which ensured the passage of power from the input shaft to the central gear and the output was the carrier of the planetary gearbox. The inputs to the system were set at 1500 rpm with a torque of 292.3 Nm. The system has already calculated the required input power, which was 45,914.4 W. The wiring diagram is shown in the Figure 2.

![Figure 2. Technical scheme in KissSys](image)
Once the boundary conditions have been entered, the calculation of the kinematics for the transmission system has started. The kinematics calculation in KissSys is important for the next step. It was found that the flow of power is the way it was expected. All connections are correctly defined for the following operations. The next step was to calculate the efficiency of the whole test bench. Once the boundary conditions for efficiency calculation have been entered, the calculation method was chosen according to ISO TR 14179-2. In the calculation of efficacy, contact analysis was not taken into account, because of the high demands on computing elements. Calculations are performed in an iterative manner. After the calculation was completed, the following results were obtained:

- Input power 45914.4 W
- Output power 43911.2 W
- Total Losses 2003.2 W
- Total efficiency 95.64 %

Total efficiency has been divided to more points. They were scattered there all partial losses. For simplification, losses was divided into two points. First point- gear meshing losses which was 1696.3 W, and second point- the other losses which was 306.9 W.

4. Design of an test bench with a closed flow of mechanical power

Design of an test bench with a closed flow of mechanical power proceeded similarly to design of an test bench with an open flow of mechanical power. But here it must have been taken into account, how to ensure the circulation of mechanical power.

As the drive the same electric motor as with an test bench with an open flow of mechanical power is used. There are also two planetary gearboxes A 2000. In addition in scheme, there are auxiliary transmission gear units and a technological gearbox. The transmission gear units (shown in Figure 3, with the number 4) serve to close the test circuit. Several alternatives were considered for the design of the transmission gear units. The most preferred variant was a variant with a bevel gears. In deciding, the condition with the greatest importance was to keep the kinematic transmission ratio $i = 1$. In order to avoid the need for additional calculations or compensations for the flow of power.

In the kinematic scheme show (Figure 3.) the distribution of components in the test bench with a closed flow of mechanical power.

![Figure 3. Kinematic scheme of the test bench with a closed flow of mechanical power](image)

The next step was to design a technological gearbox. For the design of the technological gearbox were considered, the differential, helical stage gearbox and bevel gearbox. As a technological gearbox, were selected bevel gearbox to provide a simple power connection and also maintain a kinematic transmission ratio $i = 1$. All parts of the test bench are connected by cardan shafts.
5. Modeling and calculation the test bench with a closed flow of mechanical power in KissSys

As in the previous case with test bench with an open flow of mechanical power, the KissSys program was used to model and calculate the test bench with a closed flow of mechanical power.

At the beginning, bevel gearbox were modeled and saved as a template. The planet gearbox A 2000 has already been modeled from the previous calculation, it did not have to model again. After the launch of the new project, two planetary gearboxes and five bevel gearboxes were added.

Once the test bench with a closed flow of mechanical power components have been dismantled. Links have been created between the individual parts. For the correct definition of bindings, it was necessary to determine the flow of power. Where the power will be divided and where it will be joined.

For that serves the Power Split feature in KissSys. This feature has been used to determine where power was divided and where it joined. If the function of power distribution was incorrectly defined, the program could not calculate the kinematics. And other calculations would not be possible. Subsequently, then they have just entered boundary conditions for input. The wiring diagram is illustrated in Figure 4 and 3D model is in Figure 5.

![Figure 4. Technical scheme in KissSys.](image)

These were identical to the test bench with an open flow of mechanical power, 1500 rpm and a torque of 292.3 Nm. After defining the power distribution and entering the boundary conditions for the input, the kinematics could be calculated. After kinematics calculation, the calculation of the efficiency of the whole test bench was continued. As in the first case, the system has calculated the input power of the engine. Also in this case the power was 45914, 4 W. Efficiency was also calculated according to ISO TR 14179-2.

After the calculation was completed, the following results were obtained:

- Input power = 45914.4 W
- Output power = 38411.9 W
- Total Losses = 7502.5 W
- Total efficiency = 83.66%

To calculate the total efficiency, we had to engage the test bench first as if it had an open flow of power. Subsequently, we went to the simulated closed test bench.
To do this, we had to redefine input conditions, to confirm by the following calculation the correctness of the statement. That if the input speed and input torque equal to the total losses in the test bench are preserved, in the event that a technological gearbox with the required torque is prestressed, the same power flow is maintained. There was no full torque defined at the input, but a torque was added, which in the previous calculation was equal to the total losses in the test bench. So the speed was 1500 rpm and the torque only 47, 77 Nm. In order to achieve a similar power flow in the test bench, the technological gearbox was prestressed with a torque of 292.3 Nm. Once the calculation was completed, it was found, that the statement was correct and the desired closed flow power effect has been achieved.

6. Evaluation
After completing the calculations, an evaluation was performed. The complete evaluation is in Table 1.

From the calculated data, when the power flow is open, the loss in the measuring state is 4, 36 %, which corresponds to a power of 2 kW. The engine consumption per test hour is therefore 45, 9 kW/h. At the end of the test bench is dynamometer. It operates with an output power of 43, 91 kW. Dynamometer can recuperate approximately 40% of this power, which in our case is 17, 56 kW. The total power loss in this case is 28, 35 kW. From calculation is obvious that the test bench with an open flow of mechanical power, under the test conditions mentioned above, have hourly power consumption of 28, 35 kW/h.

| Test bench with an open flow of mechanical power | Test bench with a closed flow of mechanical power |
|-----------------------------------------------|-----------------------------------------------|
| Input rpm [1/min]                              | 1500                                          | 1500                                          |
| Input torque [Nm]                              | 292.3                                         | 292.3                                         |
| Input power [kW]                               | 45.91                                         | 45.91                                         |
| Output rpm [1/min]                             | 1500                                          | 1500                                          |
| Output torque [Nm]                             | 279.6                                         | 244.58                                        |
| Output power [kW]                              | 43.91                                         | 38.41                                         |
| Total losses [kW]                              | 2                                             | 7.5                                           |
| Efficiency [%]                                 | 95.64                                         | 83.66                                         |
In the test bench with a closed flow of mechanical power, where the dynamometer is absent and the required torque is achieved by mechanical prestressing, the power consumption of the electric motor is 7.5 kW/h, which is a deviation of torque losses throughout the test bench.

7. Conclusion
It is therefore clear that the power consumption of a test bench with a closed flow of mechanical power, for the given test parameters, is almost 4 times lower than that of a test bench with an open flow of mechanical power. However, the initial financial cost to build this test bench (the use of five bevel gearboxes and a higher number of connecting cardan shafts) is eliminated with the number of hours tested. These technology gearboxes can also be used to test other types of gearboxes.

It follows from this, that the test bench with a closed flow of mechanical power is more suitable for long-term tests of gearboxes. Where the test bench with an closed flow of mechanical power appears to be financially less demanding as the test bench with an open flow of mechanical power.

Acknowledgment
This study was supported by Cultural and Educational Grant Agency MŠVVaŠ under the contract no. 040ŽU-4/2016

References
[1] Li J-Y, Gou Z-J and Li Y 2005 A Dynamic Simulation of Meshing Force in Gear Meshing Process Based on ADAMS, Machinery 3(5)
[2] Gramblíčka S, Kohár R and Stopka, M 2017 Dynamic Analysis of Mechanical Conveyor Drive System, Procedia Engineering 192 259-264
[3] Tomášiková M, Gajdošík T, Lukáč M and Brumerčík F 2017 Simulation of Planetary Gearbox, Communications: Scientific Letters of the University of Žilina 19(2A) 48-53
[4] Lukáč M, Brumerčík F, Krzywonos L and Krzyziak Z 2017 Transmission System Power Flow Model, Communications: Scientific Letters of the University of Žilina, 19(2) 27-31
[5] Liang X, Zuo M J and Feng Z 2018 Dynamic Modeling of Gearbox Faults: A Review, Mechanical Systems and Signal Processing 98 852-876