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Development of a Gear Test Rig

Metropolia University of Applied Sciences

Bachelor of Engineering

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This Bachelor's thesis conducted at VTT Technical Research Centre of Finland Ltd. with the purpose to bring the gear test rig into a finished state for certified test runs by assembling the equipment and required instruments. As well as to describe the setup and principal of the device and its measurement system. Lastly, to confirm the proper functioning by running the commissioning tests.

First, the device was studied during dismantling and reassembly with the help of team workers. Part of the information was obtained from manuals and components' specifications. Furthermore, several commissioning tests were run after the measurement system was installed and its monitoring devices were up and running. General operating principles and instructions were written while preparing the commissioning tests. Validation of the commissioning process verified that the device functioned as required.

Keywords	gear test rig, assembly, description, commissioning tests validation

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Insinöörityö tehtiin Teknologian tutkimuskeskus VTT Oy:lle. Työn tarkoituksena oli siirtää VTT:n hammasvaihdekoelaite uuteen paikkaan, sekä asentaa ja instrumentoida se koevalmiuteen sertifioituja testiajoja varten. Työn aikana laadittiin kuvaus laitteen ja sen mittausjärjestelmän kokoonpanosta ja toimintaperiaatteesta. Koelaitteen asianmukainen toiminta varmistettiin tekemällä käyttöönottotestit.

Kuvaus on kirjoitettu asennuksen ja laitteeseen tutustumisen jälkeen. Osa tiedoista saatiin oppaista ja komponenttien spesifikaatioista. Käyttöönottotestit suoritettiin mittausjärjestelmän ja valvontalaitteiden asennuksen jälkeen. Käyttöönottotestejä valmisteltaessa laadittiin käyttöohjeet ja -suositukset. Laitteen vaatimusten mukainen toiminta varmistettiin käyttöönottotestien tulosten tarkastelulla.

Työssä käytetään desimaalierottimena pistettä.

Avainsanat	hammasvaihdekoelaite, kokoonpano, kuvaus, käyttöönottotestit, tulosten tarkastelu, toiminnan varmistus

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Secondly, I would like to thank Peter Andersson, whom I can also consider my instructor. You taught me a considerable number of things like assembling the devices or the principle of the apparatus and helped me to dive into team with ease. I had a huge fun and joy to work with you. Your engineering skills kept me wondering, questioning and willing to find the solutions and not the excuses.

I am also grateful to Jukka Koskela for helping in finding the solutions, assembling the measurements of the device and providing clear instructions on how to use them.

I thank all members of VTT Tribology team and other co-workers.

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Contents

List of Abbreviations and Symbols

AC	Alternating current
FZG	Forschungsstelle für Zahnräder und Getriebebau, i.e. (Gear Research Centre, Institute of Machine Elements at Technical University of Munich)
DAQ	Data acquisition
HDD	Hard disk drive
RPM/rpm	Revolutions per minute
RHS	Rectangular hollow section
VTT	Technical Research Centre of Finland Ltd
i	Gear ratio
k	Yield stress of the material in pure shear (MPa)
M	Torque (Nm)
n	Revolutions per minute, i.e. RPM (min^{-1})
P	Power (W)
Q	Flow rate (dm^3/minute)
V_{disp}	Displacement of pump (cm^3/rev)
$z1, z2$	Number of teeth in pinion and gear, respectively
η	Efficiency
σ_y	Yield strength (MPa)
ω	Angular velocity (1 rad / second)

1 Introduction

The VTT gear test rig was designed and manufactured by VTT in spring 2015. The test runs were operated for several years until the decision to relocate and move the premises was made. The test rig was moved and reassembled in a new environment in 2020. The main objective of this thesis was to verify the adequate assembling and functioning of the apparatus for the future tests as well as to describe its principles. Thus, several problems required a solution.

The test machine needed to be assembled and installed in the new environment. Therefore, the lubrication system had to be adjusted to the structure of the working room. The crane was not reaching the device and could not be used for lifting heavy parts like the test gearbox or safety frame, etc. Because of the lower voltage of the new place the power supply system had to be readjusted. The commissioning tests were scheduled, the results should have verified the proper functioning of the device and its measuring system. For example, analogical gearbox efficiency tests were done before (Shadan, et al., 2017).

The work was started by organizing the manuals while slowly familiarizing with details.

All figures by Artur Korostavyi, unless otherwise mentioned.

2 Test apparatus and measuring system

The VTT test rig (Figure 1) design is based on FZG apparatus.

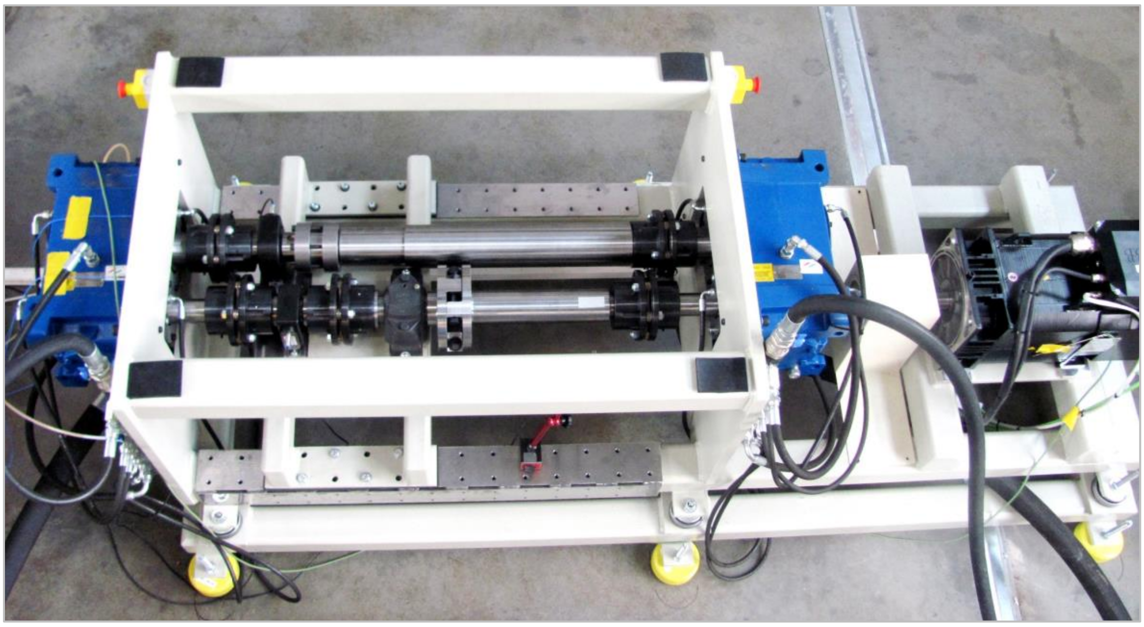


Figure 1. VTT gear test rig visual picture (Figure by Hannu Sainio, 2016).

The manufacturing and improvements were designed by Peter Anderson and Hannu Sainio. The main difference is the loading unit, which provides a possibility of setting any specific torque value between 0 – 1000 Nm. Extra 1000 – 2000 Nm can be reached by adjusting component number 6 (Table 1).

2.1 Description and assembly of the system

According to VTT internal reports (Andersson, 2014) the VTT Gear and bearing wear test rig has been designed for experimental investigations on gear failures like low-speed wear, micro-pitting, pitting, scuffing, tooth root fatigue and tooth breakage. In addition, high-speed wear of a gear and bearing damages like wear, smearing, indentations, cracks and spalling can be studied.

Lubrication related failures for gears that can be studied are such as Hertzian fatigue (pitting and micro pitting), wear (abrasive, adhesive etc.) as well as scuffing. Non-lubrication related failures include overloading and bending fatigue. Bearings can be studied in the same manner, including following phenomena:

- Wear caused by abrasive particles and inadequate lubrication.
- Smearing, or adhesive transfer of material from one surface to another when two inadequately lubricated surfaces slide against each other under load.
- Indentations caused by faulty mounting, overload and foreign particles.
- Cracks formed in different reasons, like rough treatment, excessive drive, smearing or spalling.
- Spalling due to different reason e.g. heavy loading and inadequate lubrication.

2.1.1 Frame and power train

The test rig frame is made of RHS 100x100x8. Steel plates (Figure 2) are used for assembling the gearboxes. The construction's dimensions are 2500 mm (length), 1130 mm (width) and 880 mm (height). The whole test rig weighs approximately 2 tons.

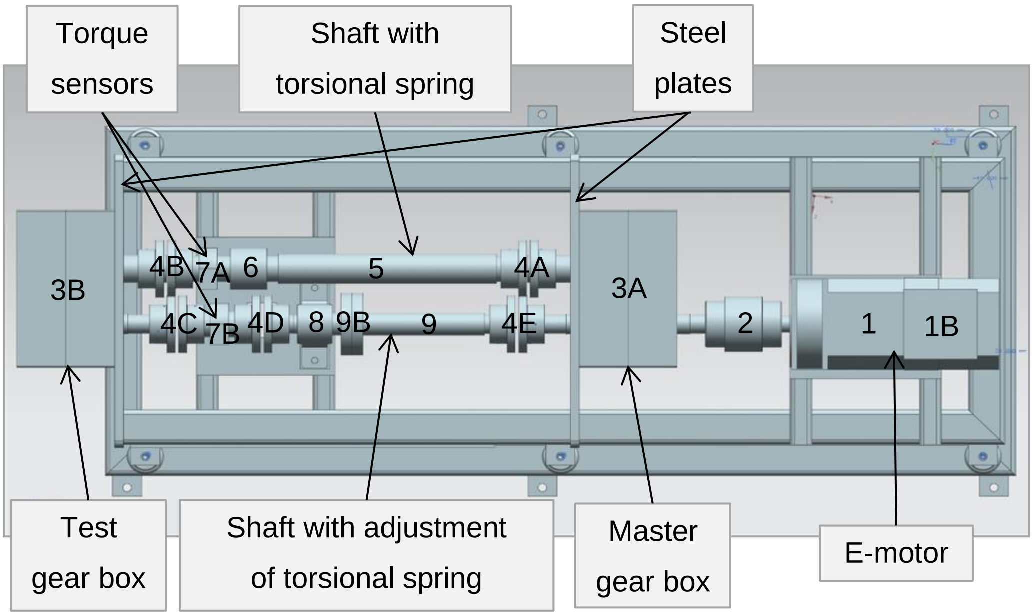


Figure 2. VTT test rig power train (Figure by Hannu Sainio, 2018).

The test machine is powered by an electric motor, which drives the input shaft (Component 9) and loops with output shaft (Component 5) (Table 1).

Table 1. VTT test rig main components and short information.

Component	Name	Manufacturer	Specifications
1	Drive motor	ABB	34.5 kW, 4000 rpm, 135.5 Hz
1B	Frequency converter	ABB	
2	Shaft coupling	ROTEX© GS	2350 Nm
3	Gearbox	STM team	ratio 1.111:1
4	Shaft coupling	ESCODISK	2000 Nm
5	Shaft with torsional spring	VTT	
6	Shaft coupling	BONFIX	3500 Nm
7	Torque transducer	datum	4000 Nm
8	Support bearing	SKF SE211	(1211 ETN9) 9000 rpm
9	Shaft with torque adjustment	VTT	
9B	Torque adjustment device	VTT	

The motor rotates both shafts and is connected to the pinion of the master gearbox (3A) with a jaw shaft coupling (2). The shaft with a torsional spring (5) is connected to the master gearbox with a disc coupling (4A). The opposing end of the output shaft (5) is connected to the test gearbox (3B) via a locking device (6), torque transducer (7A) and another disc coupling (4B). The test gearbox is mounted with two bolts on a steel plate support welded on the frame. The shaft (9) with the adjustment of a torsional spring (9B) is connected to the pinion of the test gearbox with a disc coupling (4C). The torque is thus transmitted from the test gearbox (3B) back to the master gearbox (3A) via disc coupling (4C), a torque transducer (7B), another disc coupling (4D) and support bearing in split pillow block housing (8), torque adjustment device (9B) as well as one more disc coupling (4E).

The test and the master gearboxes are mounted on supporting steel plates welded to the frame. The gearboxes have a single stage of helical gears, i.e. an input gear (pinion or drive gear) and output gear (i.e. gear or driven gear). The gear reduction ratio is i = 40/36 (≈ 1.111:1) (eq. 1), where the number of teeth in pinion z_1 = 36 and the number of the teeth in driven gear z_2 = 40 (Table 2).

$$i = \frac{z_2}{z_1} \qquad \text{(eq. 1)}$$

The input shaft (9) is the fastest shaft and has the same rotational speed as the motor. Thus, it is 11 % faster and transmits 11% less torque than the output shaft (5). The torsional spring (Figure 3) is assembled inside the output shaft (Figure 4), i.e. component 5 in Figure 2.

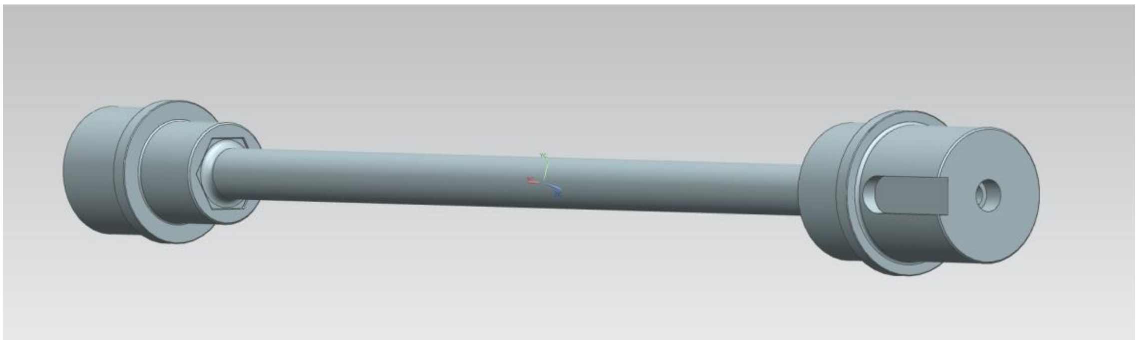


Figure 3. Torsional spring (Figure by Hannu Sainio, 2018).

The torsional spring stiffness is designed to maintain a static torque higher than 2000 Nm. The material is 42CrMo4 steel. Von Mises yield criterion in case of pure shear for the shaft is 653 Nm/mm^2 (eq. 2), which is less than the yield strength given by the supplier, i.e. 750 Nm/mm^2. Tabulated yield strength values are given as a function of diameter, since an increasing diameter has a slightly lowering effect on the yield strength of the torsional spring (Stén & Co Oy Ab, 2006).

$$\sigma_y = \frac{k}{\sqrt{3}} \qquad \text{(eq. 2)}$$

where σ_y is the tensile yield strength of the material and k is the yield stress of the material in pure shear respectively.

Figure 4. Shaft with torsional spring (Figure by Hannu Sainio, 2018).

Table 2. General information of VTT test rig (Andersson, 2014).

Dimension		Symbol	Numerical value	Unit
Shaft centre distance:		a	160	mm
Tooth face width:		b	10…50	mm
Module:		m_n	2…10	
Number of teeth	pinion	$z1$	36	
	wheel	$z2$	40	
Load torque:		M_v	0…2000	Nm
Rotational speed range:		n	100…8000 (10000)	min^{-1}
Bath lubrication volume:		V_{bath}	5	litres
Flow rate of oil supply pumps:		Q	29	dm^3/min
Lubrication oil tank volume (1 piece):		V	180	dm^3

In total, there are two oil tanks, one for each gearbox. A separate oil pump is for supplying and removing oil from tanks.

2.1.2 General principle

Thus, it can be discovered that the VTT gear test machine utilizes recirculating power loop. It is also called as four-square configuration. The benefit of such configuration is that power is needed only to overcome the frictional losses during operation. For better understanding an example is provided:

- The motor rotates the input shaft at 1000 rpm (n). This is expressed as angular velocity (ω) 2 · π · 1000 rpm / 60 = 104.7 radians per second (1/s) (eq. 3).

$$\omega = \frac{2\pi n}{60} \qquad \text{(eq. 3)}$$

- Let the pre-tightening torque (τ) on the input shaft be 1000 Nm, where the static pre-tightening torque on the output shaft is 1000 Nm · gear ratio 1.111:1 = 1111 Nm.
- Power (P) enters the master gearbox (slightly less than 1000 Nm from the input shaft and 83 Nm from the motor) 1063 Nm · 104.7 1/s = 111317 Nm/s = 111.3 kW (eq. 4). Assume the efficiencies of gearboxes are 96%, in which case the power loss in master gearbox is 4%, i.e. 4.45 kW. Thus, (111.3 - 4.45) kW = 106.9 kW goes to the test gearbox via the output shaft rotating at 900 rpm (= 94.3 1 / s), i.e. the torque of the output shaft in this context is 106.9 kW / 94.3 1/s = 1134 Nm.

$$P = \tau\omega \qquad \text{(eq. 4)}$$

- Out of the test gearbox comes 0.96 · 106.9 kW = 102.6 kW. From there it is transmitted via the input shaft, which at an angular velocity of 104.7 1/s means 102600 / 104.7 = 980 Nm.
- From 1063 Nm is missing 83 Nm, and this is taken from the engine. The motor power becomes 83 Nm · 104.7 1 / s = 8.7 kW. We reach the same result by summing the power losses of the master and the test gearboxes: 4.45 + 4.27 = 8.7 kW.

The test rig consists of two sets of helical gears placed back to back with their shafts connected in cycle. The torque requirement of the motor arises from the friction losses of the two gears. The higher the load, i.e. torque, and the higher the friction in the gears, the greater is the torque requirement for the motor. When the statically loaded system is started while the lubrication is absent, the high wear rate occurs due to metal to metal contacts.

2.1.3 Loading unit

The main component of the input shaft is a torque adjustment device (Component 9B in Figure 2) and is shown more closely in Figure 5. It is a two-part construction locked with three bolts in cycle. There is no load, while the bolts are loose. The test rig can still be started. The torque can be adjusted only when the motor has been stopped, i.e. in a static condition. The basic principle of loading is twisting the shaft with the torsional spring and storing the applied torque by locking it in position with each bolt tightened evenly every step around the circle. The tightening is dependent on the needed amount of torque. During the procedure, torque adjustment is shown on a torque transducer's display.

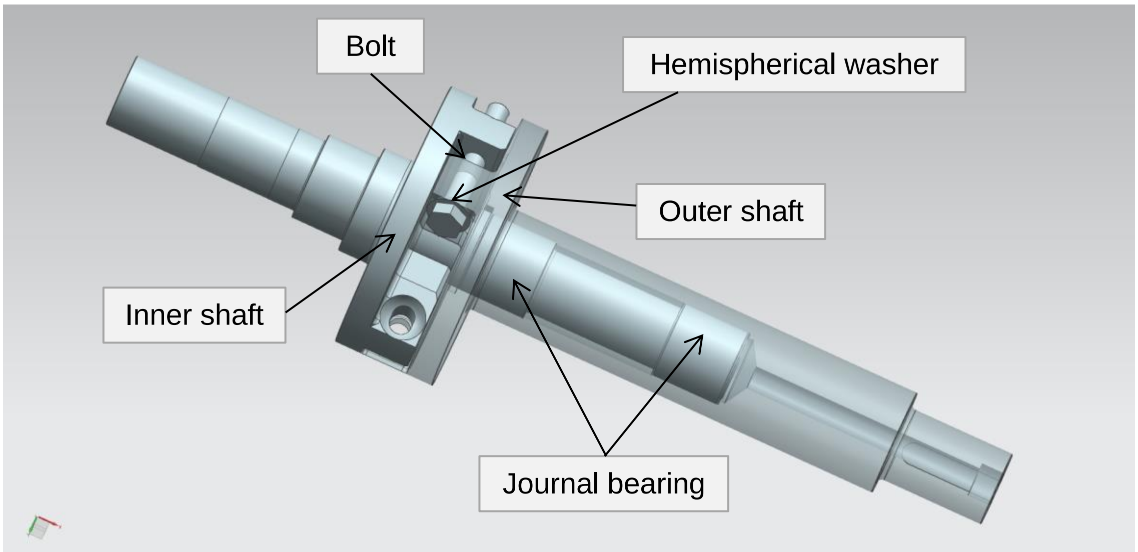


Figure 5. Torque adjustment device (Figure by Hannu Sainio, 2018). The length is approximately 670 mm.

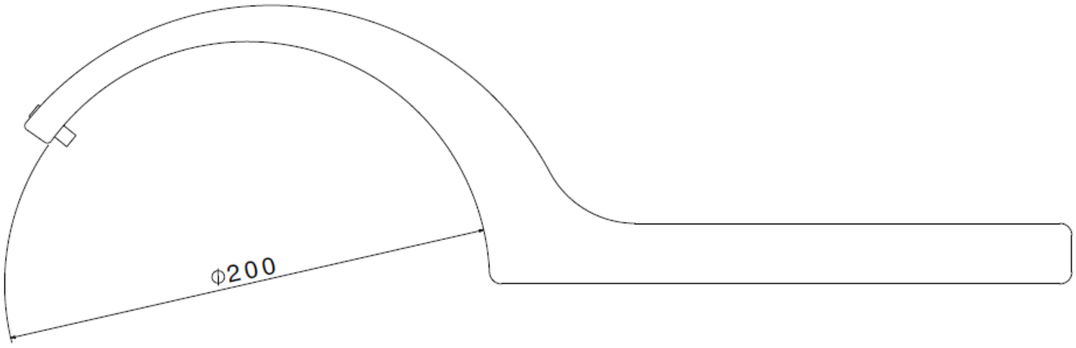


Figure 6. Hook spanner (Designed by Artur Korostavyi, 2021).

As the torque increases, rotating the shaft requires more effort. A hook spanner tool (Figure 6) was designed and manufactured for rotating the shaft efficiently. Six grooves were drilled in the outer shaft to establish a grip.

To decrease the shear force on the bolts, hemispherical washers (Figure 7) are placed under each bolt and nut. By doing that, the bolt is free to move to the sides in its length axis as during the tightening, the gap between two parts of the adjustment device is closing in the rotating motion. Therefore, the washers are also moving parts, which are lubricated with paste. Thus, the bolts are only affected by the normal force.

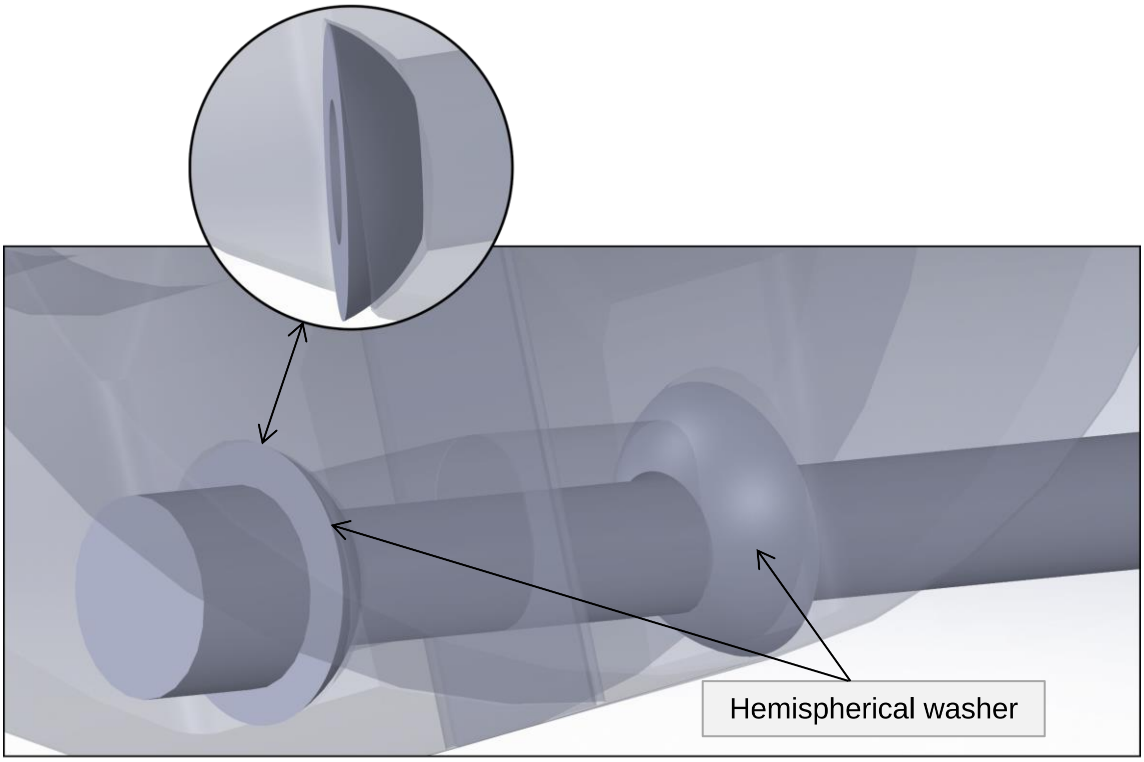


Figure 7. Example of bolt and hemispherical washers' position during torque setting showing the need for lubrication. Separate view shows the hemispherical washer from a different angle (Figure by Artur Korostavyi, 2020).

In this type of construction, the hemispherical washers change position by turning and the bolt avoids the shear stress as long as it does not touch any of the shafts.

2.1.4 Lubrication system

An individual forced lubrication circuit is provided to both gearboxes. In both circuits, a supply pump is connected with an oil hose from an oil tank to an oil distribution manifold installed close to the gear housing. From the manifold, the oil is distributed via four hoses to the bearings and through two hoses to locations above and below the gear mesh. The double oil supply to the gear mesh is a precaution for ensuring an adequate supply of oil at all operating speeds. A second pump is connected to the bottom of the gear housing and it returns oil back to the tank. The flow rate is set by the manually adjusted speed of each pump to make approximately 2 bar pressure in the oil distribution manifold, where the pressure indicators are installed. The use of two individual oil circuits allows different oils to be used in the two gearboxes.

The pump's nominal size (Figure 8) is measured in cm^3/rev and denotes the displacement (V_{disp}).

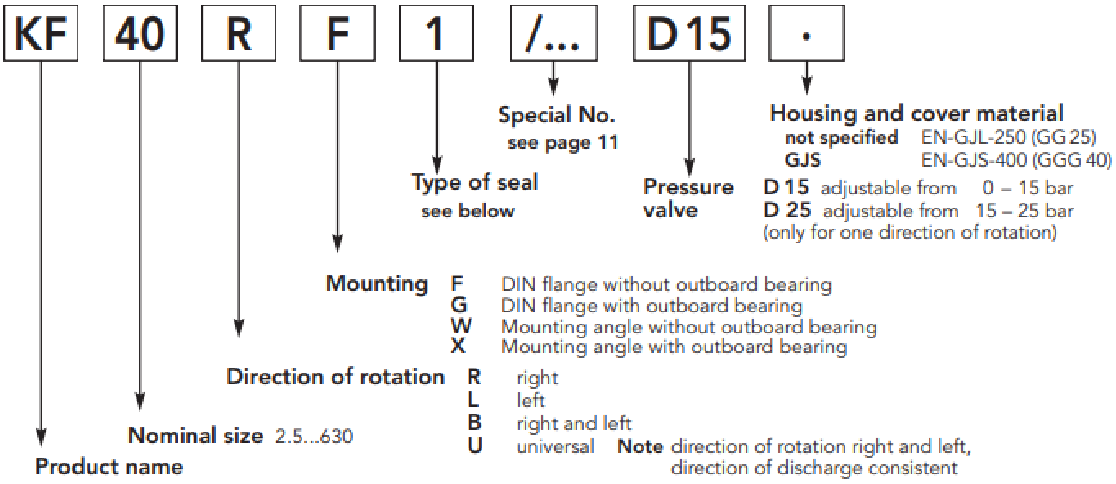


Figure 8. Explanation of the pump specification. Present pumps are KF 20 (KRACHT, 2019).

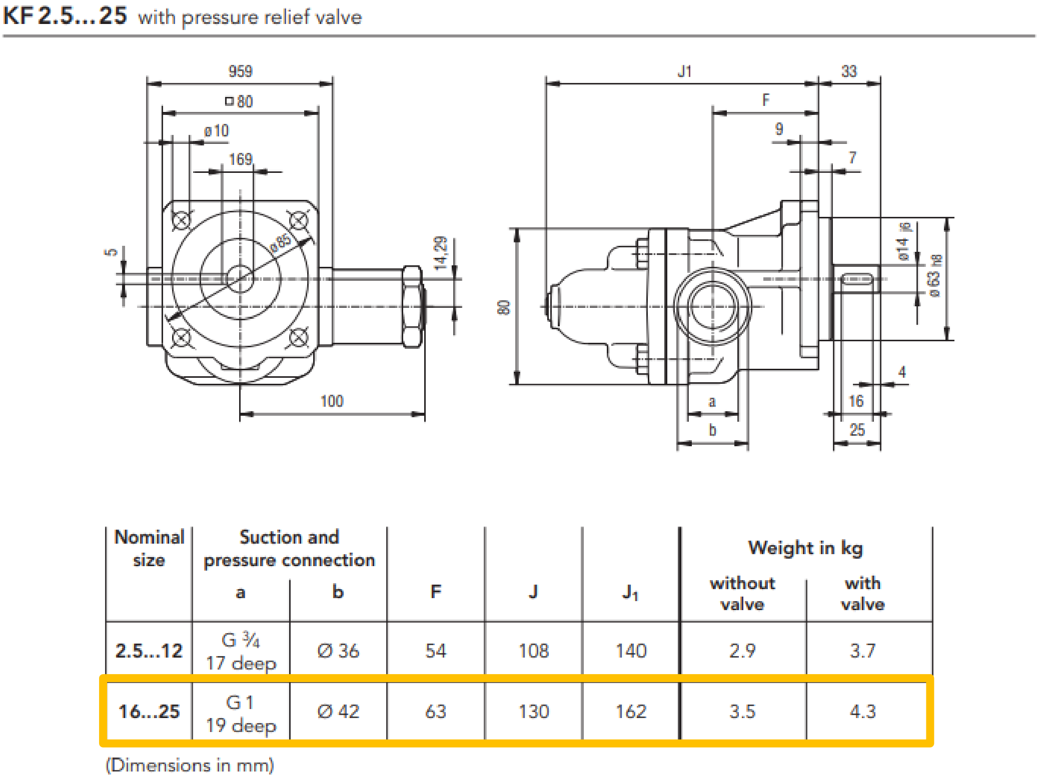
The maximum flow rate (Q) of the pumps is approximately 29 litres/minute (20 cm^3/rev · 1440 rpm = 28800 cm^3/min) (eq. 5) (Table 3, Figure 8).

$$Q = V_{disp} n \qquad \text{(eq. 5)}$$

Table 3. Components of a single lubrication system. The test rig has two lubrication systems altogether.

Component	Name	Manufacturer	Specifications
10	Oil supply pump	KRACHT	KF 20 RF 1 – D 15
10B	Frequency converter	VACON	
10C	Oil tank	EURO-HYDRO	180L
10D	Pump motor	LAMMERS	1440/min
11	Oil return pump	KRACHT	KF 20 RF 2
11B	Frequency converter	VACON	
11C	Oil tank	EURO-HYDRO	180L
11D	Pump motor	LAMMERS	1440/min

The supply pumps have pressure relief valves (Figure 9) that limit the pressure to 0 – 15 bar (Figure 8).



Nominal size	Suction and pressure connection a	Suction and pressure connection b	F	J	J_1	Weight in kg without valve	Weight in kg with valve
2.5...12	G ¾ 17 deep	Ø 36	54	108	140	2.9	3.7
16...25	G 1 19 deep	Ø 42	63	130	162	3.5	4.3

(Dimensions in mm)

Figure 9. Schematic diagram of a pressure relief valve (KRACHT, 2019)

Thus, if the oil faucet was not opened and the pressure started to increase, oil will not be supplied to the gearboxes to avoid the overloading.

2.1.5 Control system

Torque is adjusted manually and requires a set of a 24mm size socket with ratchet and a 24mm size wrench. The procedure requires caution and is time consuming. While adjusting, the torque is monitored with torque sensors (Component 7 in Table 1) on both shafts.

The return pumps can be started and adjusted only with VACON frequency converters for each pump, i.e. components 10B in Table 3. The supply pumps are also equipped with VACON frequency converters (Components 11B in Table 3). Additionally, they are provided with a control panel (Figure 10). A set of two pump’s motor speed regulators are installed on the panel.

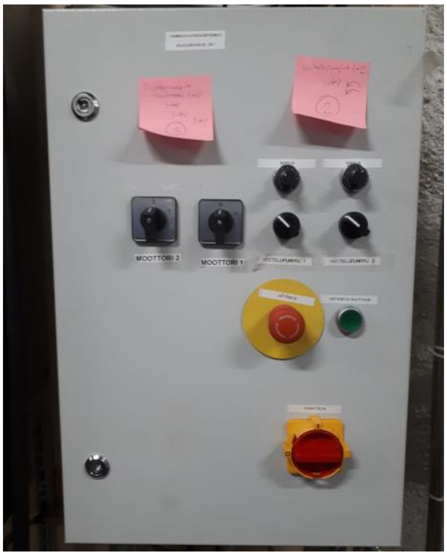


Figure 10. Remote control panel of supply pumps.

The ABB motor (Component 1 in Figure 2) speed is controlled by the ABB frequency converter (Component 1B, Figure 2) manually.

Without adequate lubrication, there is a high risk of damaging the gears after starting the test apparatus with any torque value more than zero. To prevent critical damages, a control system has been installed that shuts down device if the pre-set oil pressure is exceeded. The control system consists of 2 pressure sensors and a control relay. The control relay is connected in series with the test bench’s emergency stop, i.e. E-stop buttons. Pressure sensors are adjusted to shut down the power in case the pressure drops below 1 bar. Oil pump motors remain unaffected.

All the values of adjustments are saved in the controllers’ memory.

High temperature in the gearboxes can cause low viscosity of the oil, which may result in some damage. Therefore, temperature sensors have been installed in both gearboxes. They are limited to shut down the power supply of the motor in case of overheating the oil.

The VTT test rig cannot be started without the safety frame (Figure 11) on.

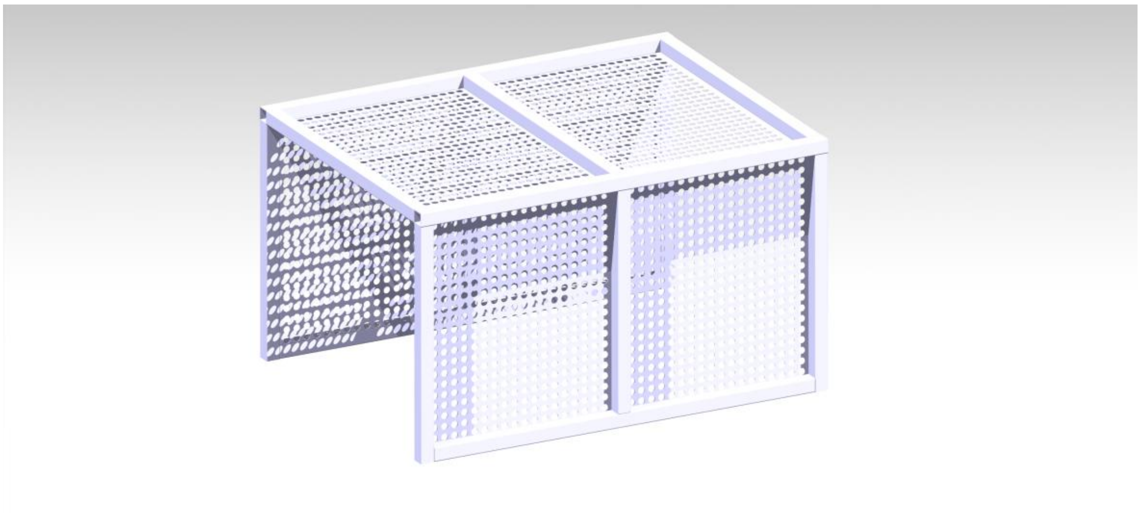


Figure 11. Old safety frame. The length is 1220 mm (Figure by Hannu Sainio, 2016).

To make operation easier (the mass of the safety frame is more than 50 kg), it was decided to modify the safety frame by adding two door-like hatches (Figure 12) with limit switches installed in both of them. That way there is no need for uninstalling the frame every time for maintenance or adjusting the torque.

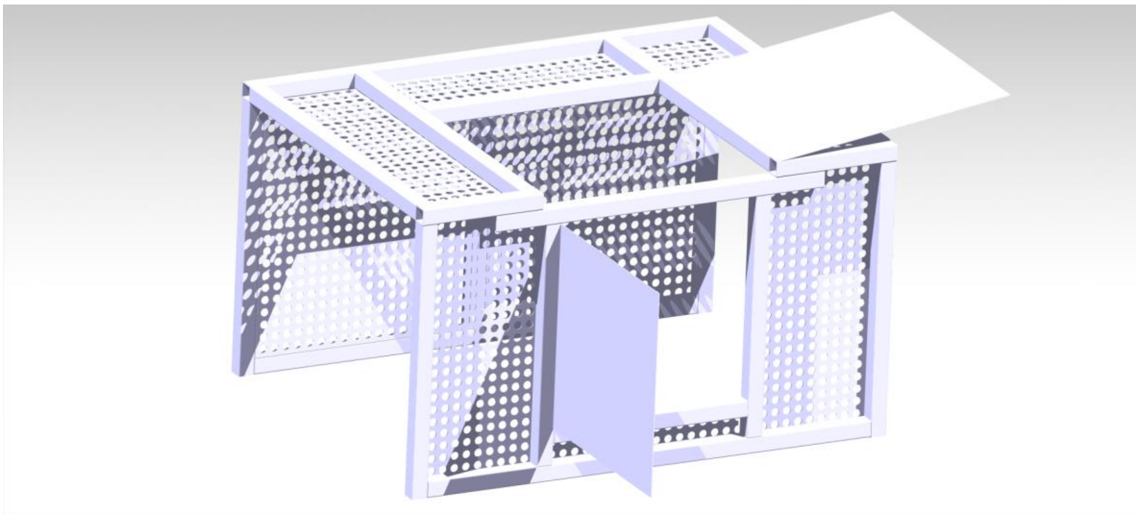


Figure 12. New safety frame with two hatches (Designed by Artur Korostavyi, 2021).

All the measurement data is saved in external data storage (HDD) as well as on the HDD of the measurement computer.

2.1.6 Auxiliary measurements system

The measuring equipment consists of a measuring computer, a data collection system and sensors. The DAQ device is a Chronos measuring device with a Cansas extension. 7 analogue channel channels are connected to the measuring device.

- The PAMAS S50 is a laser-based online system with simple integration into industrial data management systems. An automatic digital flow rate determination counts particles sizes > 4 µm(c), > 6 µm(c) and > 14 µm(c), which are indicated on the instrument display. The data is sent into PC storage.

- Tandelta sensor is used to measure the capacitance and the conductance of the oil, which changes as the oil becomes damaged. An AC electric voltage is applied across two electrodes, the change in current flowing indicates degradation of the oil.

- Datum sensor utilizes a strain gauge to measure the torque. The sensor is size 4, which torque range is 0 to 10000 and maximum turning speed is 10000 rpm.

- Monarch sensor is used to measure revolution per minute of the shafts. A visible optical red LED light source is pointed into reflective sticker placed on each the shaft. Speed range is up to 250000 rpm.

- PCB Piezotronics vibration sensors are installed on the top and on the bottom of the test gear box. Vibrations are inspected in z-axis. Measurement Range is ±500 g pk.

2.2 Occupational safety

Risk assessment was performed prior to taking the test unit in use. The most important finding was the noise level during operation, which exceeds 85 dB frequently. The noise level during driving with torque value of 1000 Nm and 1000 rpm was measured to be approximately 100 dB. The test rig is designed to run tests with a torque value up to 2000 Nm and a rotational speed up to 4000 rpm. Since an acoustic system will not be available, it is highly recommended to wear certified double ear protection (in ear plugs as well as earmuff) for safety. Other precautions are required as well to be discussed with an occupational safety organization, including working time, working shifts as well as constant control of hearing.

With the rise of the rotational speed, the result of contacting the rotating components is extremely dangerous. A safety frame (Figure 12) is needed and will be installed on the test rig prior to commissioning. The safety frame is equipped with sensors to prevent the motor from starting when the safety frame is open.

The amount of oil for lubrication is approximately 360 litres and the flow rate is 29 litres/minute. Preparations against oil leakage include a barrier on the floor around the test rig area. This precaution will decrease risks for slipping as well as oil leaking to a sewer.

2.3 General instructions for using the device’s functions and driving the device

Here is a list of general user instructions. A more detailed user manual, which contains pictures, was made for VTT's internal use only.

- Start the project computer.
- Prepare the safety clothes and devices.
- Acquire the required tools for the torque adjustment.
- Start the main powerline by its switch.
- Turn on auxiliary measurements power by two switches behind its panel.
- Switch on 25 A and (Do not switch 50 A on !!!).
- Turn on the main powerline on the frequency converters’ control panel.
- Start the return pumps first to prevent the pressure rise.
- Start the supply pumps and adjust the pressure to 2 – 3 bars.
- Check the pressure sensor display for OK status.
- Press the check button on the frequency converters’ control panel.
- Inspect the area for oil leakage or malfunctions in pumps.
- Launch all the required programs on the project computer (All the data and measures can also be seen on the computer’s screen.)
- Start the torque adjustment procedure. (Lubricate bolts, washers and nuts if needed. Monitor the torque value on the torque displays on the panel).
- Remove all freely detachable parts and tools.
- Inspect the area around the test rig for unnecessary obstacles and any visual problems, close the hatches and check the limit switchers.
- Equip the safety clothes and devices and start the test on the project laptop.
- Switch 50 A on. The motor frequency converter is started. Rpm is set to -20 (negative value to run the motor in the required way).
- Start the motor to warm up. Increase the rotational speed slowly to the required value while monitoring the whole mechanism for adequate working.
- Run the test.
- Stop the motor. Set the rotational speed to 0 for safety.
- Switch 50 A off.
- Stop the supply pumps.
- Stop the return pumps. Switch 25 A off.
- Press the red stop for safety. Turn off all powerlines.

3 Commissioning tests

3.1 Preparations for commissioning testing

Power losses in gearboxes are caused mainly by gears, bearings and seals. In order to measure the losses reliably, it requires simultaneous measurement of multiple data, such as temperature, vibrations/accelerations, torque and rotational speed. Efficiency is the ratio between output and input powers of the system (eq. 6). The efficiency (η) of the gearbox affects such parameters as driving performance, fuel consumption and emissions.

$$\eta = \frac{P_{out}}{P_{in}} \qquad \text{(eq. 6)}$$

Commissioning tests were prepared to measure the apparatus' behaviour and to ensure proper work of the device and its sensors.

Verification of the fully operational measuring system was tested by running tests of 350, 500, 750 and 1000 Nm torque at 1500 rpm each. A speed sensor was measuring the rotational speed only of the output shaft. As the ratio i = 40/36, 1500 rpm divided by 40/36 is approximately 1350 rpm. The analogical tests were run by a different scientist a few years before, who adjusted the device for maximum of 1000 Nm torque. It could also be an additional comparison to ensure correct operation of the device.

The procedure was started by turning all devices on from the back of the sensor panel. After the IMC program on the project computer was started, the drive parameters were set to the required values. Sampling rates for the measurements required some attention as well. When the signals and connections from the sensor panel were verified, the test was started.

3.2 Running the test program

The first test was started by adjusting the torque for 350 Nm. The start-up speed for the motor is -20 rpm. The negative value sets up the required rotating direction of the motor. Later on, the speed will be presented as positive values for better readability.

The closed-loop of the test rig is torsion loaded and is in torsional equilibrium. Thus, each section has equal and opposite torques. If the applied torque and the rotation at one end of a closed-loop section are in the same direction (aligned), then power will enter that section (Lee, et al., 2020)

The estimation of efficiency (i.e. losses) is dependent on the rotating direction – whether it is aligned with the direction of the set torque or opposite. Driving the motor counter clockwise, sets the energy (and power) to transmit through the master gearbox along the output shaft (Component 5 in Figure 2Table 2) to the test gearbox and further along the input shaft towards the master gearbox and the motor. Thus, the efficiency must be calculated according to eq. 7 (reverse of eq. 6).

$$\eta = \frac{P_{in}}{P_{out}} \qquad \text{(eq. 7)}$$

If the direction of rotation is clockwise, then the energy (and power) goes through the master gearbox along the input shaft to the test gearbox and continues from there slightly smaller (due to losses) along the output shaft towards the master gearbox the eq. 6 will apply.

3.2.1 350 Nm test

The speed was increased slowly in 200 rpm steps. Instruments and equipment were monitored during the start-up to be sure of proper functioning. After reaching the required speed (1500 RPM), the test was continued for 2 – 3 minutes. However, the time was too short for temperatures to stabilize, but that was not considered important in commissioning.

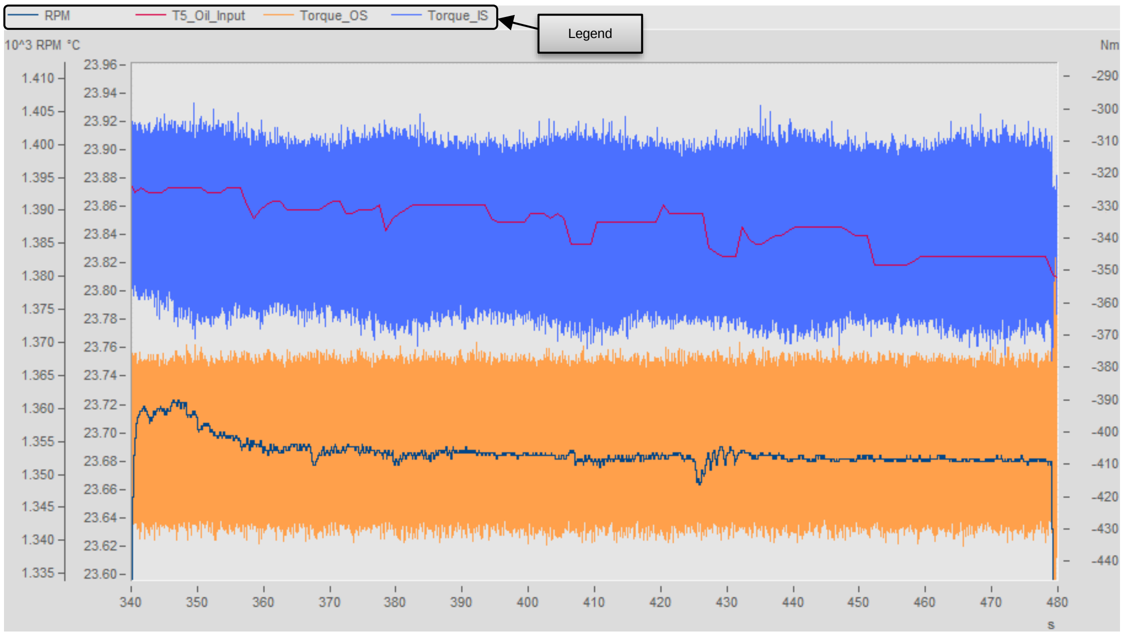
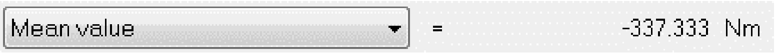


Figure 13. Measured data of rotational speed (RPM), temperature of supply oil (T5_Oil_Input), output (Torque_OS) and input (Torque_IS) torques for approximately 140 seconds.

The data in Figure 13 was used in Famos to calculate the average values of RPM, torques and supply oil temperature:

Mean value = 1.353293 10^3 RPM

Figure 14. Average value for rotational speed of the 350 Nm test.



Mean value = -337.333 Nm

Figure 15. Average value for input shaft torque of the 350 Nm test.

Mean value = -403.658 Nm

Figure 16. Average value for output shaft torque of the 350 Nm test.

Mean value = 23.8470 °C

Figure 17. Average value for supply oil temperature of the 350 Nm test.

The results from Figure 14, Figure 15, Figure 16 and Figure 17 are listed in Table 4

Table 4. Average values of the measured data. The test duration of the experiment was approximately 140 seconds. The nominal static torque was set to 350 Nm.

	Average	Set	
Rotations per minute	1353.3	1350.0	
Temperature of the supply oil	23.8		°C
Torque of the output shaft	403.7	388.9	Nm
Torque of the input shaft	337.3	350.0	Nm

The speed was approximately 1350 rpm, i.e. very close to the set value. After starting the test, the torque of the input shaft stabilized down to approximately 337 Nm, while the torque of the output shaft increased up to 404 Nm. The temperature of the oil did not change during the test.

3.2.2 500 Nm test

The torque was adjusted to 500 and the speed was increased slowly in 200 rpm steps. Instruments and machinery were monitored during the start-up to be sure of proper functioning. After reaching the required speed (1500 RPM), the test was continued for 2 – 3 minutes. The test run was finished, and the motor was stopped, although the temperature was not yet stabilized.

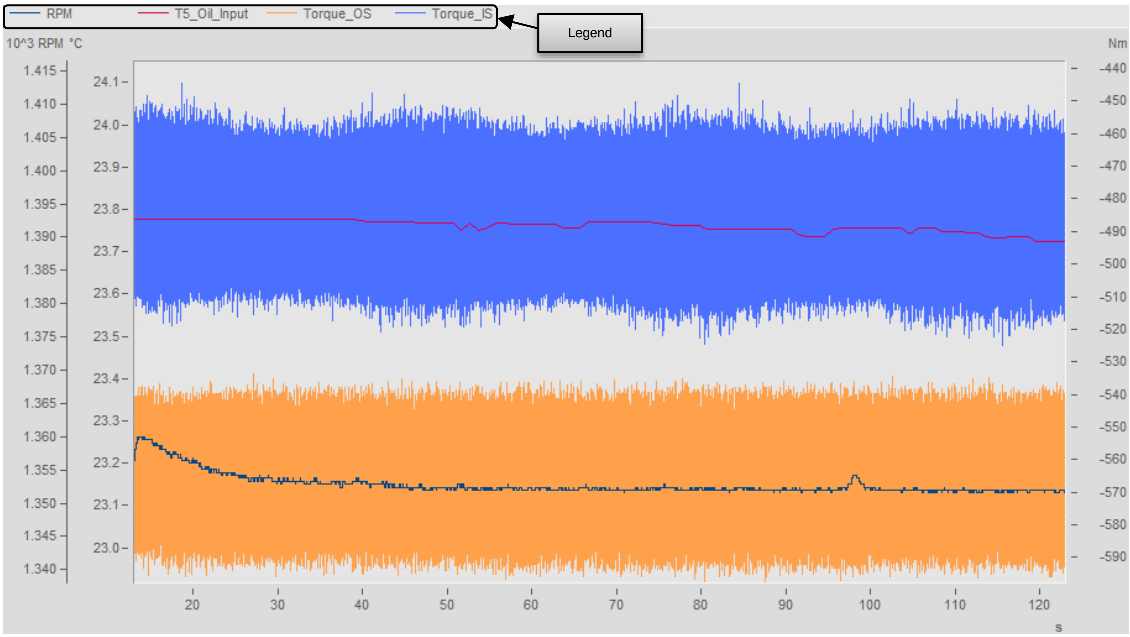


Figure 18. Measured data of the rotational speed, temperature of supply oil, output and input torques for approximately 110 seconds. The legend is as in Figure 13.

The data in the Figure 13 was used to calculate average values using the Famos software:

Mean value = 1.352671 10^3 RPM

Figure 19. Average value for the rotational speed of the 500 Nm test.

Mean value = -485.138 Nm

Figure 20. Average value for the input shaft torque of the 500 Nm test.

Mean value = -566.101 Nm

Figure 21. Average value for the output shaft torque of the 500 Nm test.

Mean value = 23.76160 °C

Figure 22. Average value for supply oil temperature of the 500 Nm test.

The results from Figure 19, Figure 20, Figure 21 and Figure 22 are listed in Table 5.

Table 5. Average values of measured data. Test duration of the experiment was approximately 110 seconds. The nominal static torque was set to 500 Nm.

	Average	Set	
Rotations per minute	1352.7	1350.0	
Temperature of the supply oil	23.8		°C
Torque of the output shaft	566.1	555.6	Nm
Torque of the input shaft	485.1	500.0	Nm

The speed was approximately 1350 rpm, i.e. very close to the set value. The average of the measured input shaft torque is approximately 485 Nm indicating losses in start-up. The temperature of the oil did not change during the test.

3.2.3 750 Nm test

The torque was adjusted to 750, and the speed was increased slowly in 200 rpm steps. Instruments and machinery were monitored during the start up to be ensure proper functioning. After reaching the required speed (1500 RPM), the test was continued for 2 – 3 minutes. Again, temperature stabilization was not considered important.

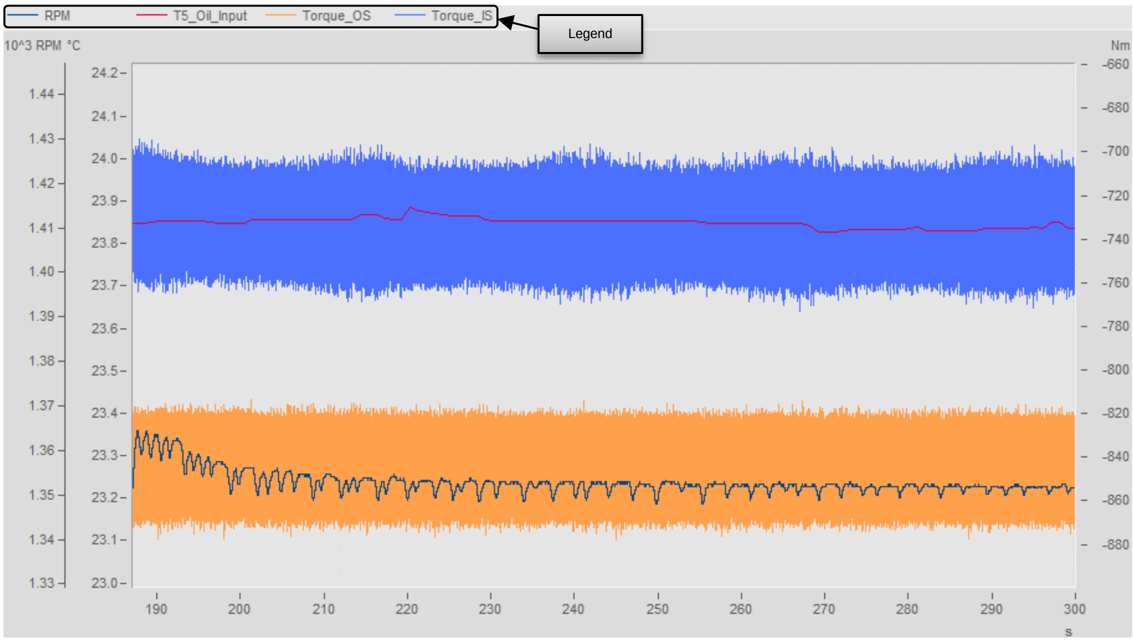


Figure 23. Measured data of the rotational speed temperature of supply oil output and input torques for approximately 120 seconds. The legend is as in Figure 13.

The data presented in Figure 23 was used to calculate average values in Famos software:


Mean value = 1.352649 10^3 RPM

Figure 24. Average value for the rotational speed of the 750 Nm test.


Mean value = -733.345 Nm

Figure 25. Average value for the input shaft torque of the 750 Nm test.

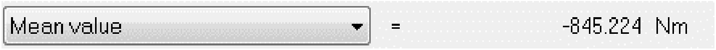

Mean value = -845.224 Nm

Figure 26. Average value for the output shaft torque of the 750 Nm test.

Mean value = 23.8502 °C

Figure 27. Average value for the supply oil temperature of the 750 Nm test.

The results from Figure 24, Figure 25, Figure 26 and Figure 27 are listed in Table 6.

Table 6. Average values of the measured data. The test duration of the experiment was approximately 120 seconds. The nominal static torque was set to 750 Nm.

	Average	Set	
Rotations per minute	1352.6	1350.0	
Temperature of the supply oil	23.9		°C
Torque of the output shaft	845.2	833.3	Nm
Torque of the input shaft	733.3	750.0	Nm

The speed was approximately 1350 rpm, i.e. very close to the set value. The average of the measured input shaft torque was approximately 730 Nm. The temperature of the oil did not change during the test.

3.2.4 1000 Nm test

The torque was adjusted to 1000, and the speed was increased slowly in 200 rpm steps. Meters and equipment were monitored during the start up to be sure of proper functioning. After reaching the required speed (1500 RPM), the test was continued for 2 – 3 minutes. The test run was finished, the motor was stopped, and finally the temperature was not yet stabilized, however.

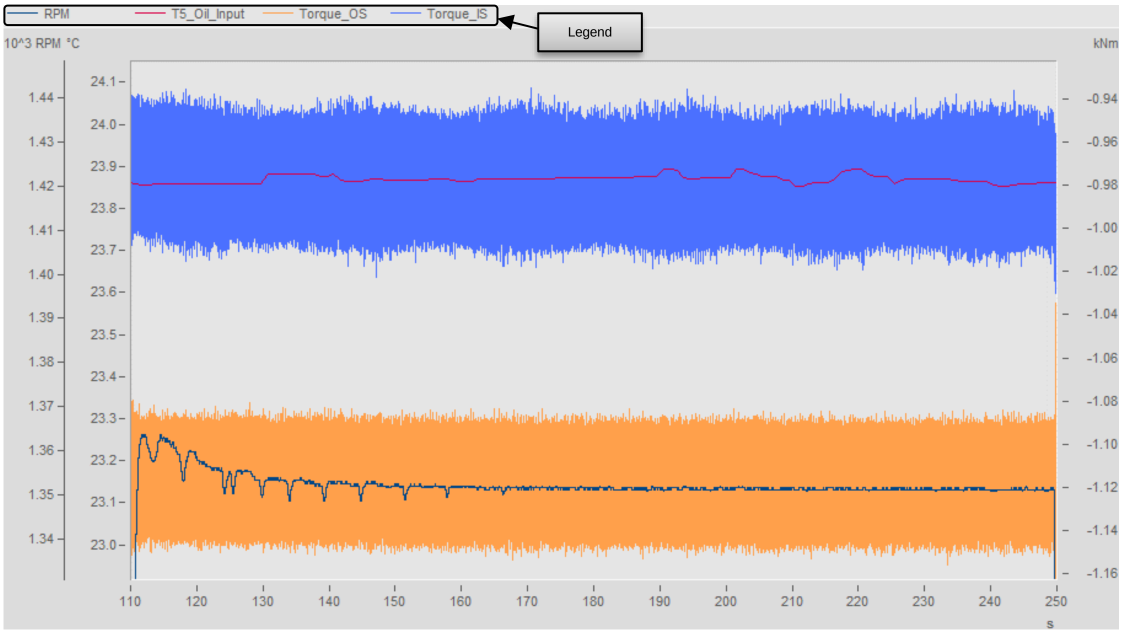


Figure 28. Measured data of the rotational speed temperature of supply oil output and input torques for 140 seconds. The legend is as in Figure 13.

From the Figure 28 average values were calculated using the Famos software:


Mean value = 1.352052 10^3 RPM

Figure 29. Average value for the rotational speed of the 1000 Nm test.


Mean value = -0.97780 kNm

Figure 30. Average value for the input shaft torque of the 1000 Nm test.


Mean value = -1.11785 kNm

Figure 31. Average value for the output shaft torque of the 1000 Nm test.

= 23.8720 °C

Figure 32. Average value for the supply oil temperature of the 1000 Nm test.

The results from Figure 29, Figure 30, Figure 31 and Figure 32 are listed in Table 7.

Table 7. Average values of the measured data. The test duration of the experiment was approximately 140 seconds. The nominal static torque was set to 1000 Nm.

	Average	Set	
Rotations per minute	1352.1	1350.0	
Temperature of the supply oil	23.9		°C
Torque of the output shaft	1117.9	1111.1	Nm
Torque of the input shaft	977.8	1000.0	Nm

The speed was approximately 1350 rpm, i.e. very close to the set value. The average of the measured input shaft torque was approximately 980 Nm. The temperature of the oil did not change during the test.

3.3 Validation of the commissioning process

As the apparatus was started as “cold” (not warmed up), the temperature increased during the test runs, which raised the oil viscosity, and the pressure fell. At that date, the apparatus had no automated pressure sensors installed which stop the motor in case of low pressure. As mentioned before, inadequate lubrication will damage the gears. Thus, constant monitoring of the supply pressure was necessary during the test. It was increased manually, when the low levels were noticed.

The torque losses were visible in the start-up, although they could not be reliably recorded. For example, after the motor was started, the torque value of the input shaft went down for approximately 20 Nm, while the torque of the output shaft increased to compensate the losses.

According to these tests, it was established that all sensors work in the way they should operate. However, there are differences between measurements with torque sensors other than the level of the torque. The torque measurement data shows different interesting phenomena, such as deviation/variation, cyclic fluctuation as well as rapid transients during acceleration. The reasons for these phenomena are not yet fully understood, but will be analysed in detail later. In the first 350 Nm test, incomprehensible jumps in the sensor readings from the start were normalized after running at 500 rpm. No explanation was discovered at the time.

The estimated efficiencies are presented in Table 8. The efficiencies are in line with general knowledge of gear efficiency (Shadan, et al., 2017), i.e. increasing torque enhances efficiency.

Table 8. Estimated efficiencies.

	350 Nm		**500 Nm**		**750 Nm**		**1000 Nm**	
	in	out	in	out	in	out	in	out
n	1503.7	1353.3	1503.0	1352.7	1502.9	1352.6	1502.3	1352.1
ω (1/s)	157.5	141.7	157.4	141.7	157.4	141.6	157.3	141.6
τ (Nm)	337.3	403.7	485.1	566.1	733.3	845.2	977.8	1117.9
P (W)	53117.7	57205.3	76356.1	80189.0	115419.6	119725.2	153825.9	158272.5
η (%)	92.9		95.2		96.4		97.2	

As the test was running the temperature of the oil was rising higher. Temperature affects the viscosity, which in return should affect the gear efficiency.

4 Gearbox removal and required tools

In 2015, GSM was the manufacturer of gearboxes in Italy and is recently known as the STM Team. The test rig has two STM team manufactured reduction gearboxes (STM team, 2016). The master gearbox is RXP1/806/ABE/1.11/ECE/N/M3 (Figure 33) and the test gearbox is RXP1/806/AUD/1.11/ECE/N/M3 (Figure 34).

Figure 33. Master gearbox.

Figure 34. Test gearbox.

RXP means that the gearboxes are reduction gears. The number 806 denotes the serial number. ABE and AUD denote the axel configuration, as is evident in the Figure 33 and Figure 34. Because the input shaft is driven by the motor, the master gearbox has a third outside connector (Figure 35) while the test gearbox has two axles (Figure 36).

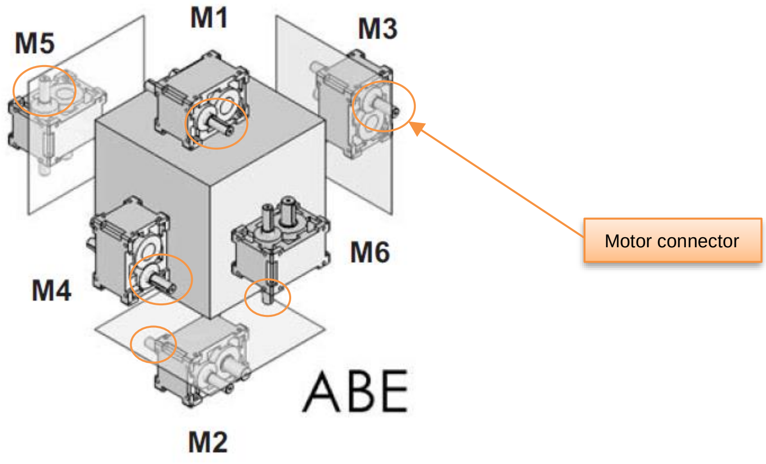


Figure 35. Shaft arrangement of master gearbox.

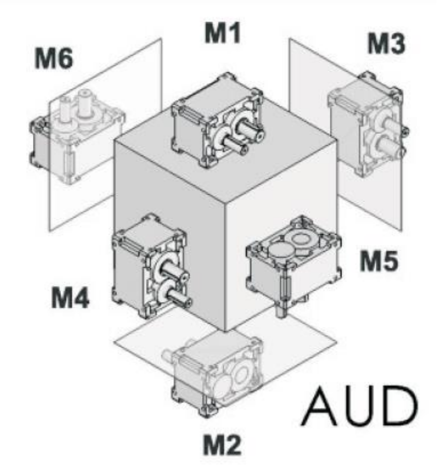


Figure 36. Shaft arrangement of test gearbox.

The housing material is cast iron (STM team, 2016). The 806-box housing size is 455 x 360 x 269 mm. The weight of both ABE and AUD gearboxes is approximately 140 – 150 kg. More detailed dimensions are given in Figure 37 and Table 9. As the 720 gearboxes have the same shaft distance, they might be used as another option in the future.

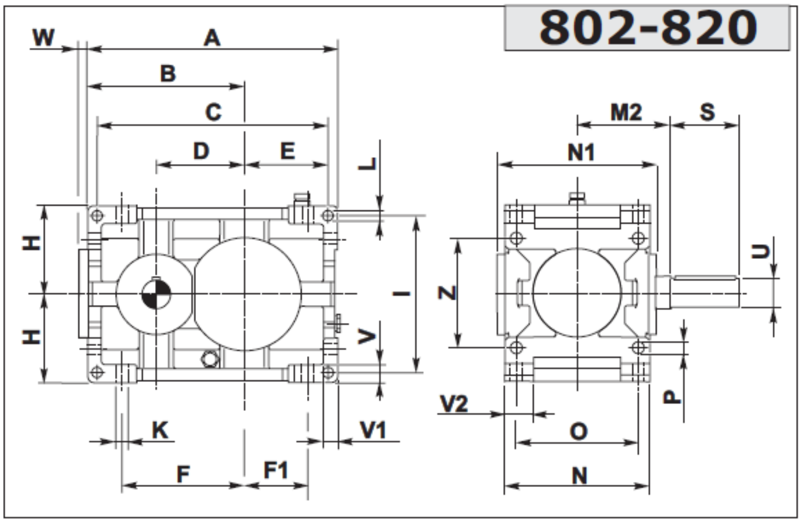


Figure 37. Dimensions of the gearbox (STM team, 2016).

Table 9. Dimensions of the gearboxes (STM team, 2016).

RX 800	**A**	**B**	**C**	**D**	**E**	**F**	**F1**	**H** h11	**I**	**K**	**Mass (kg)**
806	455	285	421	160	153	222	117	160	280	22	143
	L	**N** h11	**N1**	**O**	**P**	**V**	**V1**	**V2**	**W**	**Z**	
	18	269	271	225	22	32	25	56.5	20	200	

The side lid can be opened for a quick inspection of the test gears. It may also be manufactured from a transparent material in the future.

4.1 Gearbox removal

Due to the weight of the gearboxes (140 – 150 kg), the removal and installation require precautions and proper tools. Personal safety requires safety shoes as well as protection from oil, i.e. oil protection clothes are suggested. As the amount of spilling oil may be considerable, one needs to get prepared to limit oil leakage with oil containment booms, oil binders or oil binding rugs. There is a small oil trap inside the gearbox, where the oil cannot pass to the return pump by itself. Therefore, it must be removed manually. For example, by using a drum pump.

The tools needed for the gearbox removal are listed in following table (Table 10).

Table 10. Required tools for gearbox removal.

Crane	1000 kg		
Lifting strap	1000 kg		
Transport table	1000 kg		
Wrenches:	for oil hoses:	return	72 mm
		up	22 and 27 mm
		side	19 mm
		side	19 mm
		bottom	22 and 22 mm
	for oil manifold:	supply	38 and 41 mm
		top	27 and 27 mm
		middle (4x)	19 mm
		bottom	27 and 27 mm
	for sensors:	Pamas	12 mm
		temperature	13 and 14 mm
		Tandelta	Pliers
	for couplings:		19 and 19 mm
Hexagon wrenches:	for mounting bolts:		14 mm

The phases for removal:

- Start by removing the safety frame.
- Disconnecting the sensor cables and oil hoses.
- Open the shaft coupling closest to the gear unit.
- The transportable crane is set in a static position under the test rig.
- The gear unit is lifted by a crane. Additionally, it maybe be supported from below.

- The lifting strap is threaded through two hooks on the gearbox.

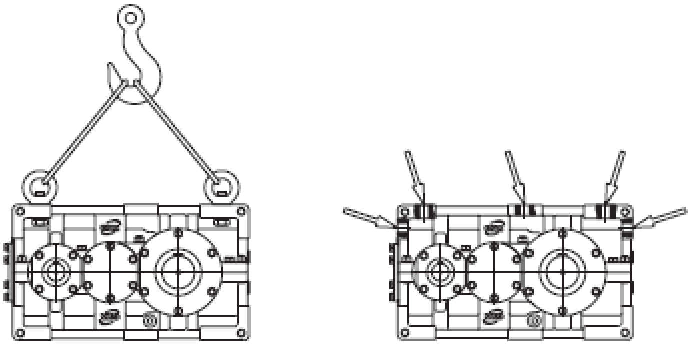


Figure 38. Example of a lifting strap usage (STM team, 2016).

- Loosen the four gear and frame mounting bolts.
- The gear unit is transported away to the stand on wheels.

When placed on the working table, the gearbox can now be opened. Equip the instruments from the Table 11 to open the gearbox.

Table 11. Instruments for gearbox disassembly.

Wrenches:	side lid	19 mm
	top	19 mm
	bottom	19 mm

Furthermore, accurate instructions for disassembly and assembly of the gearboxes are written in gearboxes’ manual (STM team, 2016).

5 Conclusions and suggestions for future development

The test machine was successfully assembled and installed in a new environment. Due to the different placing of oil tanks, the oil hoses and valves had to be rebuilt. The absence of a stationary crane led to the use of a mobile crane for heavy parts. Also, the safety frame had to be modified by adding two hatches. This made running the tests easier, since the hatches eliminated the need to remove the safety frame during test runs. A new tool for rotating shafts in the torque adjustment procedure was designed and manufactured.

Before being moved to the new environment, the device was operating at 120 A. The new hall could only provide a 63 A source. Because of the lower voltage, the device was limited to 50 A. However, it was enough to reach the required performance. The commissioning tests were run, and consequently the results verified proper operation of the device and its measuring system.

The future use of the test rig includes:

- Normal laboratory test bench for gears, lubricants and bearings
- Condition monitoring methods for testing and development
- Hybrid testing concept development
- Virtual sensing concept development
- Simulation model testing and verification

To enhance the versatility of the system, it is suggested that the electric power supply would be enhanced up to 120 A. For accelerated studies, it is recommended that the cooling system for lubricants would be taken into operation. A closed loop cooling system is recommended to avoid excessive water usage.

References

Andersson, P., 2014. *VTT gear test rig description.* Espoo: Unpublished.

KRACHT, 2019. *Gear Pumps KF 2.5...630.* [Online]
Available at: http://www.krachtcorp.com/wp-content/uploads/2019/10/KF2.5%E2%80%A6630_US_11-19_view.pdf
[Accessed: 31 December 2020].

Lee, G.-H.et al., 2020. Design of a Mechanical Power Circulation Test Rig. *Applied Sciences,* Volume 10, p. 3240.

Shadan, M., Mehdi, R. M., Somaye, D. T. & Mohsen, M., 2017. Design of a mechanically closed-loop test rig for testing aviation industry's gearboxes. *Taylor & Francis Group,* 21(4), pp. 133 - 142.

Stén & Co Oy Ab, 2006. *42CrMo4.* [Online]
Available at: https://www.sten.fi/document/1/27/aea4431/tuotee_f8be181_42crmo4.pdf
[Accessed: 7 January 2021].

STM team, 2016. *HIGH TECH Industrial.* GSM_mod.CT03 IGBD 0.1 ed. Modena: HotminDs.