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THRUST SENSOR IMPLEMENTATION INTO AZIMUTHING PROPULSION SYSTEM FOR TOWING TANK MODEL TESTS

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MASTER'S THESIS | ABSTRACT

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THRUST SENSOR IMPLEMENTATION INTO AZIMUTHING PROPULSION SYSTEM FOR TOWING TANK MODEL TESTS

The primary goal of the present Master's thesis was to develop a thrust sensor that is located at the propeller shaft. The purpose of adding a thrust sensor into the propeller shaft was to have an easy way to measure the propeller thrust against the thrust along the centerline of the ship model. The secondary objective was to create an ice propeller and pod housing for the developed sensor as 3D printing.

The thesis discusses the rules and regulations of the International Towing Tank conference about how the tests should be conducted with a special focus on calibration methods. The thrust sensor was developed mechanically and the development process included four iteration rounds. During each iteration, the properties of the sensor were improved and the design became more practical. A test bench with a reference thrust and a torque sensor was developed for the preliminary tests. The test bench allowed adding thrust and torque load into the thrust sensor.

The results showed that that there were some elements of uncertainty in the sensor when measured in the test bench. In open water tests, the propeller axis thrust sensor performed as predicted. The sensor results were in line with the measured values of the whole unit and the comparison against the simulation result produced similar results as well. The 3D printed propeller and pod housing for the sensor were able to handle the used loads and the open water tests were run successfully using the printed parts.

KEYWORDS:

Ship propulsion, Wheatstone bridge, ship model test, calibration, thrust measurement,

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Jukka Koskela

TYÖNNÖNMITTAUSANTURIN KEHITTÄMINEN POD THRUSTERI -LAITTEISTOLLE MALLIKOETOIMINTAAN.

Opinnäytetyön pääasiallinen tavoite oli mahdollistaa työnnön mittaus ohjauspotkurilaitteistolla varustetun mallin potkuriakselita, jolloin voidaan tarkastella eri tilanteissa samanaikaisesti niin potkurin työntöä kuin laitteiston kokonaistyöntöä. Toissijaisena tavoitteena oli valmistaa anturille kuori ja potkuri 3D-tulostusmenetelmällä käyttäen ABS-materiaalia.

Työssä selvitettiin mallikoetoiminnan ohjeistuksesta vastaavan International Towing Tank Conferencen ohjeistuksiin koskien laitteiston kalibrointia ja kalibrointimenetelmiä. Kehitystyön lähtökohdaksi päätettiin ottaa kaupallisesti saatavilla olevan anturin hyödyntäminen. Anturin ympärille kehitettiin mekaniikka, joka mahdollisti mittauksen suorittamisen. Mekaniikan kehittämiseksi suoritettiin neljä kehityskierrosta. Tämän jälkeen valmistettiin mekaniikka piirustuksineen. Kehitystyötä varten valmistettiin laitteiston testaukseen testipenkki. Testipenkki mahdollisti työntö- ja vääntömomenttivoiman välittämisen työnnönmittausanturille.

Tuloksina havaittiin epävarmuustekijöitä, kun mittaus suoritetaan testipenkissä. Osa epävarmuudesta johtui todennäköisesti potkuriakseliin käytetystä materiaalista, akselin suoruudessa olleesta vaihtelusta sekä voimien aiheuttamasta rakenteen vääntymisestä. Avovesikokeissa anturi toimi odotetulla tavalla. Mittaustulokset olivat linjassa sekä koko laitteiston mittaustulosten, että laskennallisten tulosten kanssa. 3D-tulostettu potkuri ja kuori toimi avovesikokeissa. Potkuri kesti mittauksissa syntyneet voimat ilman vaurioita.

ASIASANAT:

Propulsio, työnnönmittaus, wheatstone silta, kalibrointi, laivamallikoe, ruoripotkuri

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LIST OF ABBREVIATIONS AND SYMBOLS

Units

g	Acceleration of gravity
kp	Kilopond, thrust T, 1kp = N/g
kpm	Kilopond meter, T, 1 kpm = Nm/g
N	Newton, thrust
Nm	Newton meter , torque, Q
RPS	Rotations per second

Abbreviations

CCW	Direction of rotation in measurements, counterclockwise from propeller end
CFD	Computational fluid dynamics
CW	Direction of rotation in measurements, clockwise from propeller end
DAQ	Data acquisition unit
EEDI	Energy Efficiency Design Index
Futek	Sensor manufacturer, developed measurement system is described by sensor manufacturer name in DAQ and data analysis
IMO	International Maritime Organization
ITTC	The International Towing Tank Conference
KDN-250	Thruster measurement unit, manufactured by CTO S.A.
POD	Podded propulsion unit
Ref 56 f	Kempf & remmers typ 33 dynamometer
RTD	research and technological development
U2A	Load sensor, type U2A, manufactured by HBM

1 INTRODUCTION

At Third IMO GHG (Green House Gas) Study 2014 (Environment et al. 2014) was shown that during study timeframe of 2007-2012 international shipping was causing average 1000 tonnes CO_2 emissions per year. This is about 3.1% of annual global CO_2 emissions during study timeframe. It is obvious that when reducing emissions in marine traffic, it has direct influence into global emissions. If we look at total energy consumption of ship, there are margins needed. The more accurately the energy consumption can be simulated, the less margins are needed. This leads to more accurate and more optimized systems. This leads to lower emissions.

One important stage in ship design is estimation of engine power. Accurate engine power does not only affect into power plant design but it also affect EEDI (Energy Efficiency Design Index). As EEDI calculations are mandatory to new ships and for modified ships, that exceeds limitations for EEDI calculations, it is important that basic design correlate accurately to sea trials. The Figure 1 shows how EEDI calculations are made in design and manufacturing phases, and how those are verified.

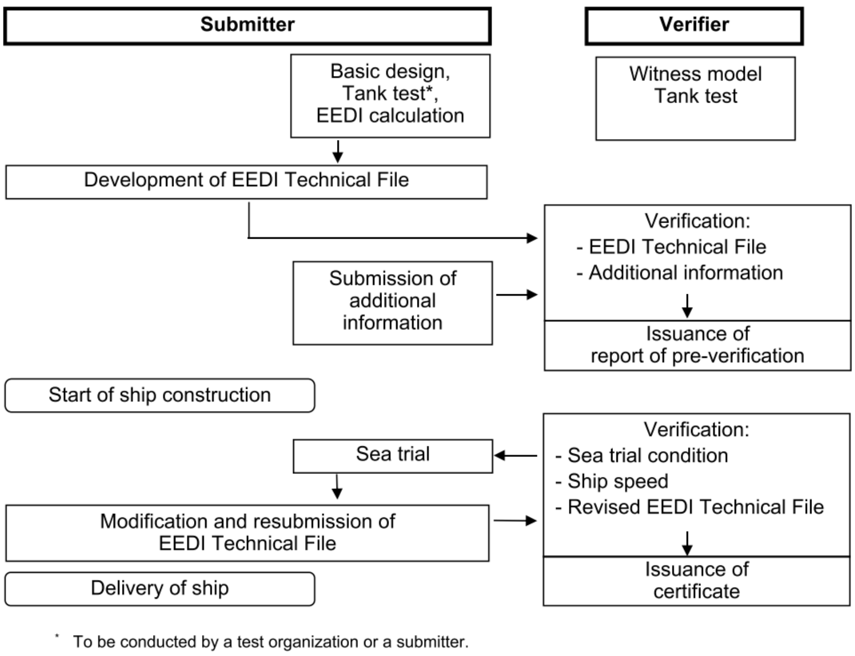


Figure 1 "Basic flow of survey and certification process".(International Maritime Organization (IMO) 2014).

In this final thesis, focus is in part tank tests, and specially thrust measurements of podded propulsion unit. Baseline was to add commercially available load sensor directly into propeller shaft. This will give direct thrust information of propeller and information how water flow affects to propeller thrust. Also implement of thrust sensor gives VTT information about difference between two measuring methods, unit thrust and propeller thrust, and evaluate relevance if thrust measurement from propeller is always needed or just in special cases. In addition, the novel thrust measurement technique enables improved validation of numerical simulation methods.

This measurement sensor will not overrule current measurement system rather working as thrust measurement sensor parallel with current system.

From previous podded propulsion tests, different kind of POD housings exists at VTT. Reference housing for final thesis was selected by smallest already used POD housing with adequate information.

Sensor measurement mechanism is finished and evaluation measurements were done in measurement test bench. In addition, POD unit open water test were done, according rules of International Towing Tank Conference, ITTC (ITTC 2017b). Model tests for hull and propulsors were not included in this final thesis.

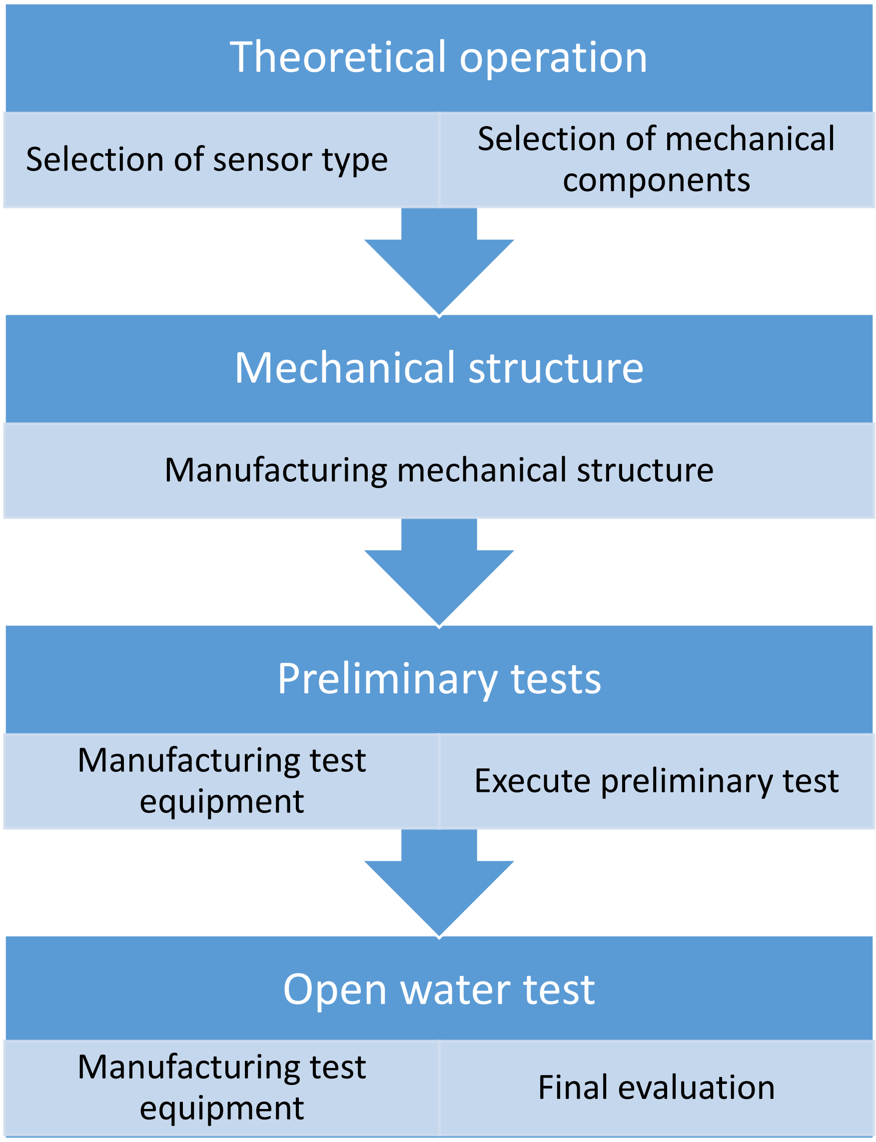
Research about different calibration methods, static and dynamic, were tested to compare tests and to make conclusion about difference in calibration methods. Goal at this final thesis was to design and test thrust measurement sensor for tank tests and especially for podded units, which makes possible to measure thrust directly from propeller shaft. For baseline design, commercial donut load censor was selected. Work was done as VTT's internal research and development project. The purpose was to create working prototype of sensor and collect enough information to be able to produce sensor and gear system that can be later manufactured with needed accuracy and quality, using materials that are specially ordered and selected for the sensor.

Secondary goal was to develop propeller and POD housing for universal use at VTT. In the future, these could be used for public research.

Some commercial products exist for measuring thrust and torque from propeller shaft. Challenge with commercial products is that usually these cannot be serviced in house. In addition, space is limited. It is possible that there will be requirements to make chances into overall dimensions to be able to fit sensor into POD housing. At that point, it is

necessary to be able to modify sensor mechanically. In most cases, this means total deconstruction of sensor.

To be able to produce and evaluate measurement sensor, there basic RTD process was decided. RTD process was following:



Each step included evaluation. If design passed evaluation, next step was taken. Some revised changes where minor, whereas some evaluations showed need of total change in design.

2 MODEL TESTS AND MEASUREMENT SENSORS

To estimate power requirements for new ships, there are model test to be made for the hull and propulsor. Tests to be performed are resistance test, the self-propulsion test and the propeller open-water test. Descriptions and purposes for these tests are introduced in book of Wärtsilä Encyclopedia of Marine Technology following:

"**Resistance tests –** These tests are conducted to provide data from which the resistance of the model, at any desired speed, may be determined. For this purpose the model is towed at speeds giving the same Froude number as for the full-scale ship, and the model resistance and its speed through the water are simultaneously measured. The running attitude of the model, i.e. sinkage fore and aft or the running trim and sinkage are usually measured."(Babicz 2016)

According of ITTC(ITTC 2017a) typical measurement system and measured parameter should be:

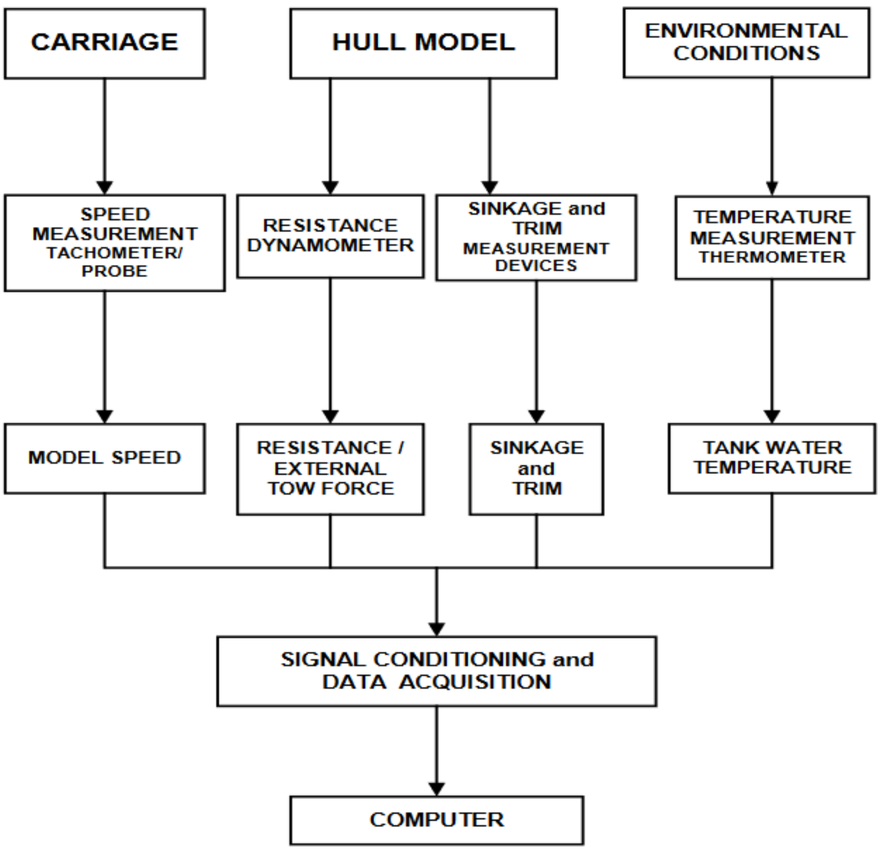


Figure 2 typical resistance measurement system(ITTC 2017a).

In practice, following setup is arranged at towing tank:

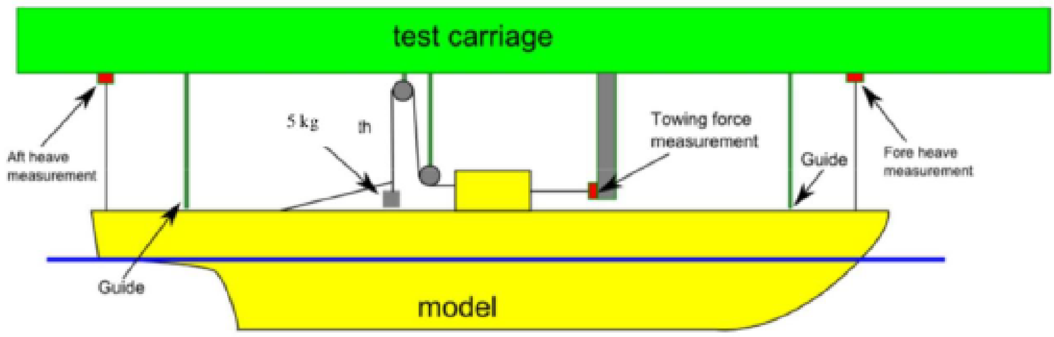


Figure 3 setup for resistance test(Aalto University 2017).

"**- Self-propulsion tests –** In the self-propulsion test, the model is towed at speeds giving the same Froude number as for the full-scale ship. During the test, propeller thrust, torque and rate of propeller rotation are measured. In many cases, stock propellers are used which are selected in view of the similarity in diameter, pitch and blade area to full-scale propeller. Propulsion tests are performed to determine the power requirements, but also to supply wake and thrust deduction, and other input data (such as the wake field in the propeller plane) for the propeller design."(Babicz 2016).

According of ITTC(ITTC 2014) typical measurement system and measured parameter should be:

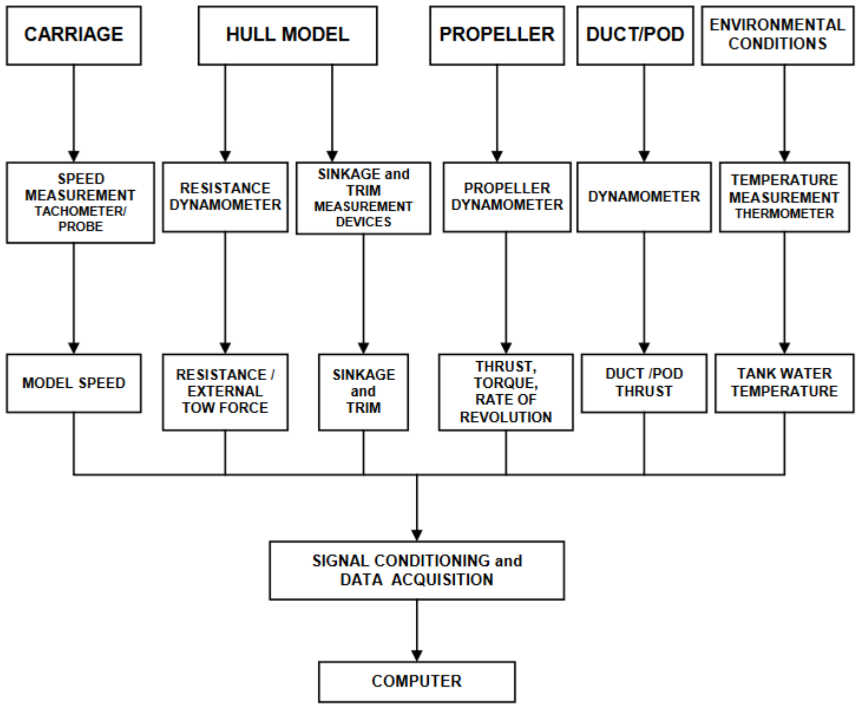


Figure 4 typical self-propulsion measurement system(ITTC 2014).

In practice, following setup is arranged at towing tank for direct shaft drive propulsion system:

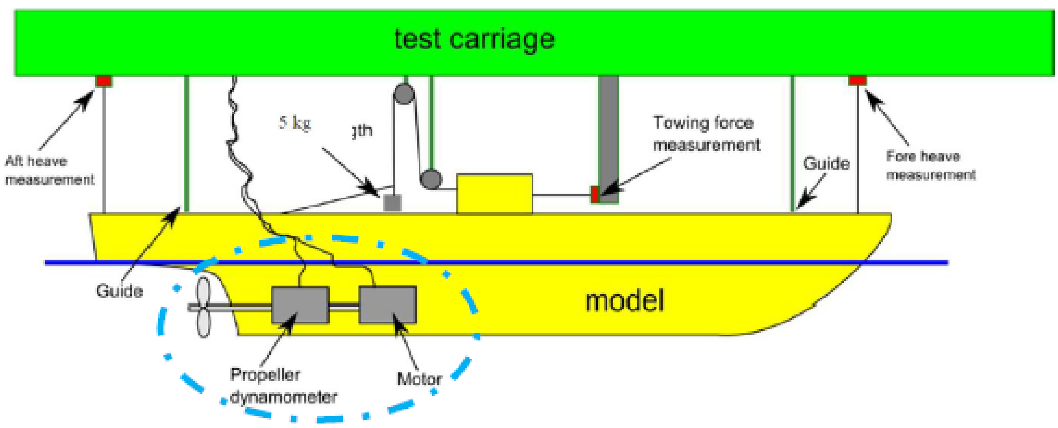


Figure 5 test setup for self-propulsion test(Aalto University 2017), direct drive.

“**Propeller open water test –** Although in reality, the propeller operates in the highly nonuniform ship wake, a standard propeller test is performed in uniform flow yielding the socalled open-water characteristics, namely thrust, torque and propeller efficiency.”(Babicz 2016)

When making open water test for propeller only, following type of open water test unit is used. This is similar system than shaft drive. In open water test unit, there exist dynamometer inside. With this apparatus, also propeller hub resistance is measured,

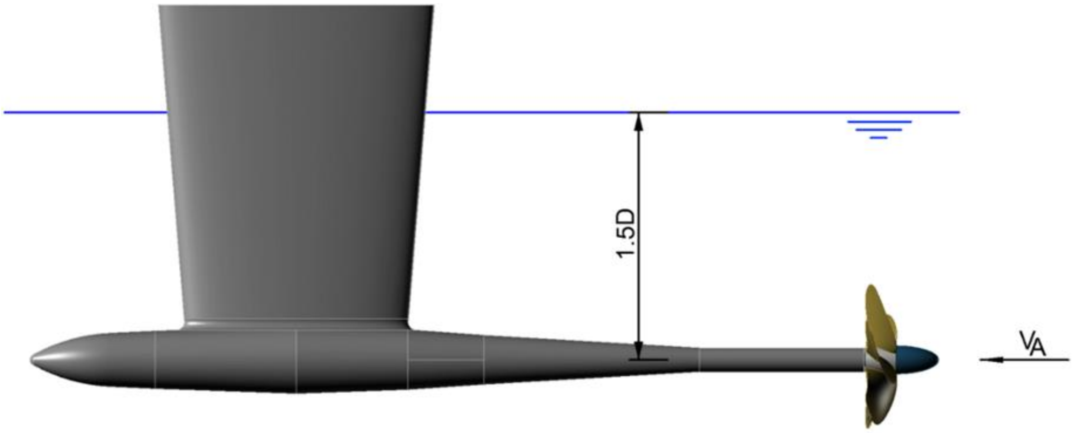


Figure 6 model of propeller propulsion test apparatus(SVA Potsdam GmbH n.d.).

To be noted when using podded propulsion units

In direct shaft drive, power to propeller is delivered through dynamometer, which can measure torque of shaft, and force in axial direction. When measuring azimuthing podded propeller units, things are somehow different. Thrust measurement can be divided into two, unit thrust and propeller thrust. Unit thrust is measured by measurement structure. This structure can be mounted into scaled model or into towing carriage. When propeller is delivering thrust, it affects into the whole device. There are two sensors, which are used to measure Forces in axial and transverse directions. In addition, torque is measured by torque sensor from power outlet shaft. Additionally, special unit for propeller thrust and torque can be implemented. Following figure presents ITTC recommendation of structure when making the unit open water test.

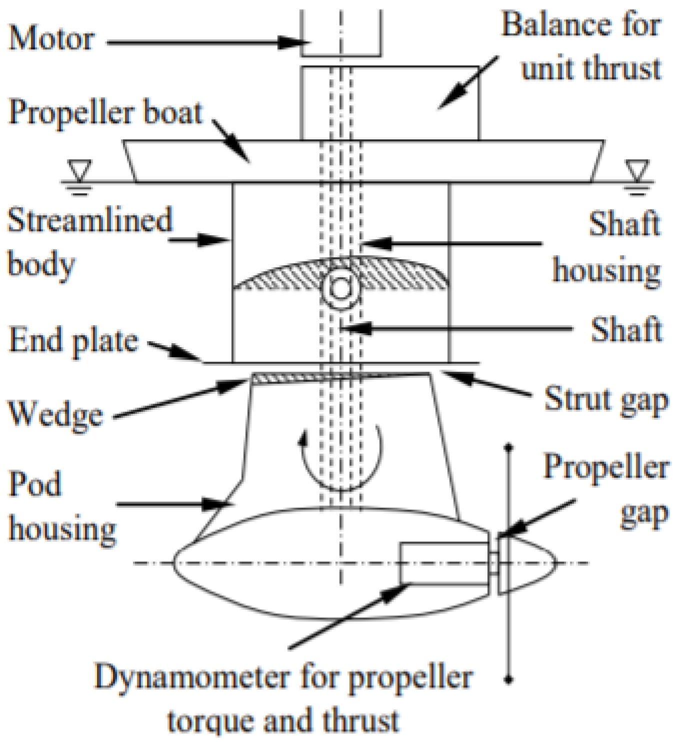


Figure 7 ITTC recommendation for unit open water test (ITTC 2017c).

ITTC recommendations are to measure thrust and torque as close as possible from propeller(ITTC 2014). Difference to measure thrust from propeller or thrust comes for example with different yaw angles. If thrust is measured from unit only, measuring unit needs to be angled into correct yaw. If yaw angle is changed, measured thrust from unit is not correlating propeller thrust directly and some calculations are needed. Usually there exist two propulsion units. However, total thrust, which is measured by change in towing force, can still be measured, but it is combined thrust for both units. Usually arrangement is symmetric, so this does not affect final estimations.

2.1 Commercial product review

When looking for commercial versions, it can be seen that some of the manufacturers are focusing on research customers only. Challenges with these are that system can be hard to implement into various scale projects. When looking for more customized products and their designs and capabilities, two different manufacturers are reviewed.

Both dynamometers works in same working principle. There is strain gauge load cell sensor that can measure both thrust and torque. In addition, temperature compensation strain gauges are installed. For operational use, there is no need to have temperature compensation, but for calibration, higher calibration accuracy, hence measurement accuracy, can be achieved.

Cussons Technology

One custom product for podded prolusion system measurement is Cussons Technology's H105. Cussons Technology is company that is specialized to manufacture teaching and research equipment for institutions and research departments(Technology n.d.).

Here are main properties of H105(Technology n.d.):

Maximum Continuous Speed (at the propeller):	2000 rpm
Gear Box ratio:	2:1
Type of load sensors:	Full bridge strain gauge
Rated Max Torque:	± 10 Nm (or ± 20 Nm)
Rated Max Thrust:	± 200 N (or ± 400 N)
Approximate POD diameter	50 mm
Approximate POD length:	300mm (Depends on gearbox supplied)

Wireless transfer makes data transfer from sensor and power for sensor. H105 includes custom made sensor and custom made gearbox. Ether unit cannot be replaced by commercial parts.

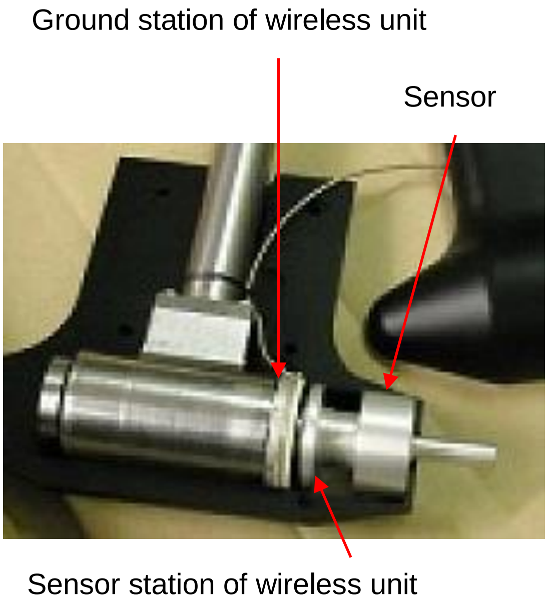


Figure 8 Cussons Technology, Sensor (Cussons Technology n.d.).

In a Figure 8 can be seen how Cussons technology has solved arrangement of ground station and connection between sensor and data accusation unit.

POD dynamometer by Ship Design and Research Centre S.A. (CTO S.A.)

CTO S.A. is ship and research centre, which provides both research services and equipment for research centres(S.A. and Ship Design And Research Centre n.d.). Main difference, when comparing Cussons Technology H105, is that CTO S.A. can provide their dynamometer wireless or using slip rings.

Figure 9, POD dynamometer by CTO S.A.(Centrum Techniki Okrętowej S.A. and Ship Design And Research Centre n.d.:15).

Example technical specification(Centrum Techniki Okrętowej S.A. and Ship Design And Research Centre n.d.:15):

Thrust (maximum):	500 N
Torque (maximum)	20 Nm
Propeller mass (maximum)	3 kg
Propeller shaft diameter Ø	16 mm

Structural difference is that telemetry is installed on the opposite side of gearbox than measurement sensor. This takes less space from the front side. Comparing this design to currently used POD models, this can provide better usage of space compared to Cussons Technology.

2.2 Operation principle of measurement sensors: Wheatstone bridge

Most of force and torque measurement sensors, which VTT uses, are based on strain gauge measurements and Wheatstone bridge. Theory behind of wheatstone bridge is simple. DAQ unit is needed to convert measured voltage into measurement results in selected units.

Wheatstone bridge was invented by British mathematician Samuel Christie and it was made best known by Sir Charles Wheatstone at 1843(Britannica n.d.). In Wheatstone bridge, measurement comparison between input voltage and output voltage can be measured. This comparison references forces that bridge is affected.

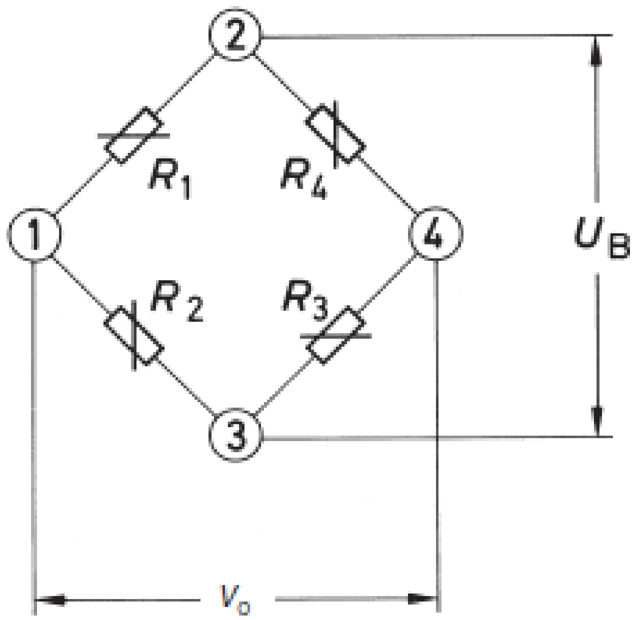


Figure 10 Wheatstone bridge coupling(Moreton 2001).

When in points 1 and 4 input voltage U_B is supplied, voltage is divided into two bridges. These bridges have resistors R1-R4. When excitation voltage V_o is measured, can changes in resistances be measured. This circuit can have external circuit, that includes resistance made by sensor and completion circuit. When measuring with strain gauges, Wheatstone bridge circuits are:

a) quarter bridge
b) half bridge
c) diagonal bridge
d) full bridge

Data acquisition units usually support these circuit units. This make possible to manufacture measuring sensors of special purposes in house.

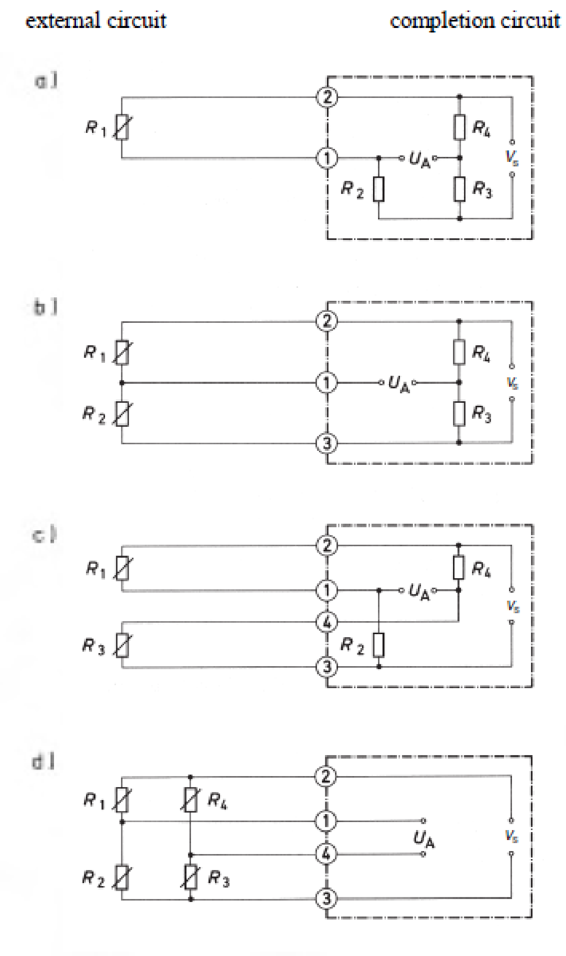


Figure 11 wheatstone bridge circuits used with strain gauges(Schicker and Wegener 2002).

For example for force measurement, following circuit can be used:

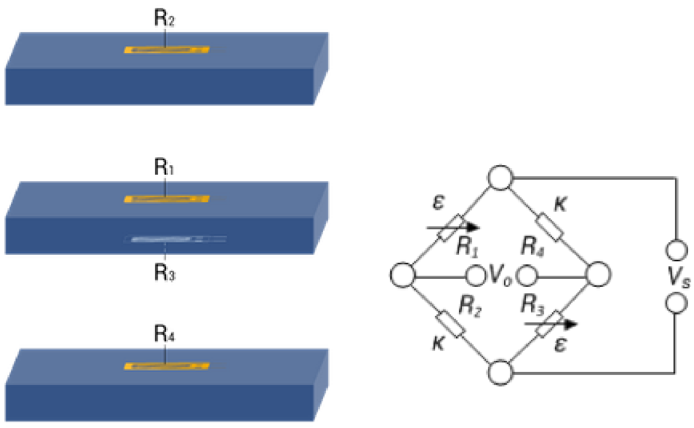


Figure 12 diagonal bridge with dummy gauges (Hall 2015).

In Figure 12 ε is measurement strain and K is so-called, dummy strain. Dummy strain is restricted from forces that affects measurement strains ε. As dummy strains are installed into same material as strains ε, but are restricted from effecting forces, except temperature, dummy strains compensate temperature changes.

When measuring torque, following circuit can be used:

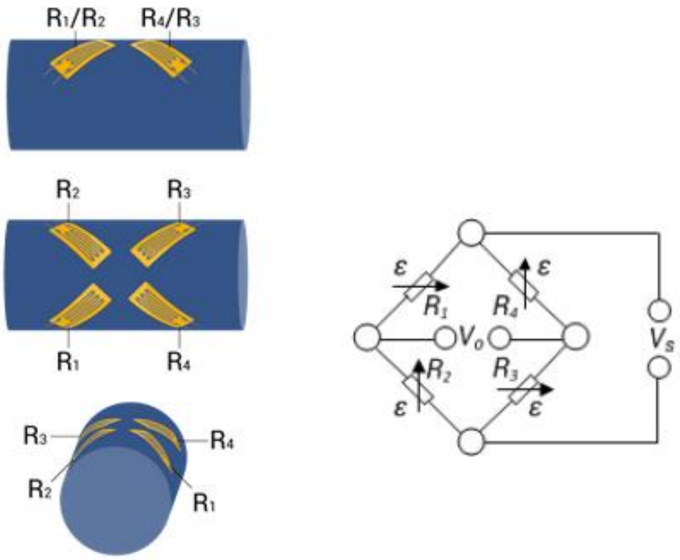


Figure 13 full bridge torque measurement(Hall 2015).

In the torque measurement, all strain gauges are installed at 45° angle to the main axis. In this circuit, also temperature compensation is achieved.

Figure 14 example of wheatstone bridge measurement shows how wheatstone bridge works in action. Bridge is manufactured by 120 Ω strain gauges. Excitation voltage of DAQ unit is 1.0V. There is force applied so that it affects into strain gauge R_1 so that its resistance is changed to 121Ω

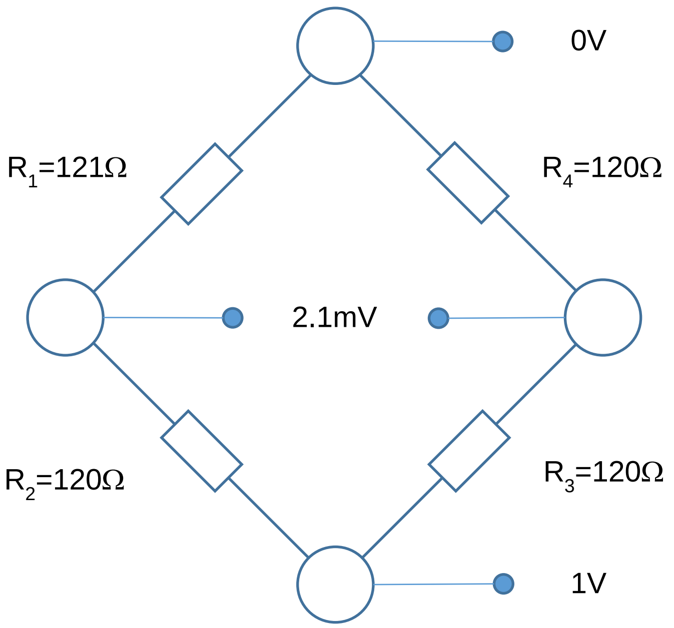


Figure 14 example of wheatstone bridge measurement

After this, positive effect can be measured as 2.1mV. Depending how strain gauges are positioned, measurement can measure strain variation in material. This variation can measure for example thrust or torque. As result is single measurement, as many wheatstone bridges as measurements is needed to build.

2.3 Sensors and measurement unit in use at VTT

Thruster unit for podded propulsion, CTO S.A. KDN-250

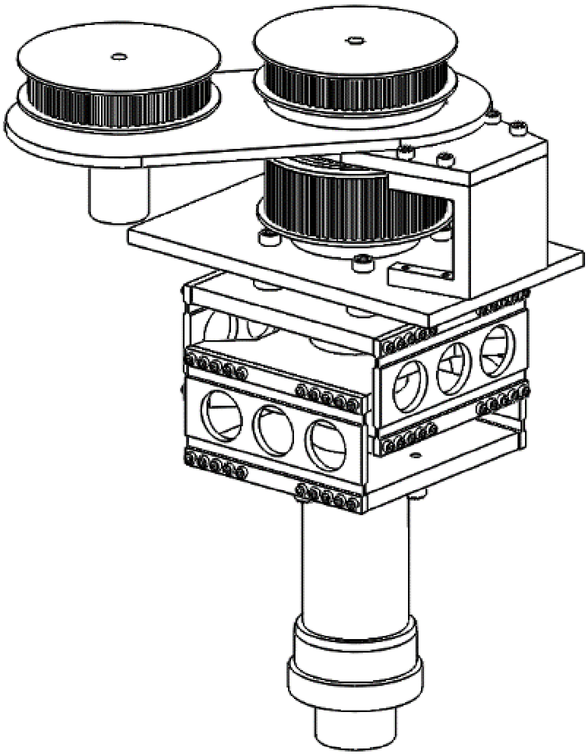
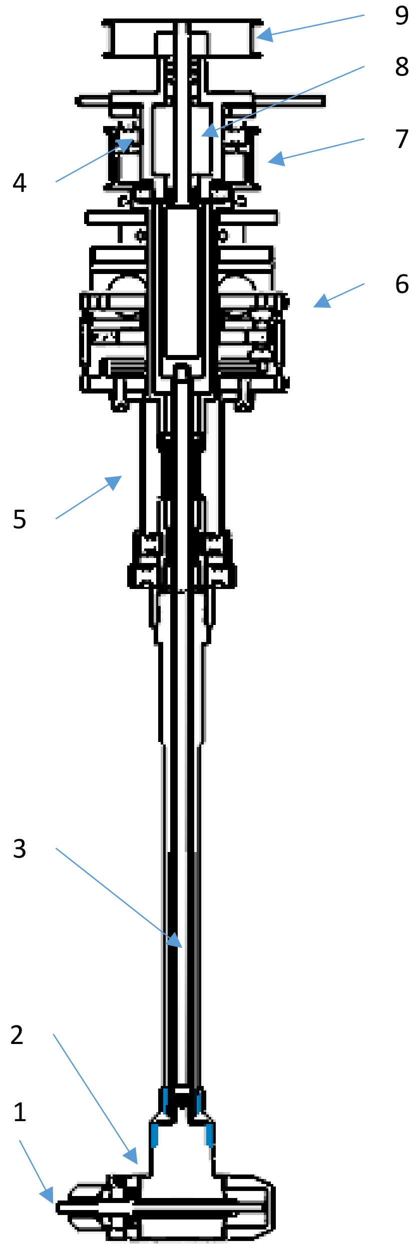


Figure 15 Thruster unit for model testing, KDN 250 type 89.

Currently at VTT is in use thruster unit for model testing made by CTO S.A. (https://www.cto.gda.pl/en). This measurement unit is made for podded propulsion units. Measurement unit in use is model KDN-250 type 89. Measuring system makes axial and transverse direction force measurements from propulsion unit structure and torque measurement from vertical shaft. Current propulsion unit consist of following construction:



1. Propeller shaft
2. Bevel gear
3. Vertical shaft
4. Drive shaft
5. bellows coupler
6. Gauge components for thrust, steering and torque
7. Propeller thrust turning mechanism
8. Slip ring
9. Drive wheel

Figure 16 Structure of KDN-250

Forces in axial and transverse directions are measured by force plate where all measuring components are assembled. This force plate is assembled into model in a way where all propulsion forces and resistance forces can be measured. Torque measurement sensor is located between top and middle bearing.

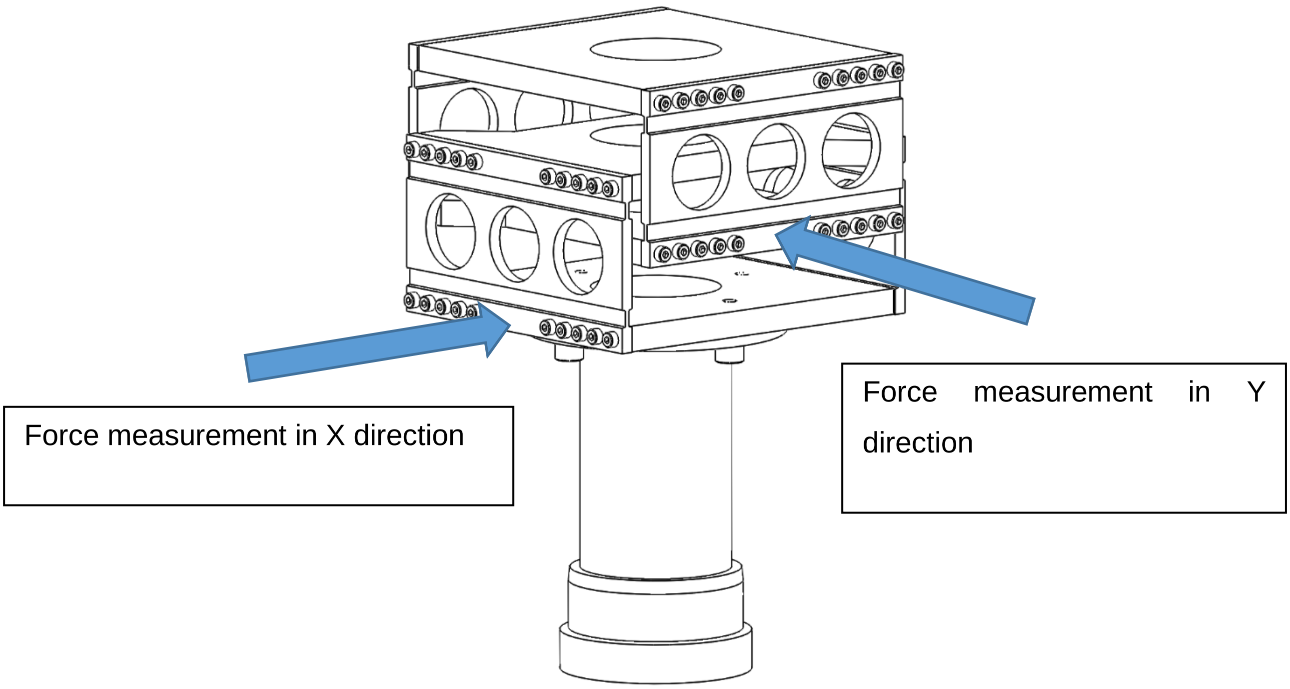


Figure 17 Force measuring structure X and Y direction.

When thrust is measured, direction of measuring force depends on the angle of installation. If propulsion unit is turned, measured force direction stays same. Main technical specifications are:

- Thrust measurement In X and Y direction, 400N (40kp)
- Torque measurement 10Nm (1 kpm)

Dynamometer for direct shaft propulsion, Kempf & Remmers typ 33

For direct shaft propulsion systems at VTT Kempf & Remmers typ 33 dynamometer is used. In this measurement sensor, there are integrated force and torque sensors. Sensor is installed between propeller shaft and propulsion motor. Unit’s technical specifications are:

- Thrust measurement X direction, 400N (40kp)
- Torque measurement 15Nm (1,5 kpm)

Load sensor HBM U2A

Figure 18 HBM U2A (HBM n.d.).

U2A load sensor by HBM has following main features:

- Sensor type Full bridge, 6-wire
- Capacity 50 kg
- Sensitivity 2mV/V

- Tolerance sensitivity
  with tensile load <±0.20 %
  with compressive load <±0.50 %
- Thread type M12

Data acquisition unit (DAQ)

For measurements at the measurement carriage at the towing tank, VTT uses HBM Quantum MX840 DAQ. Thrust measurement sensor is implemented into this unit. This makes possible to use same extension cables and same calibration and measurement methods. Main features for this DAQ are(HBM n.d.):

- 8 individually configurable measurement channels (galvanically isolated)
- Connection of more than 16 different transducer technologies per channel
- Individual sample rates up to 40 kS/s per channel, active low pass filter
- 24-bit A/D converter per channel
- Automatic channel parameterization (TEDS)
- Supply voltage for active transducer (DC): 5 V ... 24 V
- CANbus Input/Output (port 1)

Figure 19 HBM Quantum X MX840X(HBM n.d.).

Data acquisition unit (DAQ) Software Catman Easy

Data acquisition unit measurements are made by Catman software. By Catman software, it was easy to see real time measurement data as visual plot can be seen. Measurement data is saved into csv format at VTT. There is possibility to do real time data calculations, but at this work, this possibility was not used.

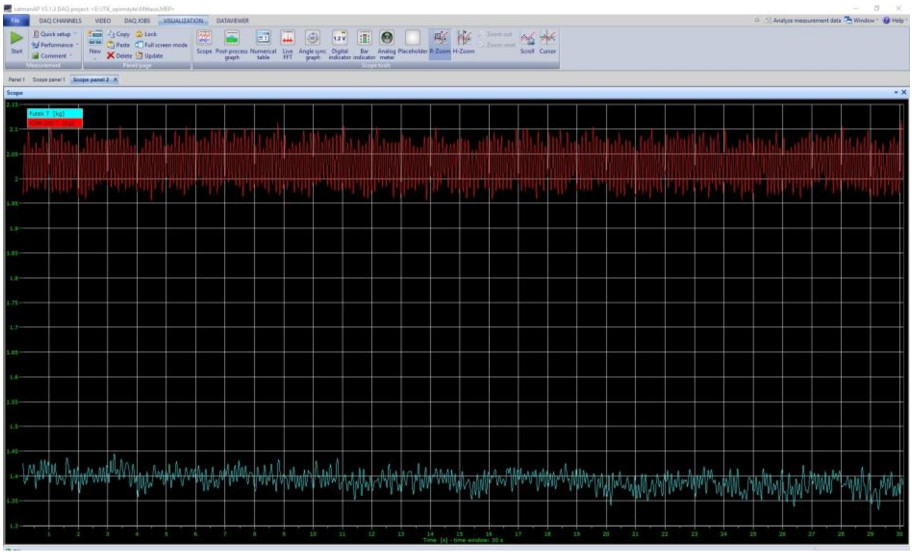


Figure 20 screen shot of measurement, HBM Catman Easy.

In a Figure 20 can be seen measurement live data. From this measurement can be followed in situation and seen if there is some abnormality in measurement signals, which can be corrected without full data analysis.

3 MECHANICAL DEVELOPMENT OF THE SENSOR

Mechanical development was made by manufacturing prototype. After manufacturing the prototype, it was analyzed and improvements to subsequent revision where made.

Possibilities to measure thrust in direction of propeller shaft are:

- Rotational force measuring plate into current system.
- Load cell implementation into propeller shaft.

As height of current system is already limited, implementation of force measuring into propeller shaft is selected.

To get force measured from propeller shaft there are two methods that seemed most suitable:

- Custom made load cell sensor into propeller shaft
- Commercial donut load cell into propeller shat

At VTT, there exists lot of experience about using strain gauges. To be able to use most of space at available, strain gauges would be the best choice. However, there are challenges to get input voltage and excitation voltage from and to rotating sensors. In addition, mechanical manufacturing would be challenging, especially to manufacture two identical parts. Because of these reasons, commercial load cell was selected as baseline for sensor.

3.1 Simplified force analysis

To determine forces that affect the measurement system, thus measurement accuracy, force path is determined.

Propeller creates thrust and torque into unit. This thrust affects into bevel gear, causing friction loss in both of bearing and gears. This added friction force affect the torque measurements. By moving thrust measurement into propeller shaft, this effect into thrust can be eliminated. Still, the torque measurements is affected. Consequently, the forces that add torque need to be taken care of.

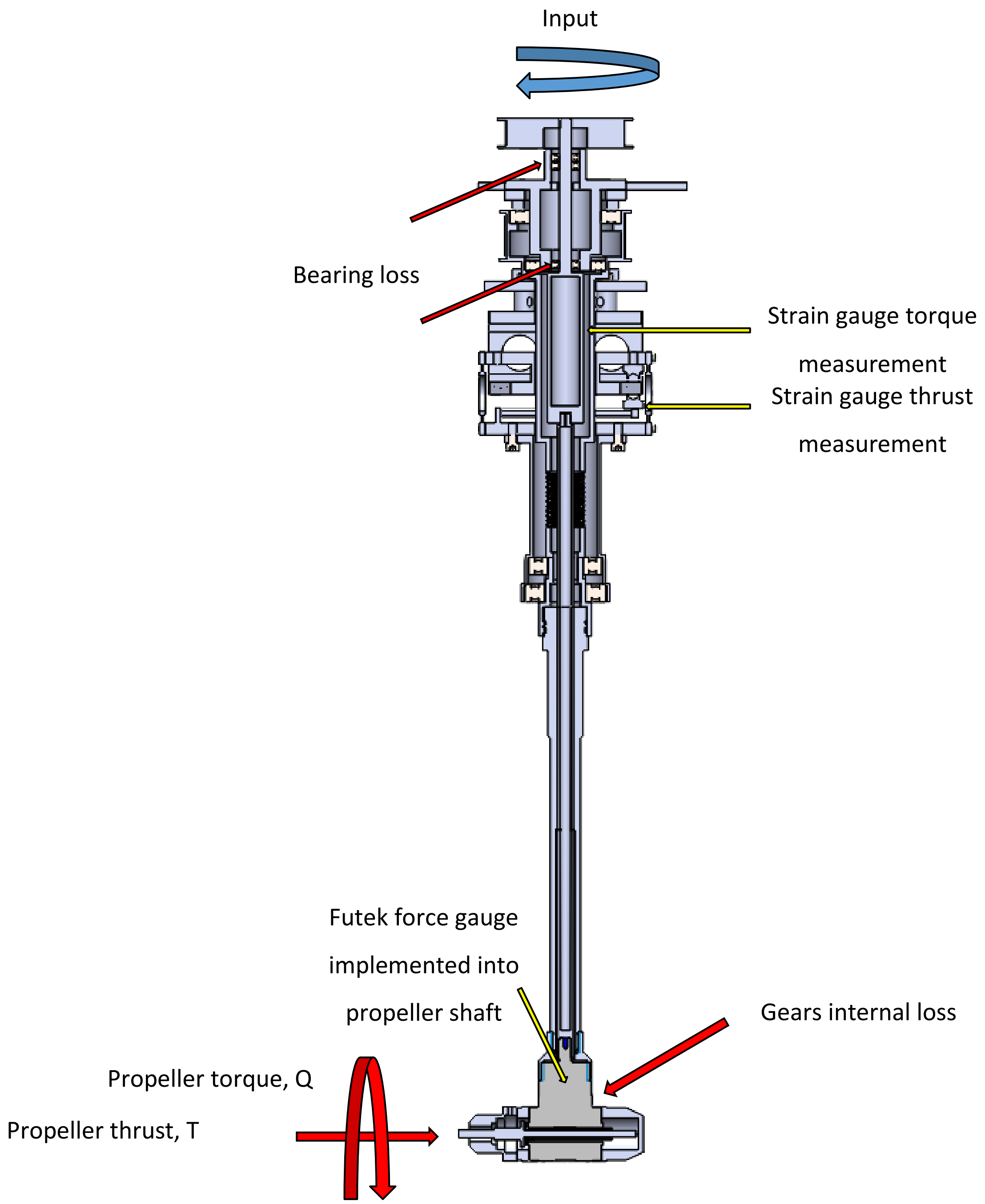


Figure 21 measurement unit and force measurement points.

When rotational power is implemented into KDN-250, power goes through toothed belt into vertical shaft. From the vertical shaft, power goes into bevel gear. At the bevel gear

vertical rotational power transfers to horizontal rotational power, that rotates propeller shaft. Rotating propeller creates thrust power that moves vessel into the direction of thrust. There are two parameters that are measured, thrust and torque. As torque is measured from vertical shaft, there are losses that need to be calculated to get propeller torque. Main losses occur in bevel gear.

In case of bevel gearbox, there are two options in bevel gear teeth, straight and spiral.

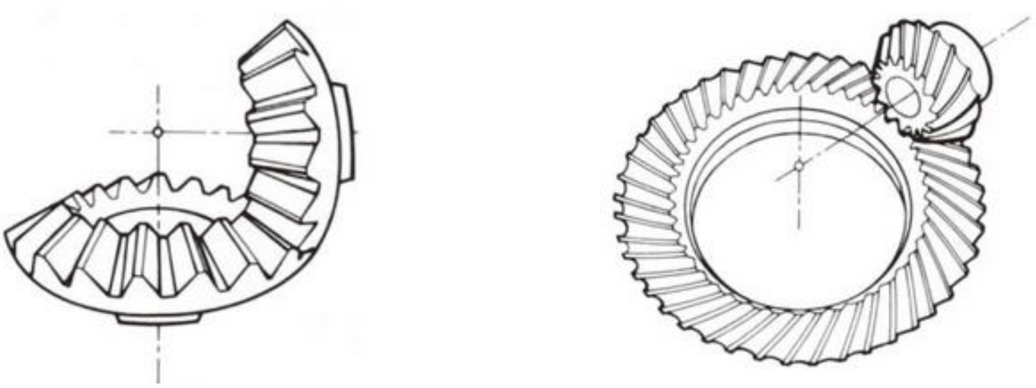


Figure 22 straight and spiral bevel gear (KHKGEARS n.d.).

Some main differences are caused because of shape of teeth. In straight teeth, there are sudden contacts between gears. This cause noise and shock vibration. Spiral gear has also higher torque and speed rate.

However, as there are advances in spiral gears, it also causes some difficulties when measuring thrust loads. When comparing forces in an intersecting axis, forces of straight teeth gear are same in both rotating directions. This makes difference when measuring accurate torques. Hence, forces are different depending of rotation, it also affects friction in bearing and this affects measured torque.

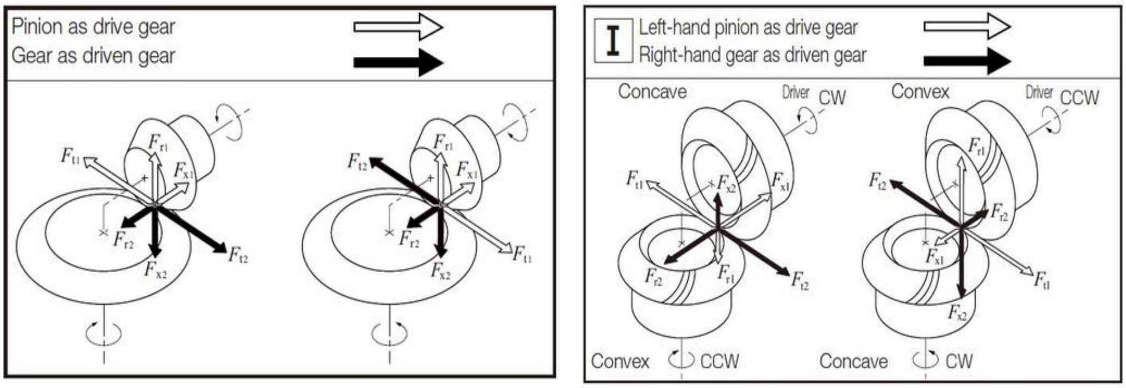


Figure 23 Direction of forces acting on straight and spiral bevel gear mesh (KHK 2018).

In the Figure 23, can be seen main difference between straight and spiral bevel gear mesh. When rotating straight teeth bevel gear into clockwise and counterclockwise directions, force F_{r2} is not affected. When rotating spiral teeth bevel gear similar way, forces are different when rotation direction is changed.

Table 1 calculation example of spiral bevel gear (KHK 2018).

2	Transverse module	m_t	mm	Set Value		2	
3	Pressure angle	α_n	Degree			20°	
4	No. of teeth	z	—			20	40
5	Spiral angle	β	Degree			35°	
6	Facewidth	b	mm			15	
7	Input torque	T_1	N·m			1.6646	—
8	Reference diameter	d	mm	zm		40	80
9	Reference cone angle	$\delta_1 \cdot \delta_2$	degree	$\tan^{-1}\left(\frac{z_1}{z_2}\right)$	$\Sigma - \delta_1$	26.56505	63.43495
10	Center reference diameter	d_m	mm	$d - b \sin \delta$		33.292	66.584
11	Tangential force	F_t	N	$\frac{2000T}{d_m}$		100.0	
				Contact Face		Convex	Concave
12	Axial force	F_x	N	$\frac{F_t}{\cos \beta_m}(\tan \alpha_n \sin \delta - \sin \beta_m \cos \delta)$	$\frac{F_t}{\cos \beta_m}(\tan \alpha_n \sin \delta + \sin \beta_m \cos \delta)$	− 42.8	71.1
13	Radial force	F_r		$\frac{F_t}{\cos \beta_m}(\tan \alpha_n \cos \delta + \sin \beta_m \sin \delta)$	$\frac{F_t}{\cos \beta_m}(\tan \alpha_n \cos \delta - \sin \beta_m \sin \delta)$	71.1	− 42.8
				Contact Face		Concave	Convex
14	Axial force	F_x	N	$\frac{F_t}{\cos \beta_m}(\tan \alpha_n \sin \delta + \sin \beta_m \cos \delta)$	$\frac{F_t}{\cos \beta_m}(\tan \alpha_n \sin \delta - \sin \beta_m \cos \delta)$	82.5	8.4
15	Radial force	F_r		$\frac{F_t}{\cos \beta_m}(\tan \alpha_n \cos \delta - \sin \beta_m \sin \delta)$	$\frac{F_t}{\cos \beta_m}(\tan \alpha_n \cos \delta + \sin \beta_m \sin \delta)$	8.4	82.5
16	Output torque	T_2	N·m	——	$\frac{F_t d_{m2}}{2000}$	—	3.329

Table 1 shows how axial and radial forces can be calculated for spiral bevel gear.

For bearing losses, SKF model for frictional moment uses:(SKF n.d.)

$$M = M_{rr} + M_{sl} + M_{seal} + M_{drag} \tag{1}$$

Where:

$$M = total\ frictional\ moment$$
$$M_{rr} = rolling\ frictional\ moment$$
$$M_{sl} = sliding\ frictional\ moment$$
$$M_{seal} = frictional\ moment\ of\ seals$$
$$M_{drag} = frictional\ moment\ of\ drag\ losses$$

There is no need to calculate all forces separately. However, for understanding phenomenon in bearings, it is noted that for example in rolling frictional moment:

$$\mathrm{M_{rr}} = \phi_{ish}\phi_{rs}\phi_{rr}(\vartheta n)^{0.6} \tag{2}$$

Where:

$$\phi_{ish} = rolling\ frictional\ moment$$
$$\phi_{rs} = kinematic\ replenishment\ reduction\ factor$$
$$G_{rr} = bearing\ debending\ variable$$
$$\vartheta = operating\ viscosity\ of\ oil$$
$$n = rotational\ speed$$

There are rotational related losses in bearings. It is also noted that losses are also depending of axial and radial loads.

There are kinetic rotational energy losses in system.

$$KE_{rotational} = \frac{1}{2}I\omega^2 \tag{3}$$

Where:

$$I = rotational\ inertia$$
$$\omega = angular\ velocity$$

For work, based on the Newton’s second law for rotation:

$$Work = \tau\theta = \frac{1}{2} I\omega^2 \quad (4)$$

Where:

$$I = rotational\ inertia$$
$$\omega = angular\ velocity$$
$$\tau = \ net\ torque$$
$$\theta = rotation\ angle$$

I for solid cylinder:

$$I_z = I_y = \frac{1}{12} m(3r^2 + h^2) \quad (5)$$

Where:

$$m = \ mass\ of\ cylinder$$
$$r = radius\ of\ cylinder$$
$$h = height\ of\ cylinder$$

Based on these presented losses and formulas, prediction that losses are not linear as rotation changes, is made.

There are some cross effect between thrust and torque. In following figure can be seen cross effect between thrust and torque.

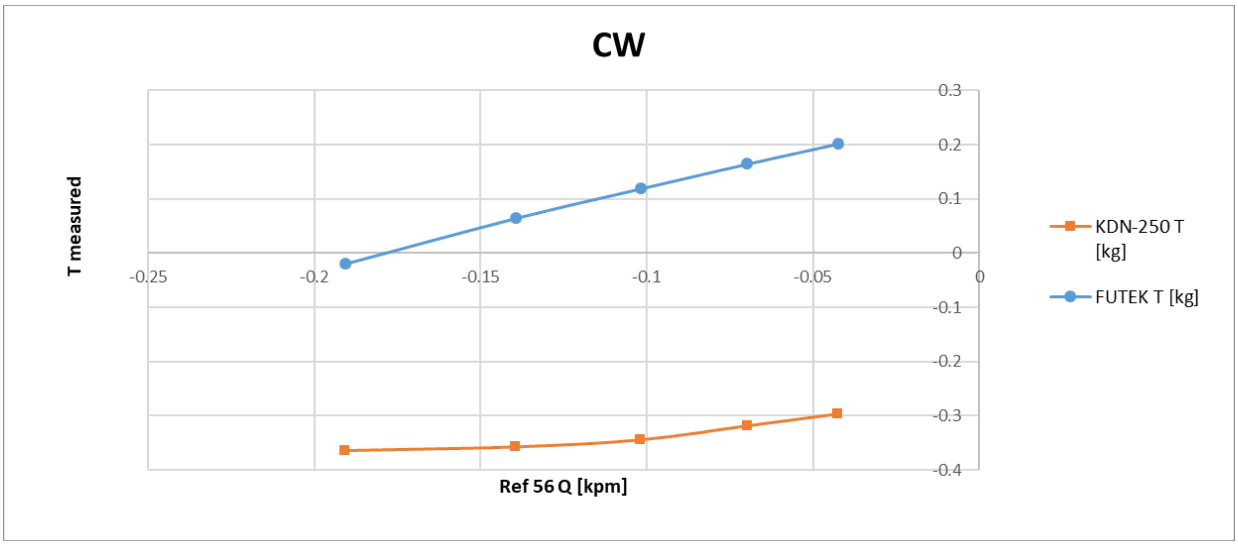


Figure 24 cross effect of thrust and torque when torque applied, revision 3.

Figure 24 is from data of dynamic torque calibration. When adding into system torque load it generates variation in the thrust measurement. This variation can be seen in both sensors thrust levels.

Following comparing cross effect between thrust and torque when applying thrust into measurement system.

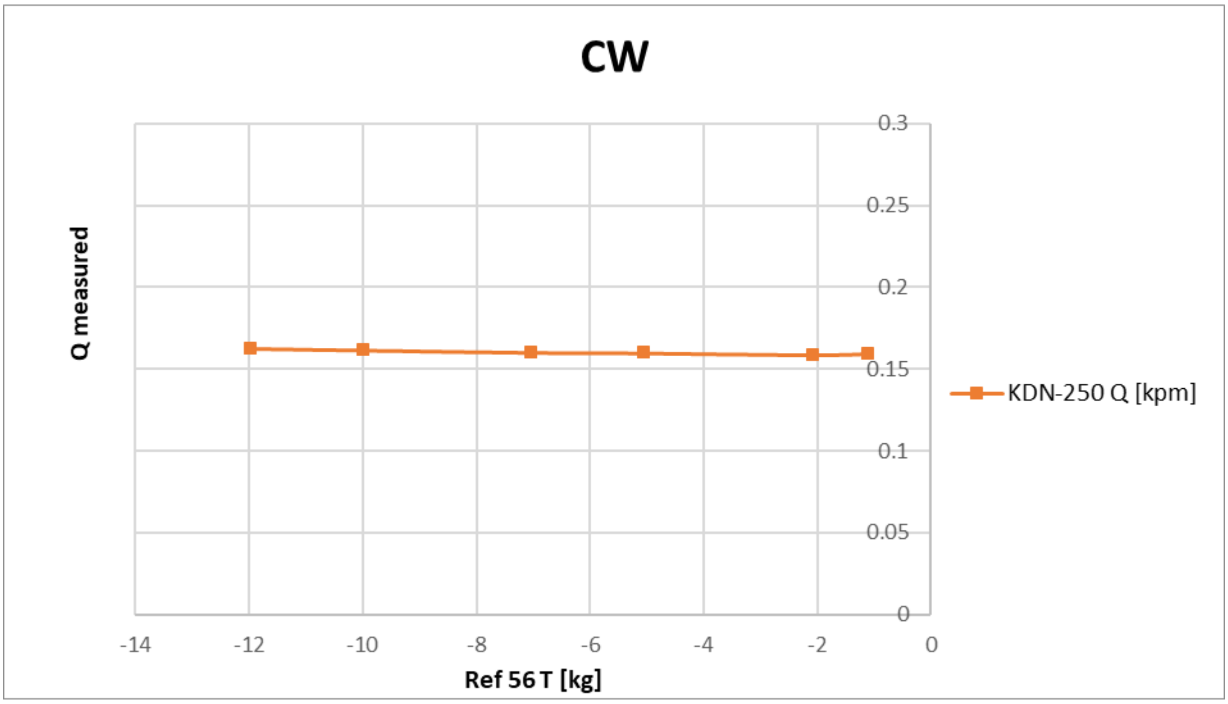


Figure 25 cross effect of thrust and torque when thrust applied.

Figure 25 is from data of dynamic thrust calibration. When applying thrust load, it does not have significant effect into torque measurement. Torque measurement of KDN-250 is not affected.

When inspecting the effect of angular velocity to measured torque, can be seen that the RPS affects the measured torque, as shown in Figure 26

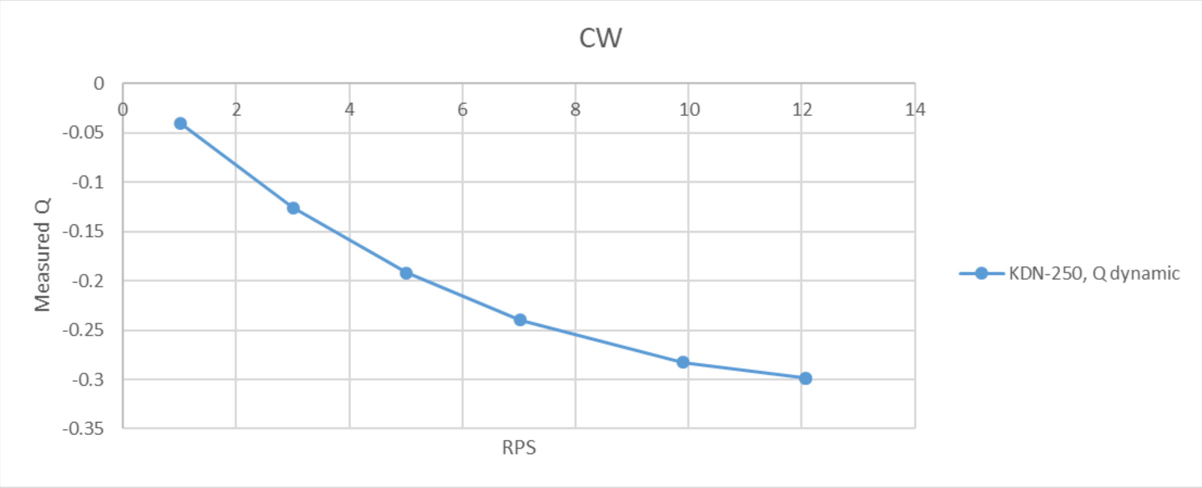


Figure 26 effect of RPS into measured Q in revision 3.

As RPS rises, also level of measured torque rises.

3.2 Thrust measurement sensor

There are physical requirements, which need to be fulfilled. These requirements are:

- Maximum torque — 2 kpm
- Maximum thrust — 30 kg
- Maximum RPS — 30 RPS
- Operational conditions — fully submerged into water. Water temperature between 15-25°C
- Measurement implementation — Implemented into DAQ by 5 pin DIN connector

3.3 Basic concept for thrust measurement

When looking for how forces are going through in force analysis, in used concept, force path is changed compared to KDN- 250. As originally, thrust force is affecting trough POD housing to thrust plate, in in new concept thrust measurement is made directly from propeller shaft. Basic concept is to measure thrust force from propeller shaft by through hole type load cell. This load cell takes load before bevel gear. Bevel gear is isolated from forces from bevel gear by allowing propeller shaft to move freely. Force is measured by load cell and by KDN – 250. This makes cross reference between thrust loads possible when steering angle is 0° and velocity is zero.

3.4 Selection of suitable gear

Main limitations for measuring system is space available and needed thrust. Without using custom made bevel gears, there are some standard sizes in stock bevel gears. This limits gear size. Most of manufacturers has about the same stock gear size and design. In practice, usable size for model tests due to limitations in torque and size has been about 50 x 50 x 50 mm. In some cases, there has been need of shave edges of gearbox to be able to fit gear into the POD housing. Because of basic concept, where bevel gearbox thrust is isolated from propeller thrust by slide mechanism, gearbox with hollow output shaft is required.

As shown in simplified force analysis, for this kind of use there would be advances to use direct teeth bevel gear. Unfortunately, there is not so much demand on markets for this kind of gears. In practice, most manufacturers are manufacturing gearboxes with spiral bevel gears only.

Based on technical requirements and basic concept, bevel gearbox made by DZ transmission SRL, model QB54 type 4 was selected.

3.5 Selection of the measurement sensor

As in paragraph *2.2,* was shown principle of measurement sensors, there is possibility to manufacture force sensor in house. However, when measuring small forces and when keeping the sensor size small, there are challenges to maintain required accuracy. Most challenging accuracy demand is aligning strain gauges. Because of this, commercially available unit is selected for sensor. For preliminary test and for development, existing force load cell of FUTEK LTH350 131345 N (3000lb) was used. Specifications for this load cell are:(Futek 2011)

PERFORMANCE	
Nonlinearity	±0.5% of RO
Hysteresis	±0.5% of RO
Nonrepeatability	±0.5% of RO

ELECTRICAL	
Rated Output (RO)	2 mV/V nom
Excitation	(VDC or VAC)18 max
Bridge Resistance	700 Ohm nom
Insulation Resistance	≥500 MOhm @ 50 VDC
Connection	#24 AWG, 4 conductor, braided shielded Teflon cable, 10 ft [3 m] long
Wiring/Connector Code	WC1

MECHANICAL	
Capacities	3000 lb [13345 N]
Weight (approximate)	3.5 oz [99 g]
Safe Overload	150% of RO
Deflection	0.002 in [0.05 mm] nom
Material	17-4 PH stainless-steel
IP	RatingIP64

TEMPERATURE	
Operating Temperature-	60 to 200°F (-50 to 93°C)
Compensated Temperature	60 to 160°F (15 to 72°C)
Temperature Shift Zero	±0.005% of RO/°F (0.01% of RO/°C)
Temperature Shift Span	±0.005% of Load/°F (0.01% of Load/°C)
CALIBRATION	Calibration Test Excitation10 VDC
Calibration	(standard)5-pt Compression
Shunt Calibration Value	100 kOhm

For final measurements and verifications Load cell of FUTEK LTH350 445N (100lb) was acquired. It has same specifications as above, expect load rating. Reason for this is measurement accuracy. As measurement output is 2mV/V and maximum, measurement values are 13345N and 445N and measurement voltage is 10V following comparison calculation can be made:

$$F_{max} = \frac{V_{Exitation}}{RO}$$

Which gives for:

13345 N sensor:	$2{,}669 \frac{N}{2\ mV}$
445 N sensor:	$0{,}089 \frac{N}{2\ mV}$

Sensor is connected into HBM MX840B by DE 15 connector. Connection of sensor is presented at appendix 1, wiring of sensor.

3.6 Mechanical design of the thrust sensor

3.6.1 Revision 1 of thrust sensor

In revision 1, main operation principle was following:

- The propeller will cause thrust force into the propeller shaft
- Force is transferred by bearings into the load sensors load sensing area

- Measured force is transferred into the gear housing
- Unrestricted axial force to load sensor
- The propeller shaft will take torque force only from gear.
- Propeller shaft will be changeable

Propulsion power was transferred by the ball bearing, W 61801-2RZ from the propeller shaft into the load censor. As same time, the ball bearings W 61801-2RZ made possible to isolate the load sensor from rotational parts. Bearing 1 also gave axial support for propeller shaft trough load sensor.

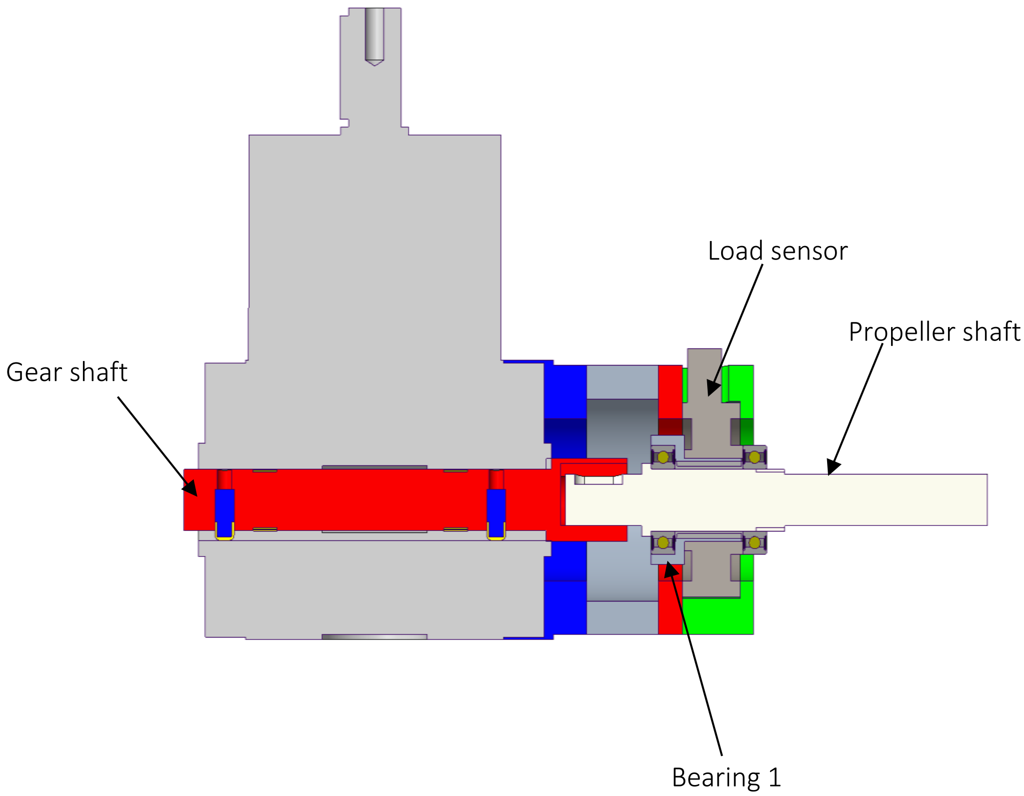


Figure 27 revision 1 internal structure.

Axial forces are affected to sensor from propeller side only. This was made by design of the sliding shaft. Sliding shaft was able to transfer torque force only. By making separate the slide shaft and the propeller shaft, it was possible to allow simple propeller shaft dimension change. This makes easier to use various podded

propulsion unit instead to have the need to manufacture sliding mechanism into all propeller shafts.

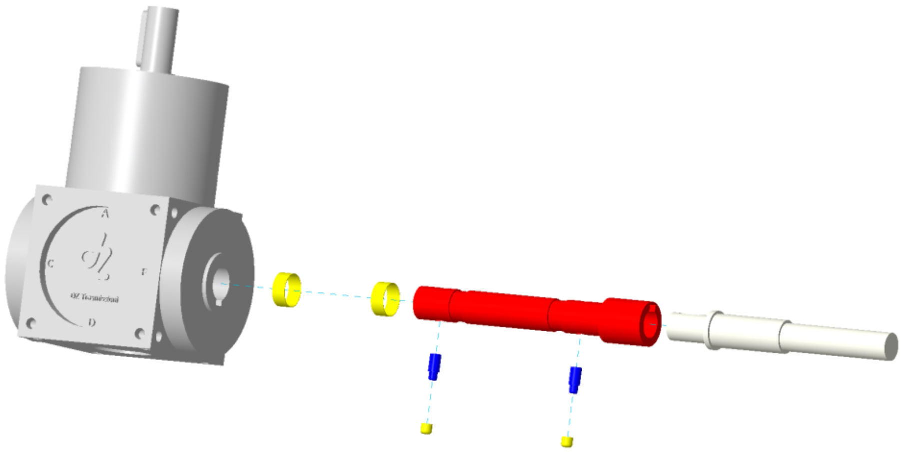


Figure 28 revision 1 propeller shaft and gear shaft.

During the manufacturing of slide shaft it was noted, that there here challenges to construct the sliders and the slide pin tips. Main challenge was part size. Also became obvious that Teflon would be too soft material for slider tips. Slider tips and sliders were too small to be able to manufacture in reasonable accuracy. At this point, design was changed to include solid brass slider pins only and the Teflon parts were left out.

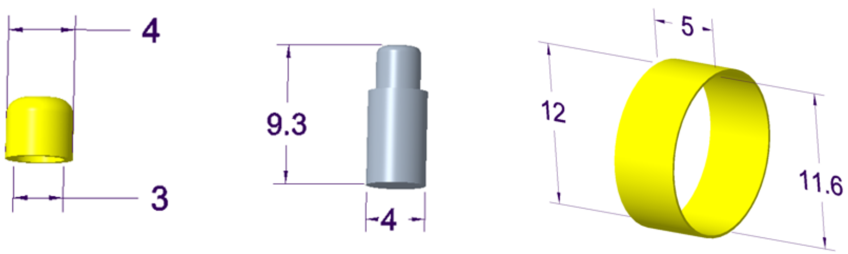


Figure 29 Revision 1 sliders.

3.6.2 Revision 2 of thrust sensor

In revision 3, main operation principle was following:

- The propeller will affect thrust force into the propeller shaft
- Force is transferred by bearings into the load sensors load sensing area
- Measured force is transferred into the gear housing
- Limited axial force to load sensor
- The propeller shaft will take torque force only from gear.
- Propeller shaft will be changeable

Following changes were made from revision 1:

- Instead of the ball bearings W 61801-2RZ, thrust was transferred into the load sensor by thrust bearings AXW12.

The assumption that there will be more movement in the two radial support bearings in axial direction than mechanical movement of the load sensor was made. With this assumption, the force is affected into the load sensor although there was support bearings between the propeller shaft and gear housing.

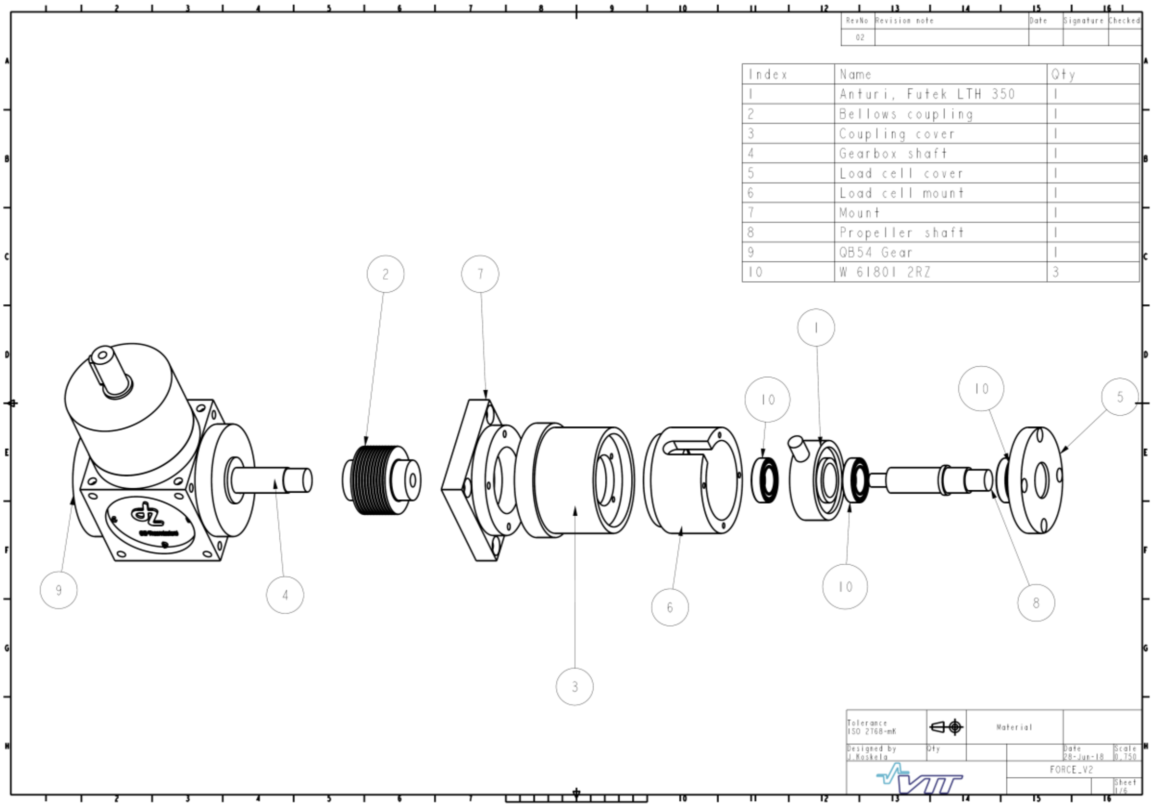


Figure 30 mechanical parts of revision 2.

The used bellows coupling was from VTT’s stock and not purchased for the sensor. Because of that, there is no data available about bellows coupling.

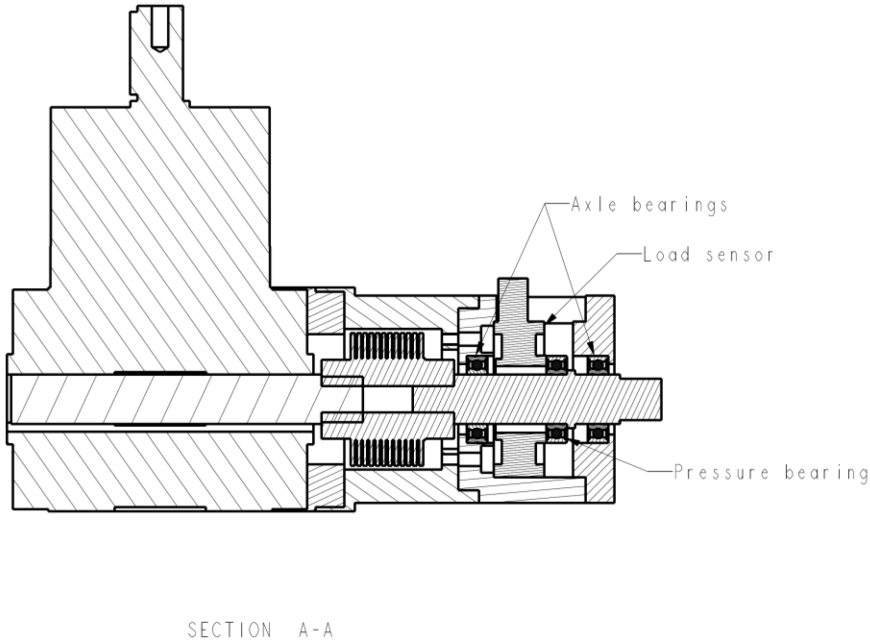


Figure 31 mechanical structure of revision 2.

In Figure 31 can be seen mechanical structure of revision 2 of thrust sensor.

3.6.3 Revision 3 of thrust sensor

In revision 3 of thrust sensor, main operation principle was the following:

- The propeller will affect thrust force into the propeller shaft
- Force is transferred by bearings into the load sensors load sensing area
- Measured force is transferred into the gear housing
- Limited axial force to load sensor
- the propeller shaft will take torque force only from gear.
- Propeller shaft will be changeable

Following changes were made from revision 2 of thrust sensor:

- Instead of the ball bearings W 61801-2RZ, thrust was transferred into the load sensor by thrust bearings AXW12.
- Possibility to measure thrust into two direction
- Sealing to prevent water to get inside sensor housing space

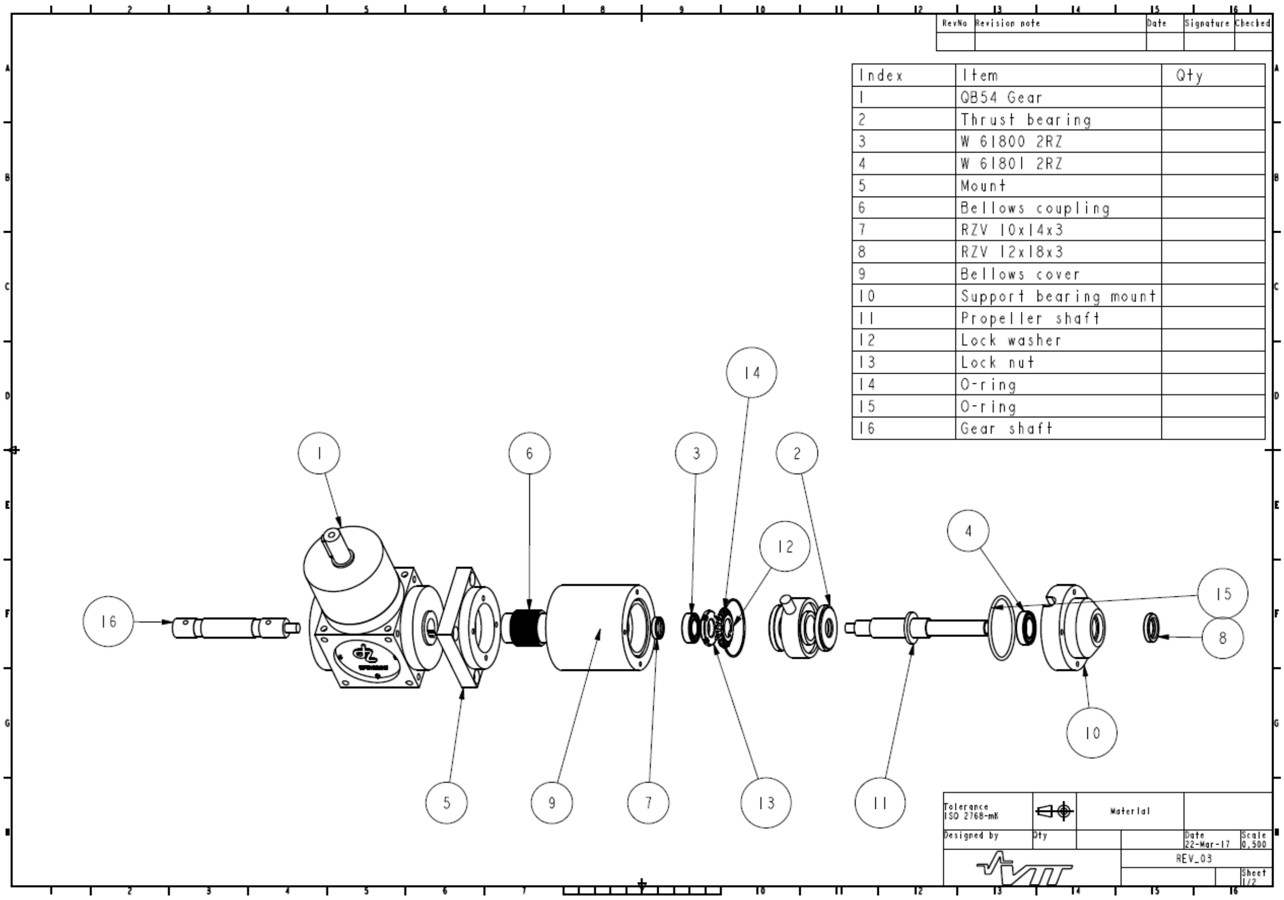


Figure 32 mechanical parts of revision 3.

Mechanically, number of parts was kept as minimum as possible. Here can be seen main parts. To be noted that coupling shaft with bellows coupling goes into gear first, then mounting adapter. There exist sealing between spaces where load cell is located. These seals cannot be seen from figure. In addition, axial support bearing for propeller shaft cannot be seen.

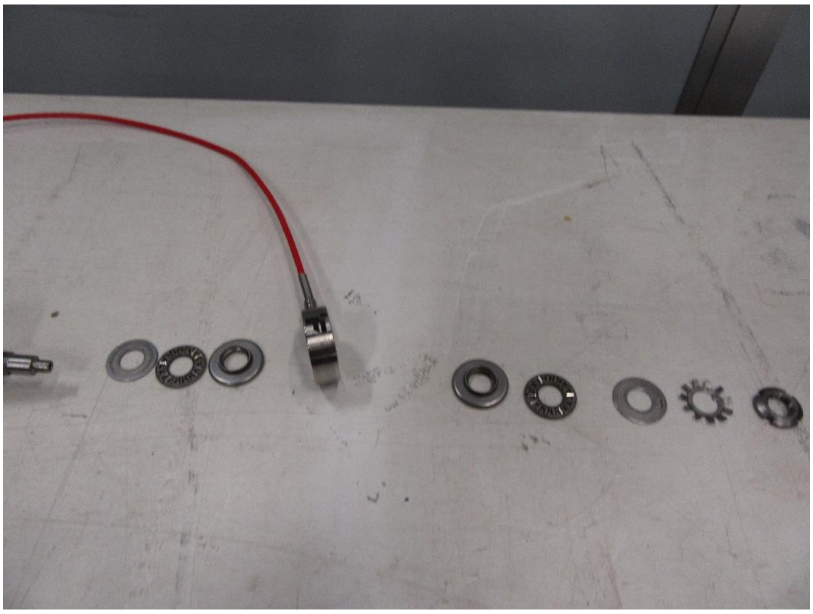
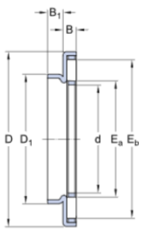


Figure 33 load sensor, thrust bearing and lock nut.

In Figure 33 unassembled load cell without shaft can be seen. Needle roller thrust bearings are type SKF AXW12 with thin universal washer LS 1226. Technical specification for AXW12 is:



DIMENSIONS

d	12 mm
D	29 mm
D_w	2 mm
E_a	min. 14 mm
E_b	max. 25 mm
D_1	16 mm
B	3.2 mm
B_1	3 mm

Figure 34 SKF AXW12 dimensions

And calculation data:

Basic dynamic load rating	C	9.15 kN
Basic static load rating	C_0	30 kN
Fatigue load limit	P_u	3.45 kN
Reference speed		5000 r/min
Limiting speed		10000 r/min

Figure 35 SKF AXW12 data for bearing calculations

3.6.4 Revision 4 of thrust sensor

Changes from revision 3 to revision 4 where following:

- Bellows coupler is moved into another side of gearbox
- W61800 and 61801 ball bearings where replaced to NB SR8UU linear and rotational ball bearings
- RZV axial seals where removed

As in results in test bench was noted, there exists differences between static and dynamic calibration values. Estimation for this was that ball bearings might not give enough free movement to force sensor. This affects into measurement accuracy, especially when making static calibration. Nippon bearing, bearing manufacturer, has product line where is combined stroke bush bearing which allows also rotation.

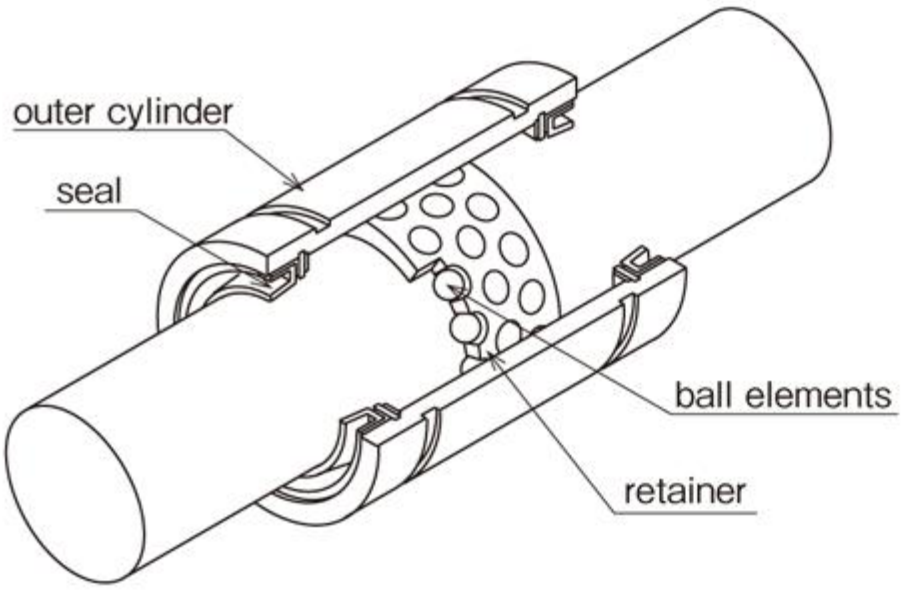


Figure 36Nippon Bearing stroke bush bearing (NB Europe n.d.).

In addition, this improves seal sliding frictional losses, when seal diameters are reduced.

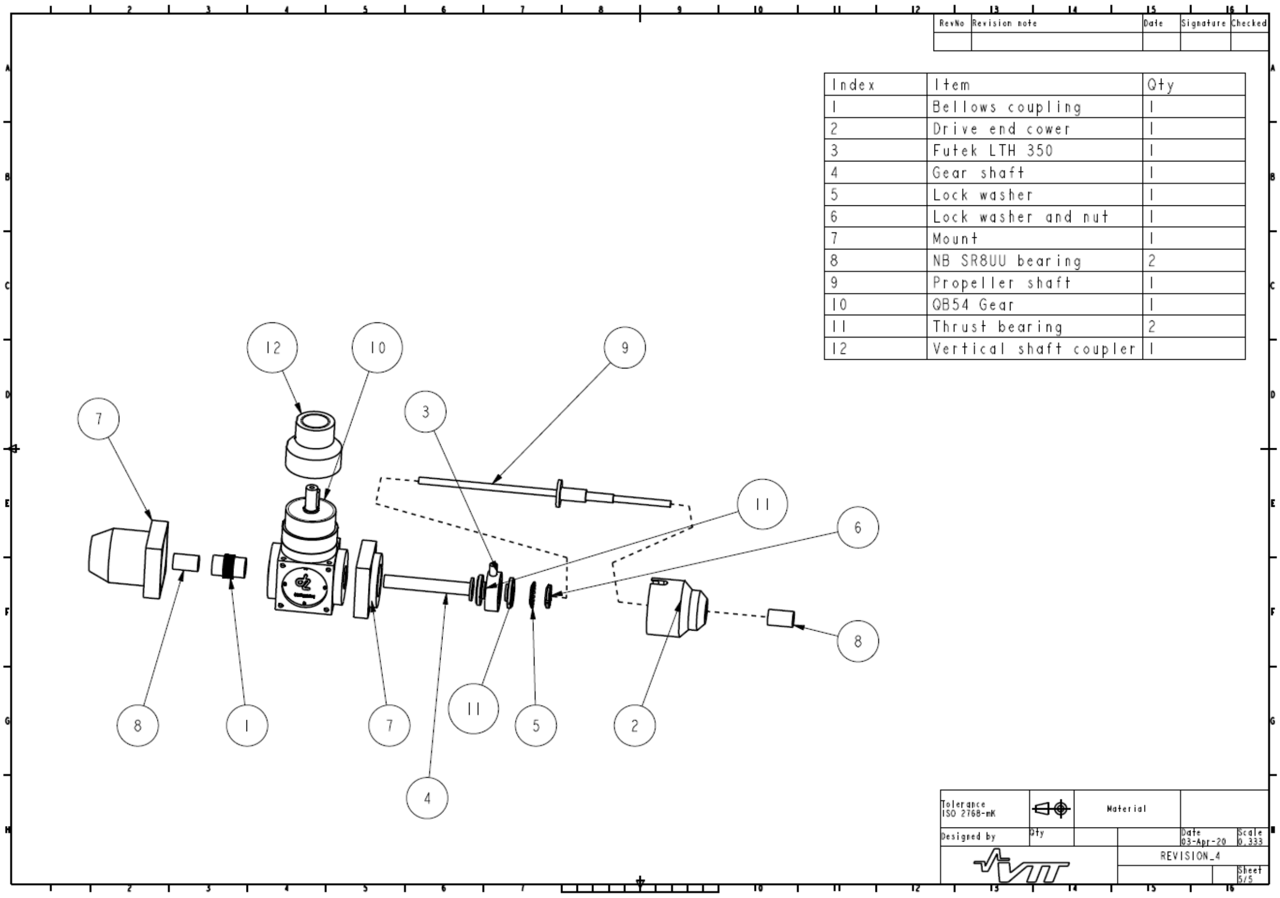


Figure 37 mechanical parts of revision 4.

For connecting bevel gear into KDN-250, thread, size M48 was machined into casing of input shaft. At VTT, there exists several standard length of power shafts for between bevel gear and KDN-250. Adapter for power shaft (item 12) was manufactured and installed into input shaft.

4 CALIBRATION

To calibrate test setup, two calibration methods are tested and compared. According of International Towing Tank Conference (ITTC) Recommended procedures and guidelines(ITTC 2014)3.3.2.1 and 3.3.2.2 about thrust and torque calibration is noted that static calibration methods are acceptable, but dynamic calibration is preferred if suitable. Same notification is made in book measuring torque correctly(Schicker and Wegener 2002). As noted in paragraph *3,* there are internal friction losses that can effect measurement accuracy.

4.1 Static calibration

At VTT, currently the sensors are calibrated statically. Calibration is made by using precise weights and level arms. There will be applied thrust and torque into the sensor separately and calibration correction values are calculated for thrust and torque individually.

Figure 38 inspected precision weights for sensor calibration at VTT.

Weights for calibration are certified and inspected regularly.

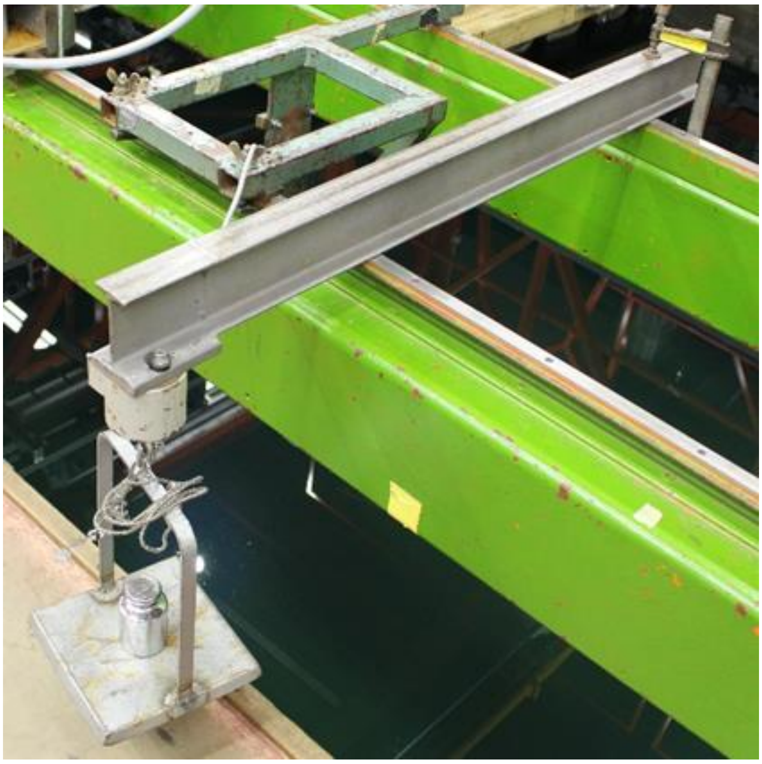


Figure 39 ship hull resistance sensor calibration at VTT.

When calibration is made with scale, measurement is zero balanced before adding any weight.

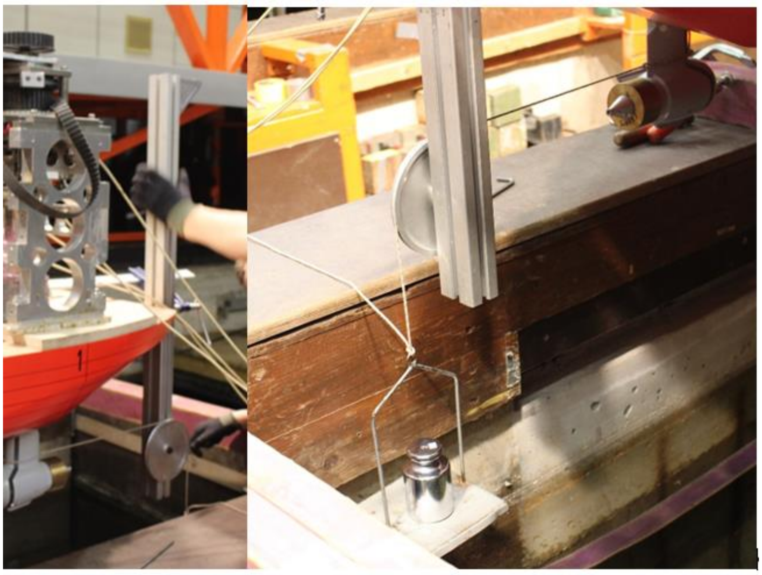


Figure 40 thrust calibration of KDN-250 at VTT.

With some measurements, support wheel is needed to be possible to use weights.

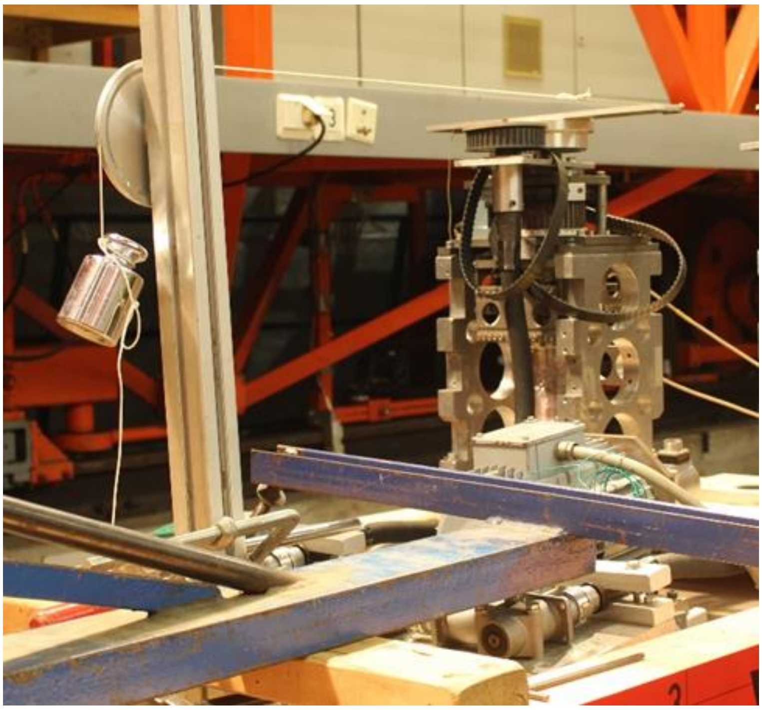


Figure 41 torque calibration of KDN-250 at the VTT.

Torque calibration measurements are made with level arm.

In the measurements, there are dynamic friction calibration made. In Figure 40, brass friction calibration load can be seen. This load has the same mass as propeller that will be used in model tests. Ship model shall be stationary in calm water and mass is rotated in steps within the rotation speed ranges, which are used in tests. This gives result of friction forces at different rotation speeds. In the final analysis, corrections for thrust and torque will be calculated.

As KDN-250 measures thrust from whole unit, also POD hull resistance needs to be measured. This is made by installing in place of propeller a piece that has dimension of the propeller boss. This resistance measurement is made in same speeds than with the propeller. When the POD resistance is accounted for in the propulsion measurement, propulsion thrust can be calculated , and later extrapolated to full scale values.

As in paragraph *3.1,* was shown; there are gear forces that affect the measurement results. Because of this, also calibration correction value of gear reduction is calculated. The final total thrust and torque values are::

$$T_{total} = MT * a_t - MT_u - MT * a_{ft} - MT * a_{gt} \tag{6}$$

$$Q_{total} = MQ * a_q - MQ_u - MQ * a_{fq} - MT * a_{gq} \tag{7}$$

Where:

$$T_{total} = Total\ thrust$$
$$MT = Measured\ thrust$$
$$a_t = sensitivity\ slope\ of\ thrust\ calibration$$
$$MT_u = propulsor\ unit\ resistance$$
$$a_{ft} = friction\ slope\ sensitivity\ of\ thrust$$
$$a_{gt} = gear\ slope\ sensitivity\ of\ thrust$$

$$Q_{total} = Total\ torque$$
$$MQ = Measured\ torque$$
$$a_q = sensitivity\ slope\ of\ torgue\ calibration$$
$$MQ_u = propulsor\ unit\ resistance$$
$$a_{fq} = friction\ slope\ sensitivity\ of\ torque$$
$$a_{gq} = gear\ slope\ sensitivity\ of\ torque$$

It is to be noted that as in paragraph 3.1, was shown, gear losses are different, depending rotational direction. Because of this, gear slope sensitivity is needed to determine in both directions. When making static thrust calibration, it has small or no affect into sensor calibration values, when making level arm calibration, like in Figure 41.

(Go, Seo, and Choi 2009) presented study, where similar dynamometer than commercial product, presented at paragraph *2.1*, was used. At this study, 2x2 calibration matrix was presented to eliminate the effect that when measuring thrust, it has small influence into torque and torque has small influence into thrust. As for validation test bench was made, comparison between calculations of current method and using method presented by (Go et al. 2009).

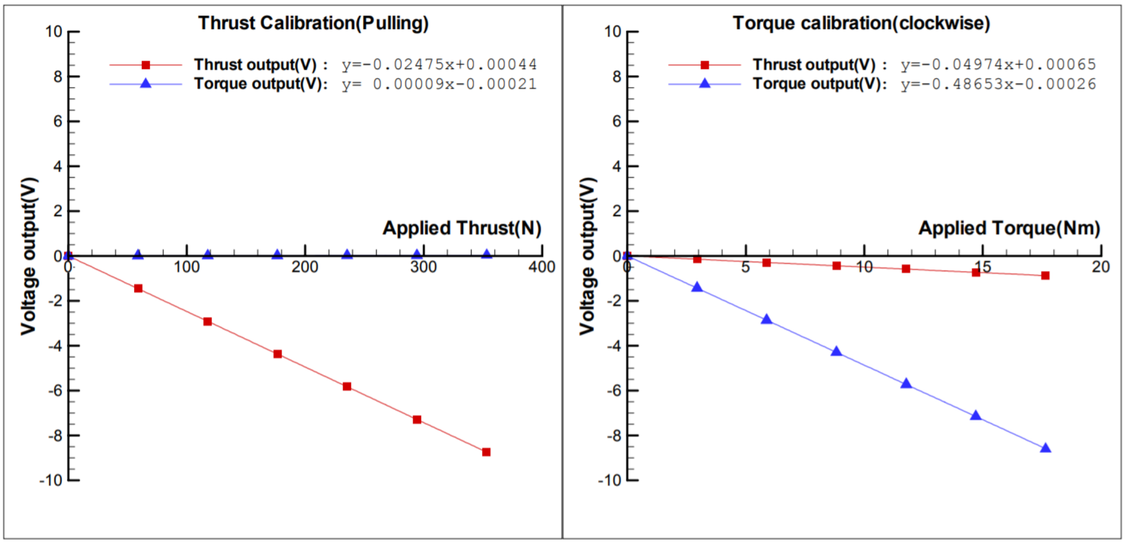


Figure 42 Cross coupling effect of propeller dynamometer (Go et al. 2009)

To take account of interaction effect, following linear equation was presented (Go et al. 2009):

$$\left.\begin{aligned} MT &= a_1 * AT + b_1 \\ MxQ &= a_2 * AT + b_2 \\ MQ &= a_3 * AQ + b_3 \\ MxT &= a_4 * AQ + b_4 \end{aligned}\right\} \quad (8)$$

Where

Mx	= *measured output of thrust*
MxQ	= *measured cross output of torque*
MQ	= *measured output of torque*
MxT	= *measured cross output of thrust*
AT	= *applied thrust loading*
AQ	= *applied thrust loading*
a_{1-4}	= *slope sensitivities*
b_{1-4}	= *offset*

As thrust and torque are applied simultaneously, linear equation was combined to:

$$\left.\begin{aligned} M &= A \cdot L + B \cdot I \\ \begin{bmatrix} T_{total} \\ Q_{total} \end{bmatrix} &= \begin{bmatrix} a_1 & a_4 \\ a_2 & a_3 \end{bmatrix} \cdot \begin{bmatrix} AT \\ AQ \end{bmatrix} - \begin{bmatrix} b_1 & b_4 \\ b_2 & b_3 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \end{aligned}\right\} \tag{9}$$

Where:

T_{total} = *measured output of thrust*

Q_{total} = *measured output of torque*

Finally, thrust and torque was calculated:

$$\left.\begin{aligned} L &= A^{-1} \cdot M - A^{-1} \cdot B \cdot I \\ \begin{bmatrix} AT \\ AQ \end{bmatrix} &= \begin{bmatrix} a_1 & a_4 \\ a_2 & a_3 \end{bmatrix}^{-1} \cdot \begin{bmatrix} T_{total} \\ Q_{total} \end{bmatrix} - \begin{bmatrix} a_1 & a_4 \\ a_2 & a_3 \end{bmatrix}^{-1} \begin{bmatrix} b_1 & b_4 \\ b_2 & b_3 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \end{aligned}\right\} \tag{10}$$

(Go et al. 2009)

With these calculations difference between applied loads and calculated loads where in study 0.5%(Go et al. 2009) or less.

4.2 Dynamic calibration

With manufactured test bench, dynamic calibration was possible to make. Because of the structure of thrust measurement sensor, it was predicted that dynamic might be needed for calibration. For this calibration, Kempf & Remmers type 33 dynamometer was used as dynamic calibration reference sensor. At same time, dynamic calibration method was tested for KDN-250 also.

Measurement calculation where made by following formula for static:

$$\begin{bmatrix} T_{total} \\ Q_{total} \end{bmatrix} = \begin{bmatrix} a_T & a_{TxQ} \\ a_{QxT} & a_Q \end{bmatrix} \cdot \begin{bmatrix} T_{measured} \\ Q_{Measured} \end{bmatrix} - \begin{bmatrix} y_{0T} \\ y_{0Q} \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} T_{total} \\ Q_{total} \end{bmatrix} = \begin{bmatrix} a_T & 0 \\ 0 & a_Q \end{bmatrix} \cdot \begin{bmatrix} T_{measured} \\ Q_{Measured} \end{bmatrix} - \begin{bmatrix} RPS_{fitT} \\ RPS_{fitQ} \end{bmatrix} - \begin{bmatrix} y_{0T} \\ y_{0Q} \end{bmatrix} \quad (12)$$

And for dynamic

$$\begin{bmatrix} T_{total} \\ Q_{total} \end{bmatrix} = \begin{bmatrix} a_T & 0 \\ 0 & a_Q \end{bmatrix} \cdot - \begin{bmatrix} RPS_{fitT} \\ RPS_{fitQ} \end{bmatrix} - \begin{bmatrix} y_{0T} \\ y_{0Q} \end{bmatrix} \quad (13)$$

Where:

a_{dT}	*= slope sensitivity of thrust*
a_{dTxQ}	*= slope sensitivity of cross trust of torque*
a_{dQ}	*= slope sensitivity of torque*
a_{dQxT}	*= slope sensitivity of cross torque of thrust*
$T_{measured}$	*=measure value of thrust*
$Q_{measured}$	*=measure value of torque*
RPS_{fitT}	*=RPS correction of thrust*
RPS_{fitQ}	*=RPS correction of torque*
y_{0dT}	*= offset of thrust*
y_{0dQ}	*=offset of torque*
$T_{measured}$	*=measure value of thrust*
$Q_{measured}$	*=measure value of torque*

With two different calculations of static correction, comparison dynamic friction measurements and method of cross effect measurement can be done.

5 PRELIMINARY TESTS

First preliminary test where made by same setup that in revision 1 of thrust sensor preliminary tests.

When preliminary test for revision 1 of thrust sensor was made. it was noted that cross reference between thrust and torque will be needed to measure, the test bench which design and development is presented at paragraph 5.2 Thrust and torque test bench, was developed for preliminary tests.

As results were very promising, it was noted that there is possibility of the need to have both positive and negative thrust. In mechanical structure of revision 2 of thrust sensor there is no possible to measure into the two direction, as manufacturer of load sensor has specified load only to the one direction.

5.1 Preliminary test method and equipment

Preliminary test of the revision 1 of thrust sensor where made by using of FUTEK LTH350 rated to 131345N (3000lb) load sensor was installed into mounting bracket, made of aluminum profile by Bosch Rexroth (Bosch Rexroth AG 2018), and using HBM U2A load cell as reference sensor.

Thrust force was created by turning threaded coupler and amount of load measured by reference sensor. By this setup, there was no possibility to make torque load. 3-phase electric motor with frequency converter was used to turn gear. Measurements where measured and recorded by HBM Quantum X MX840X.

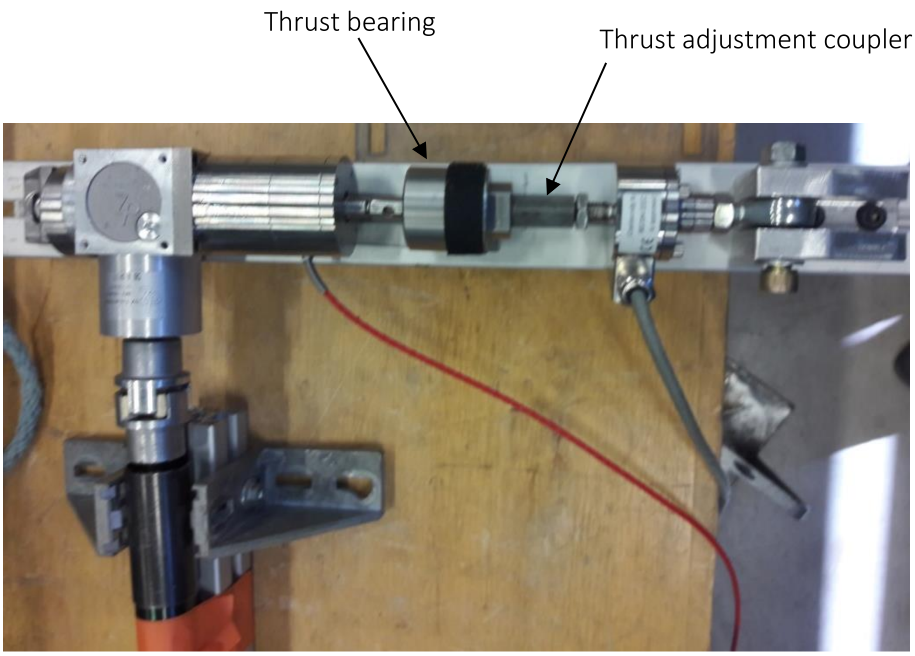


Figure 43 revision 2 of thrust sensor in preliminary test bench.

Figure 44 static calibration of thrust sensor revision 2 of thrust sensor.

Static calibration was made by setting weights of 1, 2, 5 and 10 kilograms on the propeller shaft.

5.2 Thrust and torque test bench

To be able to make dynamic tests and calibrations, torque and thrust test bench was made after revision 1. Requirements for test bench were:

- adjustable turning speed
- adjustable torque
- adjustable thrust
- current torque and thrust measurement system can be implemented
- developed thrust measurement sensor can be implemented
- reference thrust and torque sensor can be implemented
- possibility to make static torque and thrust calibrations without need to remove sensors

Based on earlier experience, aluminum profiles provided by Bosch-Rexroth(Bosch Rexroth AG 2018) was selected to be used for test bench frame. Using this versatile construction can be achieved and modification, if necessary is easy. Test bench has two main structures, main frame and load frame. Main frame supported structure and made possibly to mount propulsion motor and measuring units. This main frame is usually used at unit open water tests.

Main frame

Main frame of test bench is made for unit open water tests. Into test frame, there is 3 phase, 3kW, electric motor mounted. In addition, pulse sensor is mounted into electric motor. This motor gives power for KDN-250 in unit open water tests. At these tests, KDN-250 is mounted at lower crossbars. Thrust measurement sensor was installed into KDN-250 in same way as it would be installed in at the towing tank measurements.

Angle bar legs with rolls are for easy moving of the unit. As the unit is moved into towing bridge, these legs are removed.

Figure 45, main frame without KDN-250.

There exist standard mounting bars for KDN-250 to allow easy install and adjustment. Power from motor is delivered into KDN-250 by flexible shaft. This makes possible to install motor and KDN-250 more freely. From flexible shaft, power is transferred into KDN-250 by tooth belt. It is noted that tooth need to be installed relatively loose. If tooth belt is installed too tight, it can affect to the measurement results.

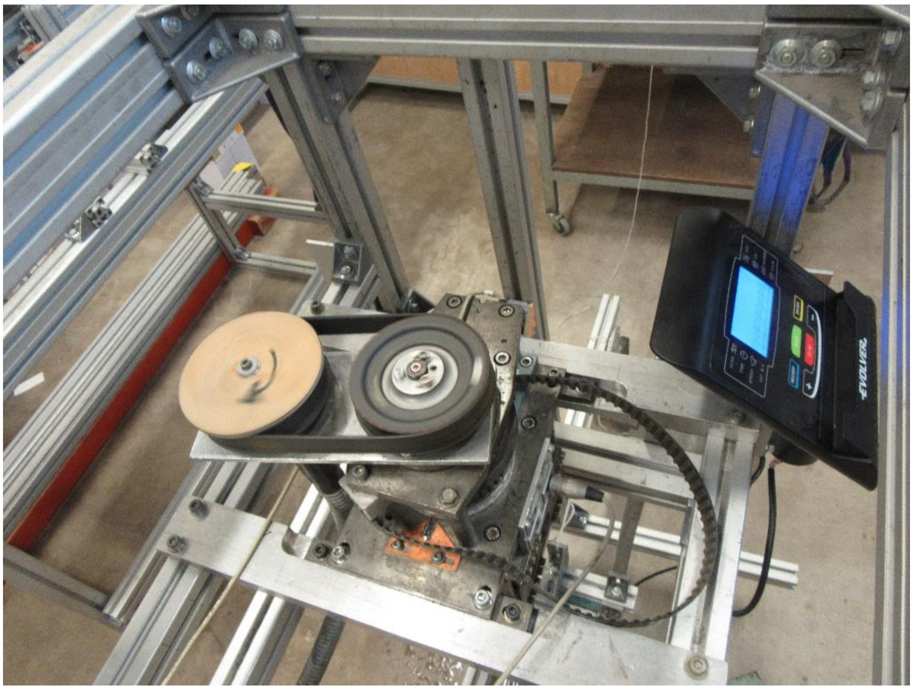


Figure 46, KDN-250 installed into main frame.

Load frame

To be able to create necessary torque mechanical brake was needed. Problem with mechanical brakes, is that the disk starts to heat and friction between brake disk and brake pads changes. To be able to keep constant level of torque with mechanical brake, feedback from torque would be needed and torque would be needed to adjust automatically in real time.

Instead of mechanical brake, permanent magnetic brake with adjustable load was used. For achieving magnetic brake, commercial exercise cycle was purchased. From exercise cycle was used:

- Flywheel
- Adjustable permanent magnet frame
- Adjusting motor of magnet frame
- Control module of magnet frame

For reference measurement, Kempf & Remmers typ 33 dynamometer was used and mounted into load frame. This dynamometer worked as reference measurement sensor. As there was also KDN-250 installed into main frame, there was existing two reference sensors. The advance of this is that here was no need to apply accurate load:

- when torque load was applied, KDN-250 measured torque with all losses and Kempf & Remmers typ 33 dynamometer measured applied torque.
- when thrust load was applied, Kempf & Remmers typ 33 dynamometer measured applied load and KDN-250 measured load transferred main frame.

Load frame was isolated from thrust forces from main frame by using aluminum bars, which allowed movement in X direction relatively easy.

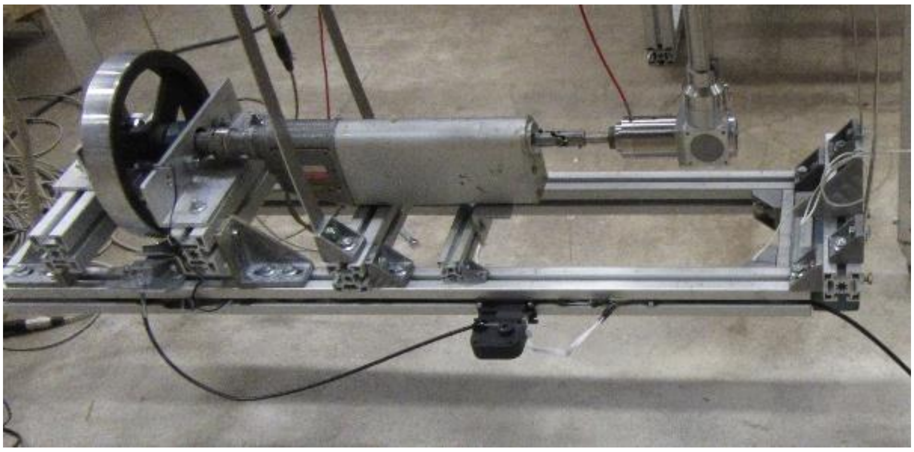


Figure 47 measurement setup in measurement frame.

At torque load side, torque wheel was mounted to Kempf & Remmers Typ 33 dynamometer by flexible shaft coupling. Torque wheels shaft was replaced and original bearings were replaced by flanged bearings. Bearings were installed into angled aluminum bar, which is mounted into Bosch aluminum profile. This makes possible to align torque wheel with Kempf & Remmers typ 33 dynamometer.

Torque load is created by combination of mass and adjustable permanent magnetic brake shoe. Magnetic brake shoe was hinged from another edge. When torque load was applied, magnetic brake shoe moves closer to torque wheel and adding torque.

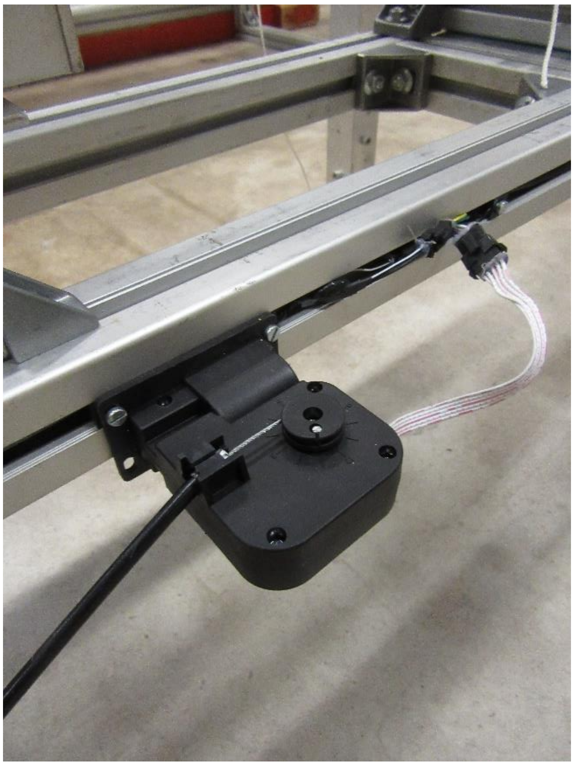


Figure 48 servomotor for permanent magnet brake shoe distance adjustment.

Brake shoe adjustment was made by original servomotor, which was installed into measurement frame.

In addition, pulse sensor from original exercise bike was used. It was needed because controller of servomotor was monitoring rotation of exercise bikes pedals. If controller did not receive message from pulse sensor within 5 minutes, it turned system into standby mode.

Test bench operation

There are three adjustable values at test bench, RPS, torque and thrust. Because it is possible to overload sensors, especially KDN-250, careful load increase is needed. Rotation of test bench is started first and after that load can be applied.

Thrust load is created by weights. These weights can be loaded before test bench is started.

Following cautions need to be noted:

- As system starts and stops, high peaks at torque values can be reached. Because of this, only 50% of capacity of KDN-250 should be used in normal use.
- Thrust load higher than 15kg should not be used.
- When RPS rises, also torque level rises if using same torque setting.
- It is necessary to cool bevel gear by water spray. Increase in gearbox temperature affects into gear loss forces.
- Temperature of torque wheel should be noted. Extra caution is needed when operating test bench. When creating torque, temperature of torque wheel can be over 50 °C.
- When doing any adjustments, frequency converter should be turned off.

Figure 49 control board for torque adjustment.

Controller has several different type load models. These models had variable load settings, depending from what kind of exercise profile was used. It was important to check what load setting from controller was. If standby mode was reached, controller selected different load mode. Current settings made possible to use load settings from 1-9 in lower RPS. So carefulness for operation was needed not to overload KDN-250.

Frequency converter was used for motor speed control. Frequency converter was Dinverter Type DIN3380400B.

Figure 50 frequency converter panel and user interface.

This frequency converter was operated from remote controller. Remote controller has buttons for start, stop, directions 1 and 2 and rotation speed control. Setup buttons set rotation speed. These setup values are depending of presetting of frequency converter. Input voltage for control is 10V. Setup buttons divide this voltage into 999 steps. With current frequency converter setup, setting 50 was equal to 1 RPS from motor.

Thrust sensor was mounted into Kempf & Remmers typ 33 dynamometer by joint coupling. For mounting into KDN-250 was used standard podded propulsor mounting shaft. There exist mounting shafts of different length at VTT. Different length is needed because same mounting system is used to mount KDN-250 into ship model. Depending of height of model aft, correct mounting shaft is selected.

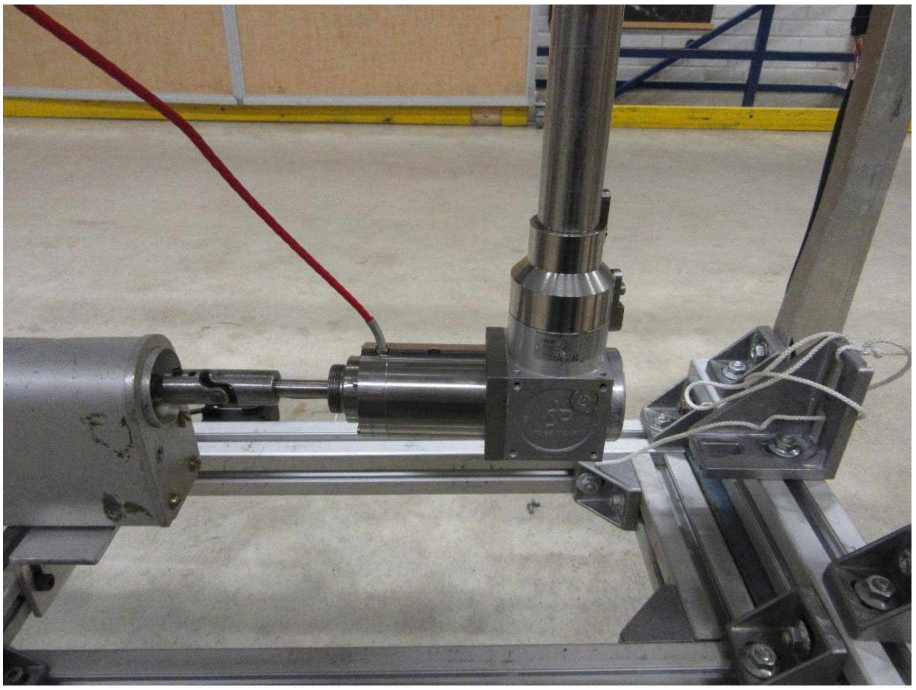


Figure 51 coupling between thrust measurement sensor and reference sensor.

For applying thrust load, there was low stretch cord used. Cord was knotted into measurement frame.

From measurement frame, cord was inserted through wheel to weight frame. When using weight frame, it is important to remember to weight frame also. When making calibration measurements, easiest way to take care of this is to make zero level adjustment with weight frame.

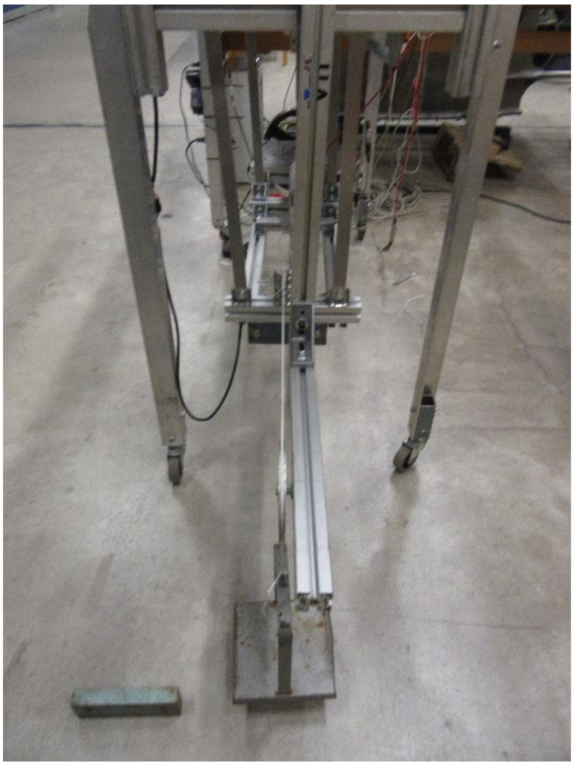


Figure 52 thrust load bucket for adding mass.

This same load system was used for static calibration and measurements. For static torque calibration. Level arm system and weights was used.

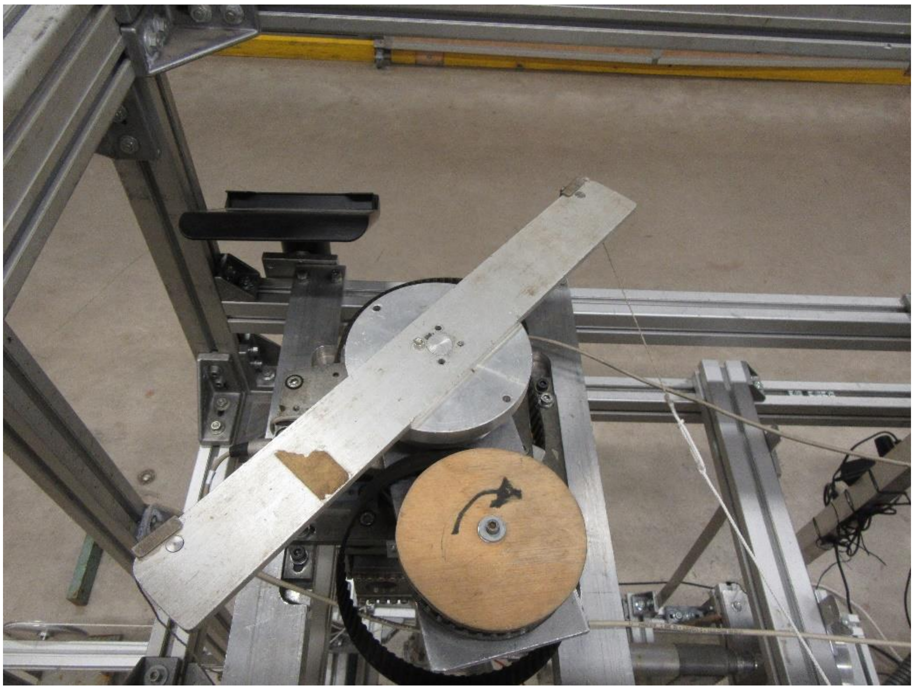


Figure 53 Level arm for torque measurement and arrow of rotation.

Level arm. Length of 0,25m was used, by removing tooth belt from KDN-250. Level arm was installed into belt wheel.

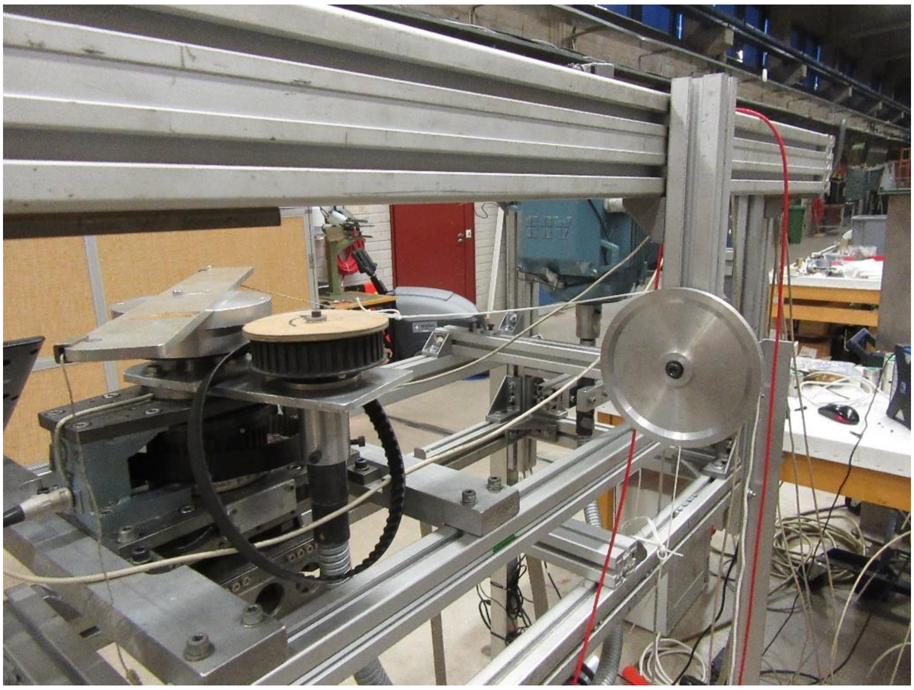


Figure 54 Support wheel for torque and thrust calibration.

Support wheel for cord was used to make possible to put up weight. As maximum measure torque of KDN-250 is low, no weight frame was used for torque calibration.

6 EXECUTION OF VERIFICATION MEASUREMENTS

Calibration was made in test bench. Two methods, static and dynamic was used. Calibration was made by following process.

Static torque calibration:

- When measuring torque, torque load was created by level arm and weights. Instead of using weight as reference, Kempf & Remmers typ 33 dynamometer was used as reference sensor.
- Rotational movement of measurement sensors was limited by locking rotation using iron bar to prevent torque wheel to rotate.
- Cross thrust was measured against reference sensor

Static thrust calibration

- When measuring thrust, load was created by weights. Instead of using weights as reference, Kempf & Remmers typ 33 dynamometer was used as reference sensor
- Rotational movement of measurement sensors was limited by locking rotation using iron bar to prevent torque wheel to rotate.
- Cross torque was measured against reference sensor. Small weight was used to create counter torque zero level. Cross torque was measured against reference sensor.

Dynamic torque calibration:

- When measuring torque, torque load was created by torque wheel. Torque was increased at levels 1, 2,3,5,7 and 9. Kempf & Remmers typ 33 dynamometer was used as reference sensor.
- RPS at calibration was 1 RPS
- Cross thrust was measured against reference sensor

Dynamic thrust calibration

- When measuring thrust, load was created by weights. Instead of using weights as reference, Kempf & Remmers typ 33 dynamometer was used as reference sensor
- RPS at calibration was 1 RPS
- Load level at torque wheel was 0
- Cross torque was measured against reference sensor.

Measurements were made by adding different load for thrust and torque. Limitations for loads where torque sensors. Level of torque was kept under 0.5 kpm. Reason for this was that there were significant thrust load when adding revolutions into system and monitored thrust loads raised to near 0.9 kpm when accelerating to rated speed. Because of this, revolutions higher than 12 RPS was not used.

7 UNIT OPEN WATER TESTS

7.1 POD housing and propeller for open water tests

For open water tests, POD housing and propeller were designed for thrust sensor revision 4. Pulling POD type vas selected. Both, POD and propeller, are designed so that main dimensions are similar to existing products. To be possible to use models for public research, these are designed for this purpose only. Therefore, there does not exist similar POD or propeller in full scale. Both POD and propeller are designed to fit into ship model that is used for student works and presentations at VTT. Manufacturing method was 3D printing with ABS printing material.

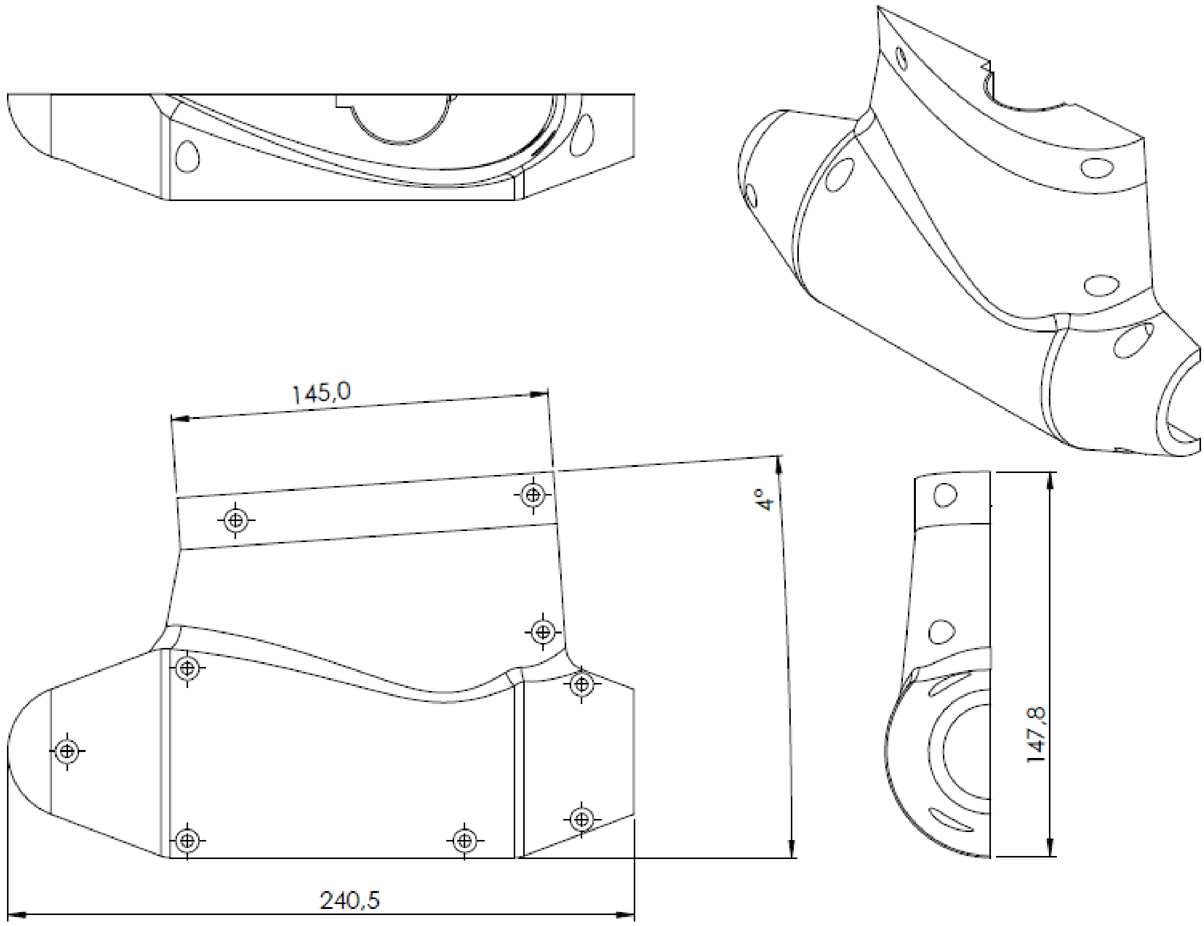


Figure 55 main dimensions of POD.

The strut of the POD unit is designed according symmetric NACA four digit airfoil. Airfoil is type NACA 0040. This allowed needed space inside POD for thrust sensor revision 4.

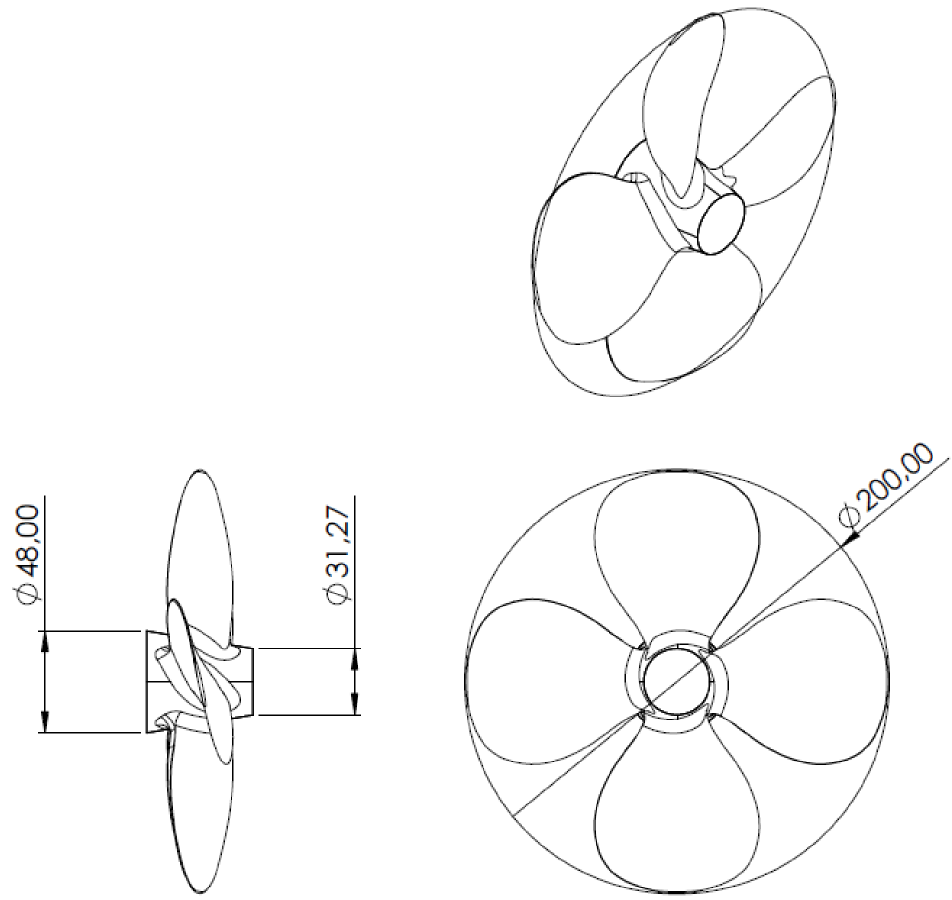


Figure 56 propeller for open water tests, main dimensions.

Propeller is based on that of a reference vessel.

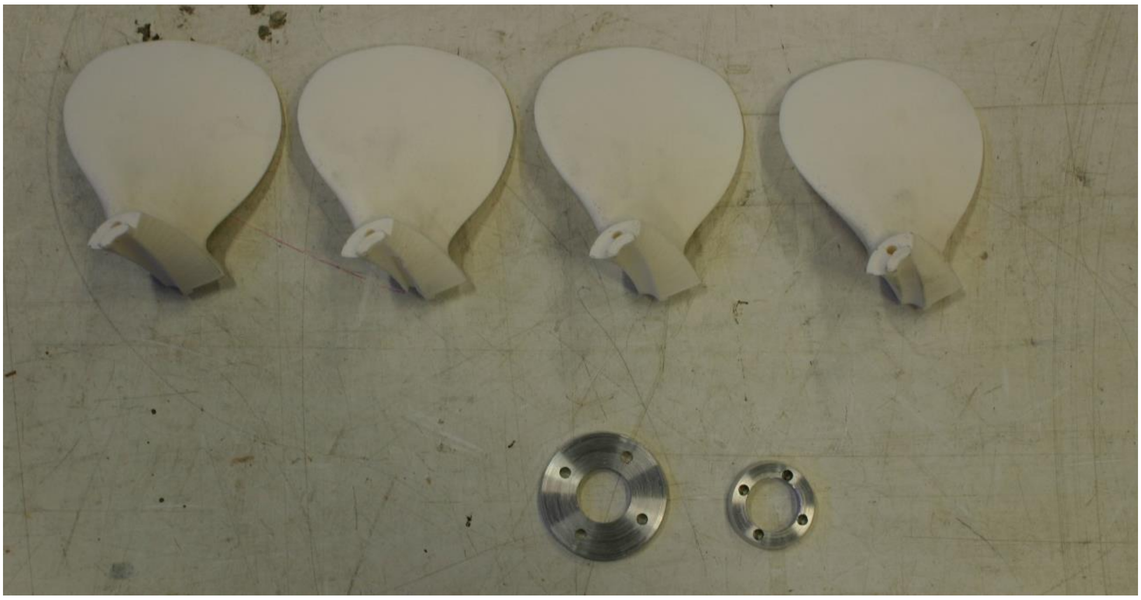


Figure 57 printed propeller blades.

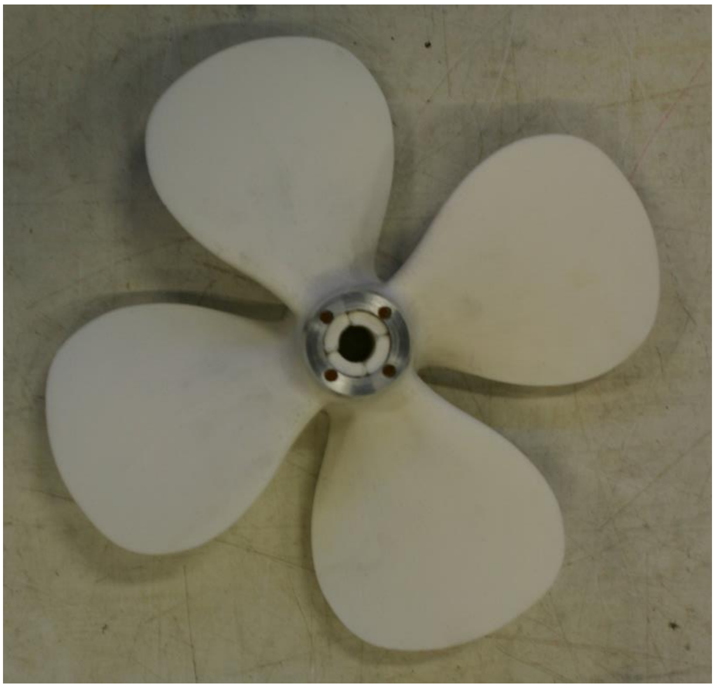


Figure 58 assembled propeller.

In Figure 57 and Figure 58 can be seen printed propeller. Propeller blades where printed separately to optimize propeller blade angle against 3D printer print head. Blades where glued and for alignment and for support structure of blades, aluminum front and back where used.

Figure 59 assembled POD.

In Figure 59 can be seen the assembled POD unit. White parts are for open water tests. Top part is used to align propeller axis with open water measurement frame. White bladeless boss is used when measuring POD housing resistance without the propeller.

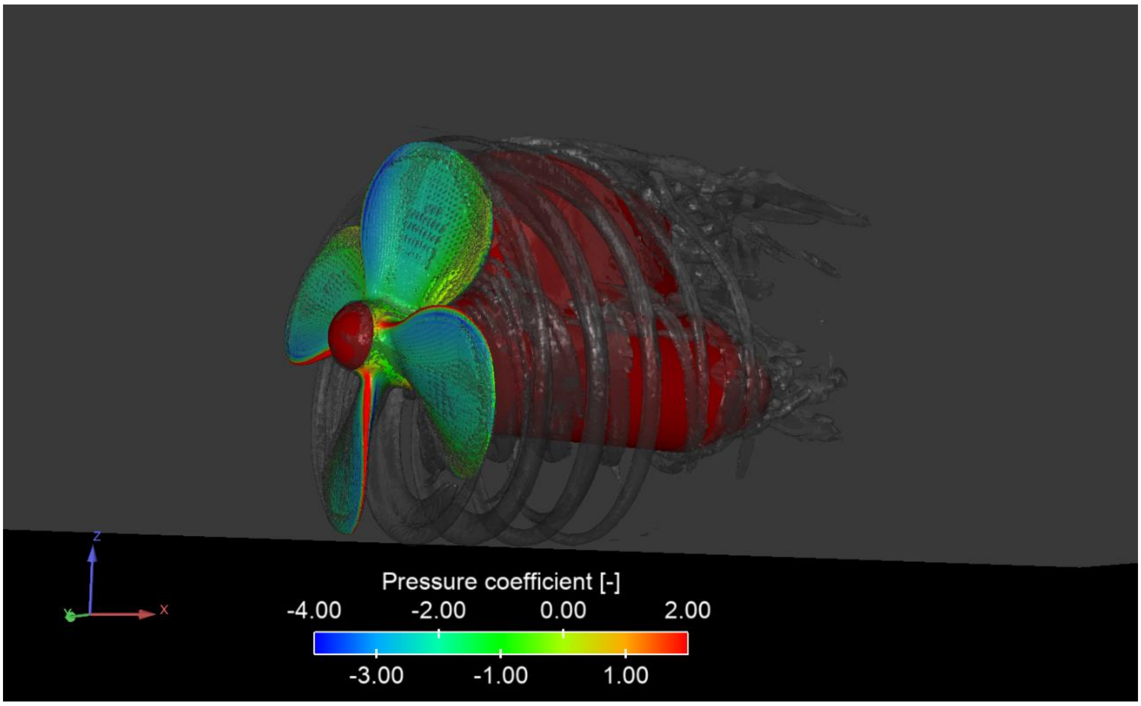


Figure 60 CFD analysis.

In Figure 60 can be seen pressure coefficient estimations for POD housing and propeller in open water test. Figure is from CFD analysis made by Ville Viitanen, research scientist at VTT oy.

7.2 Test matrix

Open water test was run according following table:

Table 2 open water test parameters.

Open water test matrix		
		n [rps]
		16
No.	J	VA [m/s]
1	0	0
2	0.1	0.319
3	0.2	0.638
4	0.3	0.957
5	0.4	1.276
6	0.45	1.435
7	0.5	1.594
8	0.55	1.754
9	0.6	1.913
10	0.65	2.073
11	0.7	2.232
12	0.75	2.392
13	0.8	2.551
14	0.85	2.71
15	0.9	2.87
16	0.95	3.029
17	1	3.189
18	1.05	3.348
19	1.1	3.508

Where:

$$J = \text{ advance number}$$

$$n = \text{propeller rate of revolutions}$$

$$VA = \text{towing carriage speed}$$

Results were given as dimensionless thrust coefficient (K_T) value.

$$K_T = \frac{T}{\rho n^2 D^4} \tag{14}$$

Where:

$K_T = Thrust\ coefficient$

$T = measured\ thrust, (N)$

$\rho = mass\ density\ of\ water, \frac{kg}{m^3}$

$n = propeller\ rate\ of\ revolutions, (rps)$

$D = propeller\ diameter, (m)$

Measured thrust values where compared to CFD calculations made by Ville Viitanen, research scientist at VTT Oy.

7.3 Measurement procedure

Propeller shaft thrust measurement sensor was implemented into 3D printed POD housing.

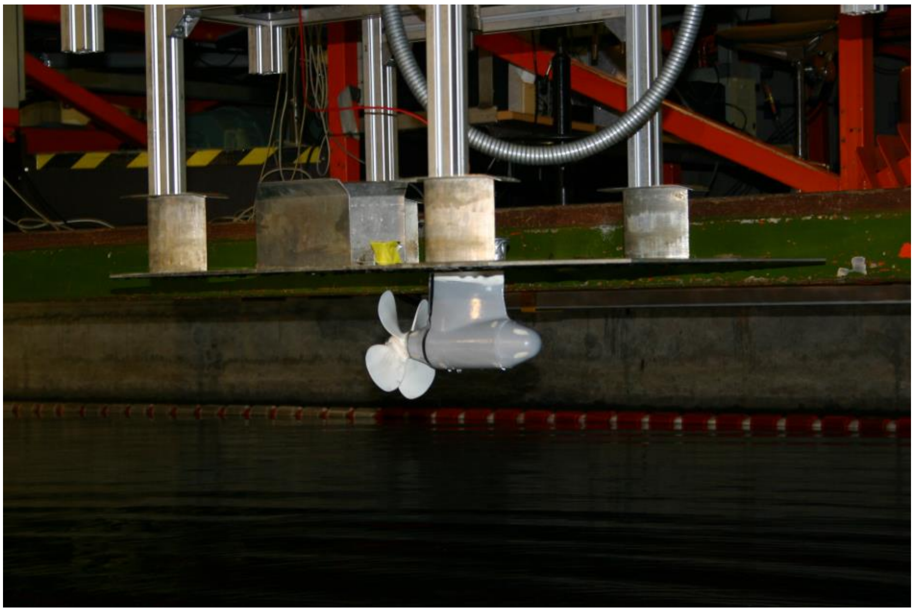


Figure 61, open water test setup.

At Figure 61 can be seen how developed propeller, POD housing and propeller shaft thrust sensor are placed in a test unit. End plate of test unit is submerged right under water surface. As water flows above end plate, all support legs have streamlined body. In the measurements, following data was collected:

$$towing\ tank\ carriage\ speed$$
$$KDN - 250\ thrust\ and\ torque$$
$$Propeller\ shaft\ thrustfrom\ thrust\ sensor$$
$$revolutions\ of\ propeller\ from\ 3 - phase\ electric\ motor\ encoder.$$

8 RESULTS

Uncertainty analysis for thrust measurement sensor was not done. As in test bench, there was a reference sensor in use. Measurement results of the thrust measurement sensor where referenced against the reference sensor result.

8.1 Calibration and cross terms

Table 3 Calibration results.

Test bench thrust calibration of revision revision 3, Futek			
direction of rotation	slope sensitivity	offset	calibration method
Clockwise	0.9874	-0.3265	Dynamic
Counterclockwise	0.9934	0.2166	Dynamic
Clockwise	1.4559	0.2939	Static
Counterclockwise	1.3474	-0.0493	Static

Test bench thrust calibration of revision 3, KDN-250			
direction of rotation	slope sensitivity	offset	calibration method
Clockwise	1.0008	0.1544	Dynamic
Counterclockwise	1.0001	-0.0977	Dynamic
Clockwise	1.0088	-0.025	Static
Counterclockwise	0.9989	0.0568	Static

Test bench thrust calibration of revision revision 4, Futek			
direction of rotation	slope sensitivity	offset	calibration method
Clockwise	1.081	0.1068	Dynamic
Counterclockwise	1.0824	0.00769	Dynamic
Counterclockwise	1.0433	0.0631	Static

Test bench thrust calibration of revision revision 4, KDN-250			
direction of rotation	slope sensitivity	offset	calibration method
Clockwise	1.015	0.0797	Dynamic
Counterclockwise	1.0165	0.119	Dynamic
Counterclockwise	1.0144	0.0331	Static

Calibration results are produced by excel from data chart trend line and trend line equation. These are presented for revision 3 at appendix 3, Figure 77 and Figure 78 and for revision 4 in appendix 4 Figure 82 and Figure 83.

As there was some uncertainty in a test results when measuring cross term effect of thrust and torque, these measurements were not analyzed. Although from charts presented at appendix 4, Figure 84 to Figure 88 can be seen that when sensor is influenced by thrust, torque does not have significant variation.

8.2 Preliminary test results of revision 1 of thrust sensor

In preliminary test, it was noted right away that load does not remain constant. Gear affected the measured load. Tests were not continued.

8.3 Preliminary test results of Revision 2 of thrust sensor, static measurement

Table 4 thrust sensor revision 2 measurement.

U2A [kg]	Revision 2 of thrust sensor [kg]	Difference between measurements	
7,395	7,439	-0,044	-0,59 %
14,991	15,033	-0,042	-0,28 %
10,453	10,518	-0,065	-0,62 %
13,654	13,725	-0,071	-0,52 %
11,749	11,815	-0,065	-0,55 %
8,919	8,969	-0,050	-0,56 %
10,715	10,790	-0,075	-0,70 %
12,323	12,390	-0,067	-0,54 %
14,777	14,861	-0,085	-0,57 %
11,984	12,060	-0,076	-0,64 %
9,714	9,758	-0,044	-0,45 %

When static measurements were made for revision 2 of thrust sensor, it can be seen form Table 4 above. As seen from table, revision 2 of thrust sensor gave results in static stage with relatively high accuracy.

8.4 Test bench results of revision 3 of thrust sensor

In a test bench run, there existed variation in measurement results. Altough measurements gave results with reasonable accuracy when averaged, deviation

between single results between different thrust and torque combination loads where not at acceptable level.

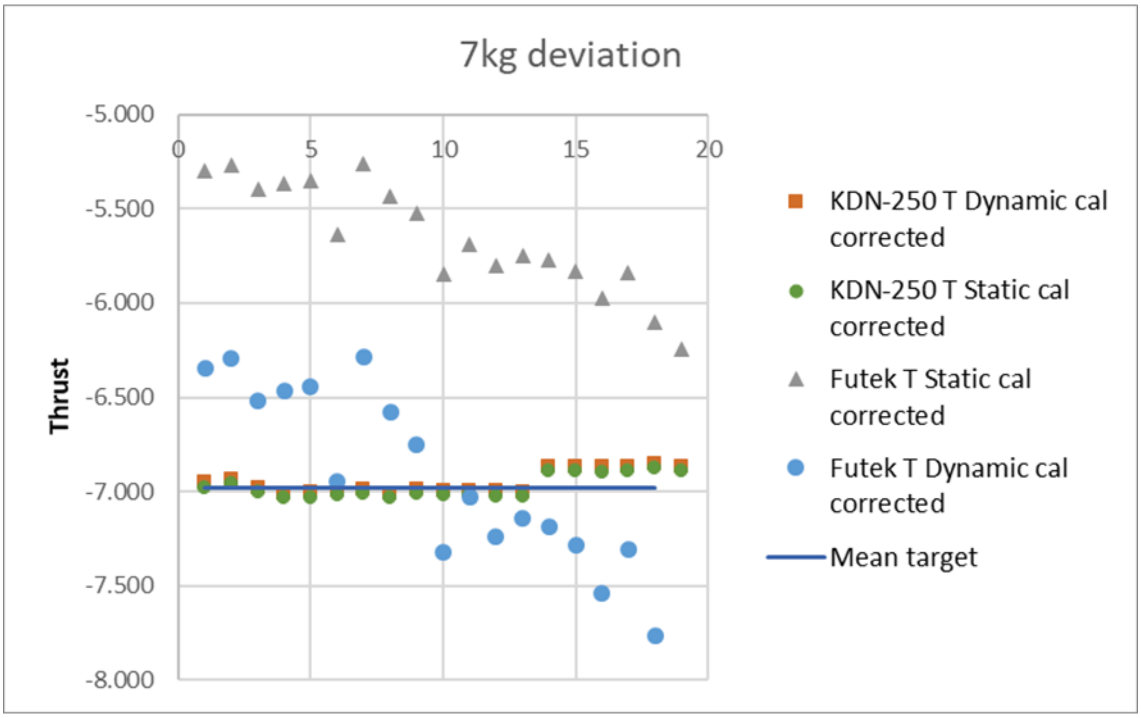


Figure 62, 7kg measurement results, revision 3.

Form Figure 62 can be seen the difference between calibration methods and variation against mean target of 7kg load. Measurement result for all load levels can be seen at appendix 3, from Figure 79 to Figure 81.

8.5 Test bench results of revision 4 of thrust sensor

In a test bench run of revision 4, improvement in terms of less deviation between the measurements with the same thrust load.

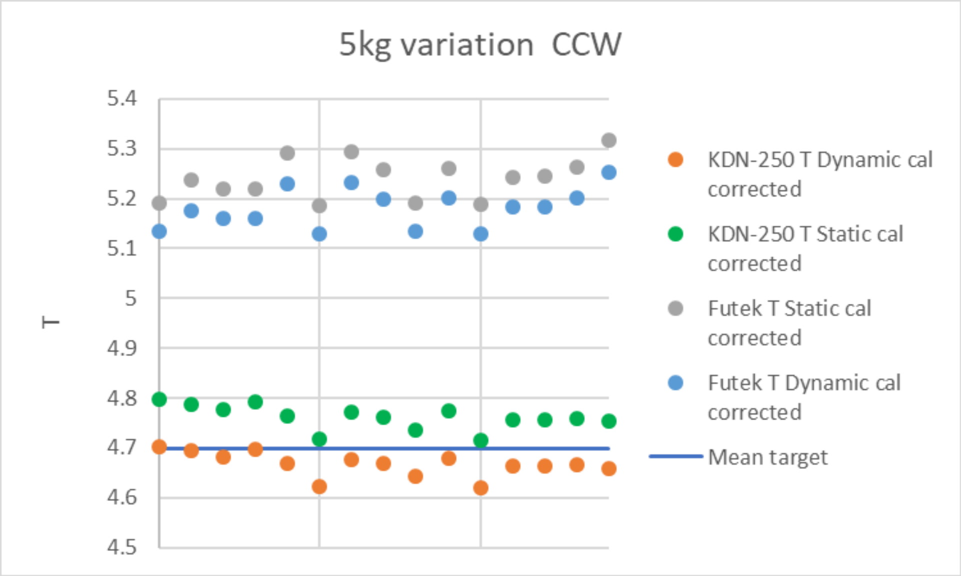


Figure 63 thrust load measurement, 5kg calibration weight as load, CCW direction.

As in results for the 5kg load measurement, deviation between the highest and the lowest measurement is relatively lower than in measurements for revision 3.

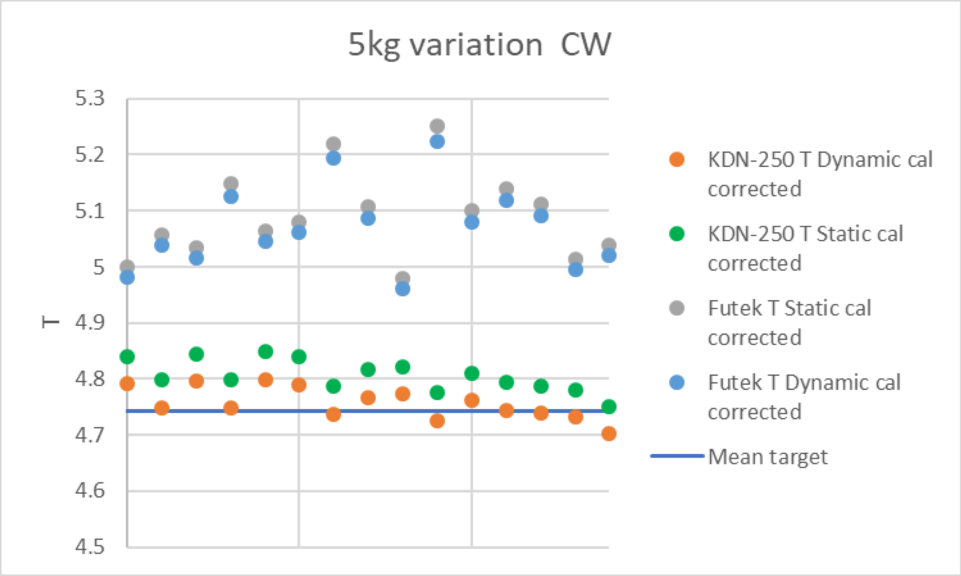


Figure 64 thrust load measurement, 5kg calibration weight as load, CW direction.

In Figure 64 can be seen that some higher deviation exists when rotation is made in clockwise direction. Similar variation can be seen in the measurement results of KDN-250. From this can be seen that variation in load levels reflects into measurement result in a same way for both sensors. All measurement results are presented in appendix 4, Figure 89 to Figure 96.

8.6 Open water test results

Open water test results are presented as figures to show measurement trend.

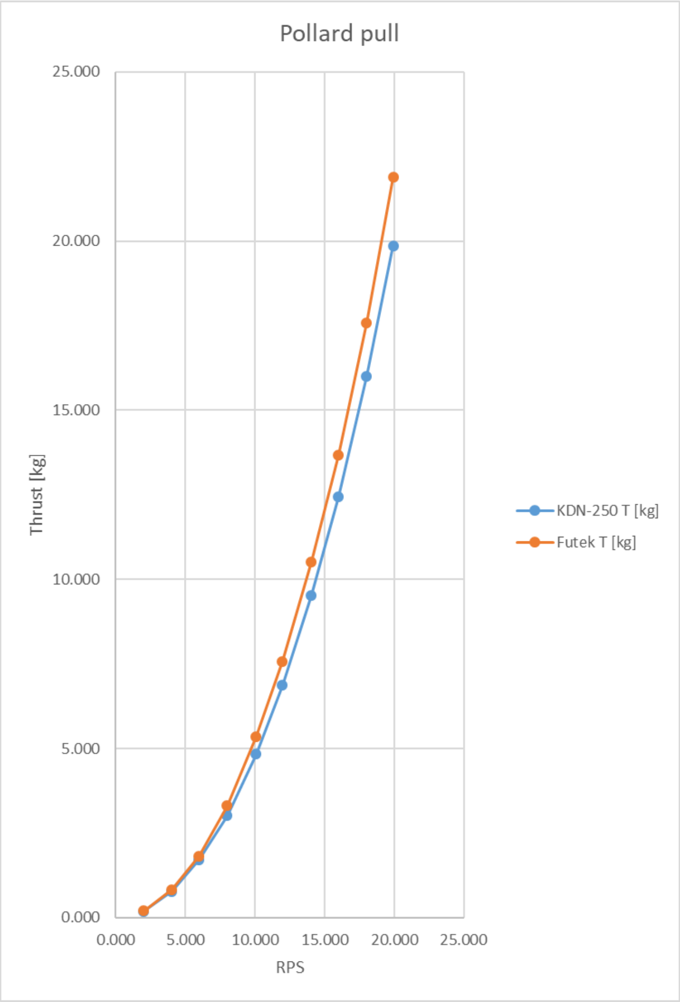


Figure 65 pollard pull test.

From Figure 65 can be seen that measurement curve of Futek, propeller shaft torque sensor and KDN-250, unit follows each other.

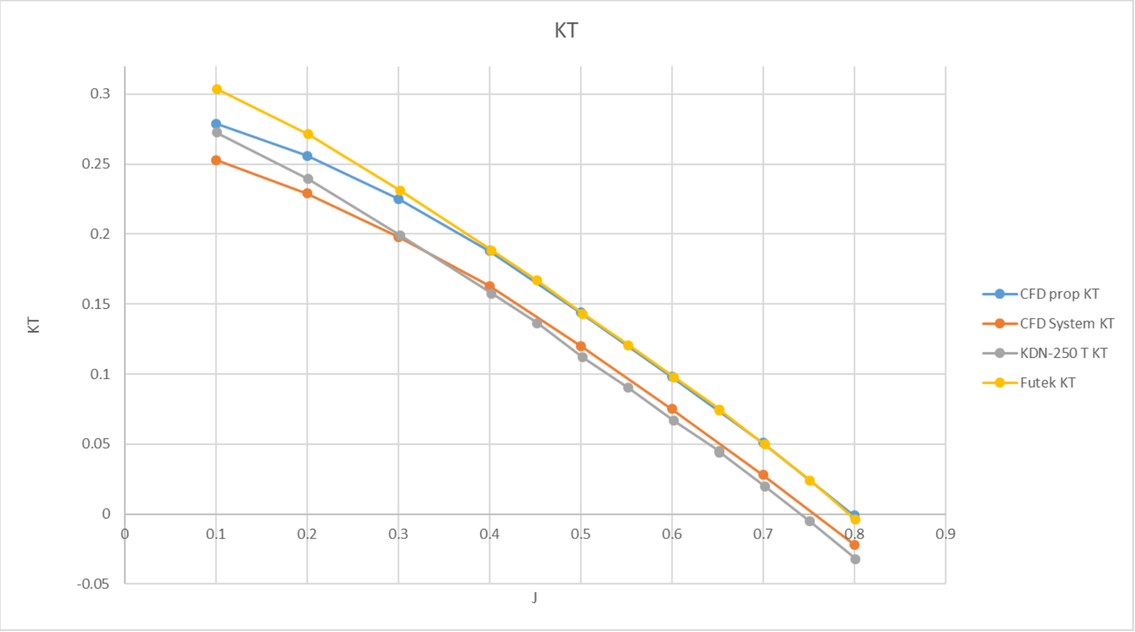


Figure 66 Thrust coefficients from the open water tests. Comparison of measurement results of the different sensors. Additionally, CFD simulation results are shown.

When comparing measurement results and CFD calculations, measurement curves follow each other.

9 DISCUSSION

9.1 Calibration method comparison

The calibration was made in both methods, dynamic and static. As propeller shaft thrust sensor was calibrated, comparison between static and dynamic calibration was also made for KDN-250. In following figures can be seen linear trend lines and trend line equations:

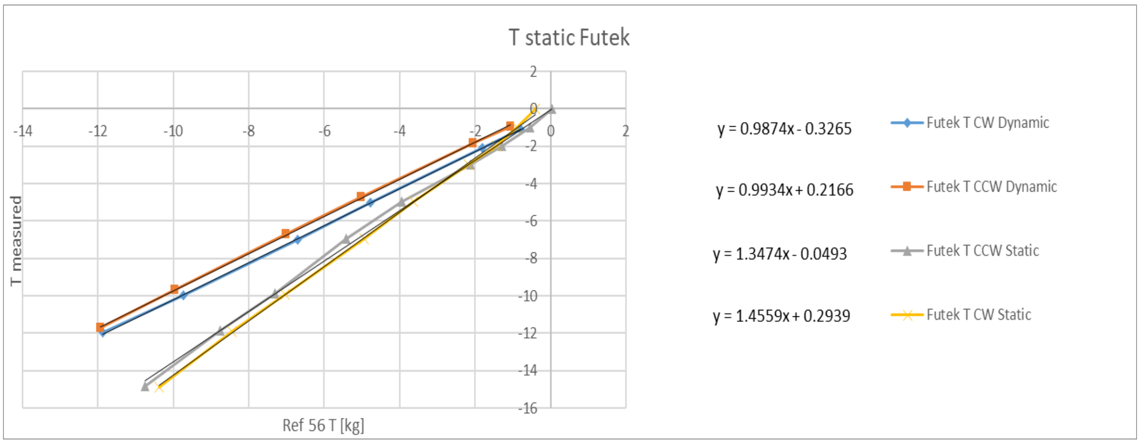


Figure 67 calibration of thrust sensor revision 3.

When looking the propeller shaft thrust sensor calibration curves of propeller shaft measurement sensor at Figure 67, it can been seen that there is significant variation between static and dynamic calibration.

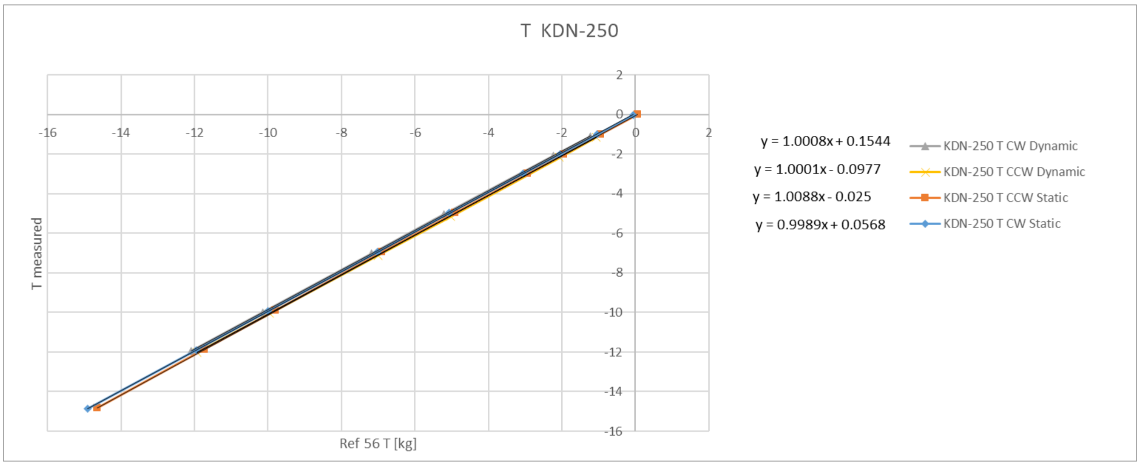


Figure 68 thrust calibration of KDN-250 revision 3.

When same comparison was made in KDN-250 results, can be seen that the variation comes from difference how sensor operates when static or dynamic load is applied.

In following table different calibration values are listed and comparison between static and dynamic calibration multiplier.

Table 5 calibration correction values of revision 3.

			Futek		KDN-250				Note
			T		Q		T		
Cal type	Direction of rotation		a	y_0	a	y_0	a	y_0	
Static	CW		1.4559	0.2939	-0.4252	0.0065	0.9989	0.0568	
Static	CCW		1.3474	-0.0493	-0.4401	0.0092	1.0088	-0.025	
Static	CCW		0.5617	-0.8664			0.9964	-0.1333	Direction 2
Dynamic	CW		0.9874	-0.3265	-0.4567	0.0337	1.0008	0.1544	
Dynamic	CCW		0.9934	0.2166	-0.4562	-0.0006	1.0001	-0.0977	

Futec cal difference T	CW	32 %
	CCW	26 %
KDN-250 cal difference T	CW	0 %
	CCW	1 %
KDN-250 cal difference Q	CW	-7 %
	CCW	-4 %

Following is an example of the reference measurement of the revision 3. In the measurement, thrust load was applied by 5kg weight and test setup is rotated speed of 5.019 RPS. With the slope values from Table 5, following calculation was made by using correction values for static and dynamic calibration:

Table 6 calculation when using static and dynamic correction value of revision 3.

				Futek		KDN-250	
Ref 56 T [k	KDN-250 X [	FUTEK T [kg	R [1/s]	Static	Dynamic	static	Dynamic
-5.051	-5.213	-5.167	5.019	-7.816	-4.775	-5.151	-5.063
				35 %	-6 %	2 %	0 %

It can be seen from Table 6 that propeller thrust sensors calculated value, when static calibration correction was used, differs 35% from reference sensor value. Based on this, assumption that static calibration cannot be used for propeller axis thrust sensor revision

3. Because of this, when analyzing following revision 3 data, there is no comparison between static and dynamic data of propeller axis thrust sensor.

Although from calibration data of KDN-250 can be seen that there is no significant difference between dynamic and static calibration. Based on these results, it was noted that when sensor is located at rotating shaft, there was need to rotate shaft also during calibration. It was also noted that when there is significant difference between dynamic and static calibrations, there might be issue that force was not transmitted without losses to sensor.

When studying cross effect between thrust and torque loads, clear correlation between thrust and torque was not achieved.

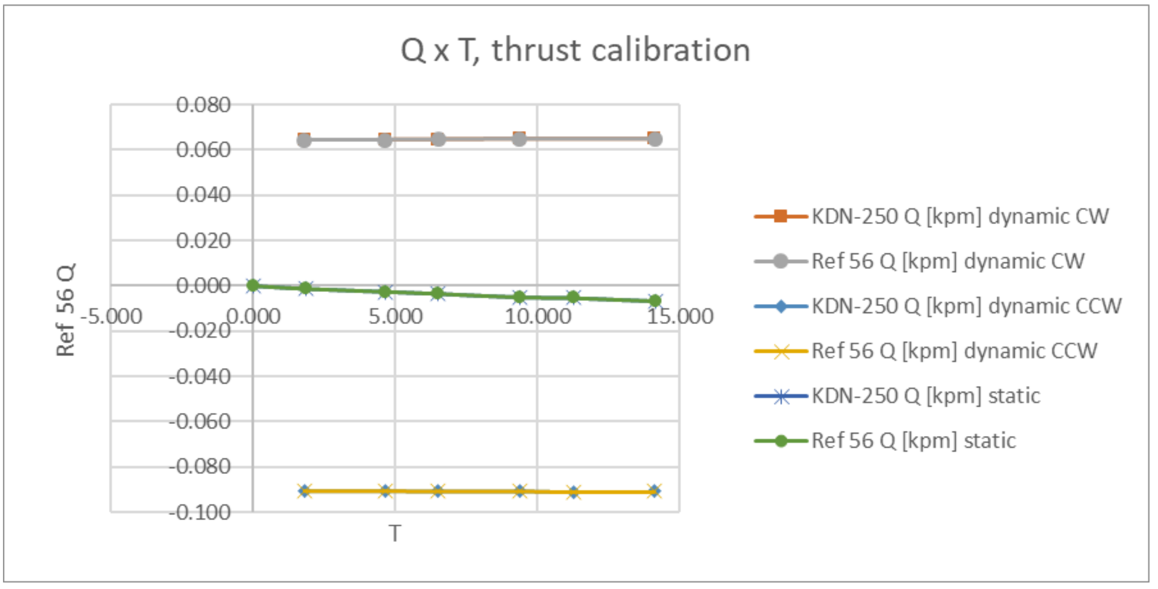


Figure 69 thrust against torque, revision 4 calibration measurements.

Calibration data Figure 69 shows that in calibration measurements there was no significant torque change noted when calibration thrust was applied. Difference in torque level between calibration methods is present because there is no zero level balance done between measurements.

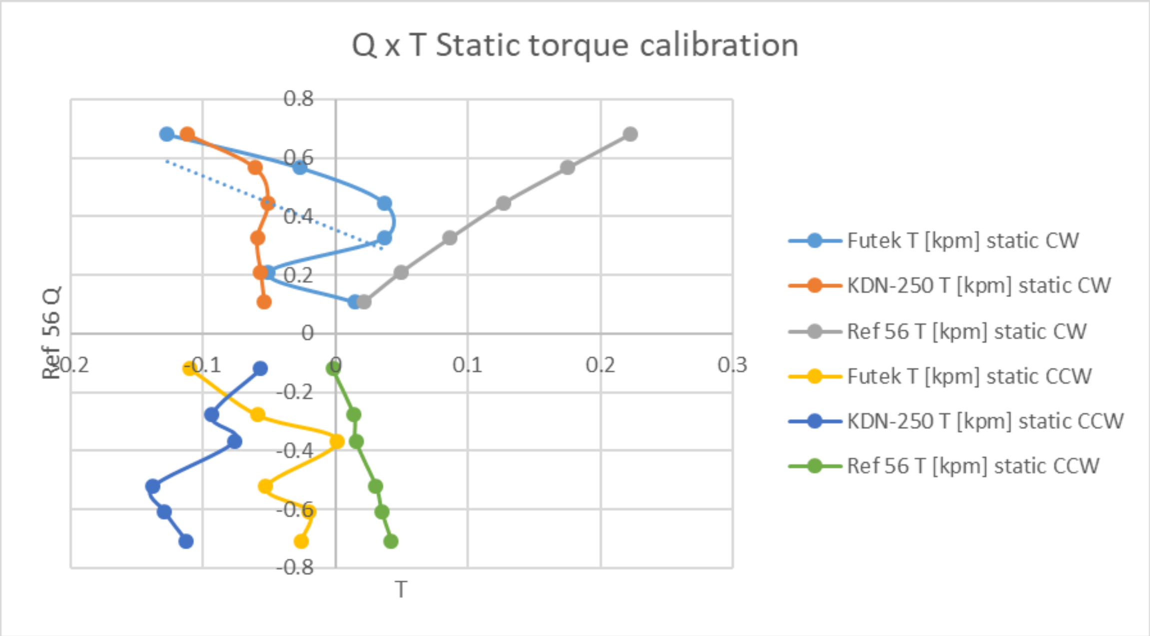


Figure 70 torque against thrust revision 4 calibration measurements.

Situation changes when comparing data at Figure 70. Relation between thrust and torque was seen, but variation in measurement results makes it complicated to perform linear curve fitting based on the data. Especially static measurements of propeller axis thrust sensor do not form a curve that can be easily used as calculation correction. This was the reason that cross effect was not used for analysis, when analyzing measurement test bench data.

At appendix 4 Figure 86 and Figure 87 and shows the same phenomenon measured differently. When applying RPS, changes in thrust and torque were measured. When using result of cross terms of calibration in calculations according chapter 4 , calculation results went off. The measurements made showed that phenomenon exists, but the used method was not suitable and reliable to use.

Figure 71 propeller axis structure.

It was suspected that when propeller torque was applied it caused misalignment between reference sensor and propeller axis sensor. The used structure can be seen at Figure 71. As if misalignment exists, joint between reference sensor and propeller axis thrust sensor causes fluctuating force into propeller axis. This can cause variation that is difficult to calculate. It is anticipated that this kind of effect should not happen, when making open water tests.

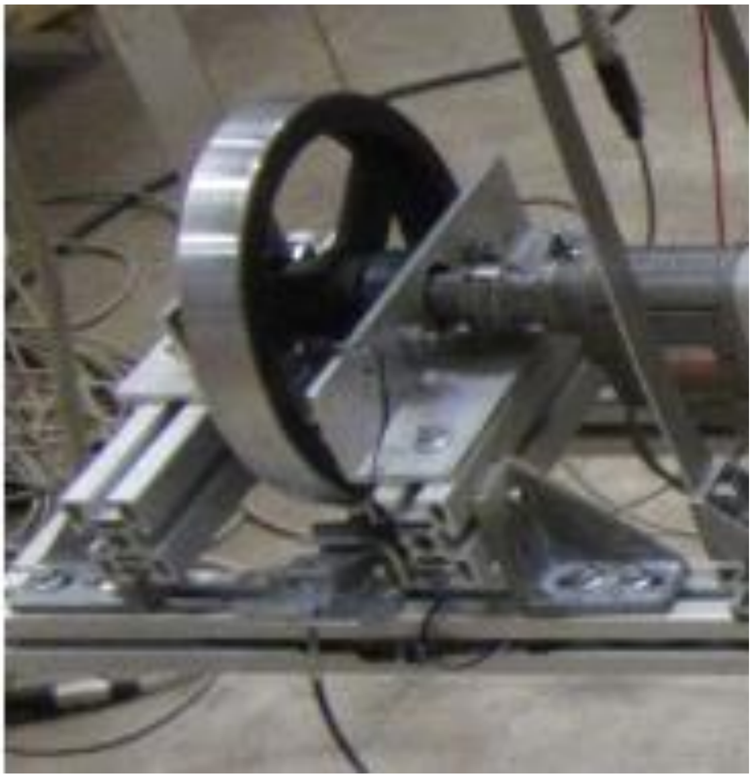


Figure 72 torque load wheel.

Mass of torque load wheel was 5kg. This was also suspected to cause uncertainty into cross reference measurements.

9.2 Preliminary results of revision 1 of thrust sensor

In preliminary test, it was noted right away that load does not remain constant. Gear affected the measured load. As RPS raised, load of measurement sensor raised also. From this, the assumption is that the slide shaft design is not working properly. Two issues became obvious:

- As in paragraph 3.1, Simplified force analysis, was noted that bevel gear structure creates axial forces. As adequate frictionless movement of the slide shaft was not reached, the slide shaft will not fully restrict thrust force from gear side. As movement was not predictable, it was difficult to calibrate and estimate exact load from gear side that affects the load sensor, as there was not noted exact point where sliding mechanism allowed the slide shaft to move. In addition, wear of the connection between the gears shaft and the sliding shaft would probably create

inconstant areas, where sliding would be restricted.

- Slide connection between the slide shaft and the propeller shaft was not adequate to provide needed radial support and axial alignment. This was seen as radial movement of the propeller shaft.

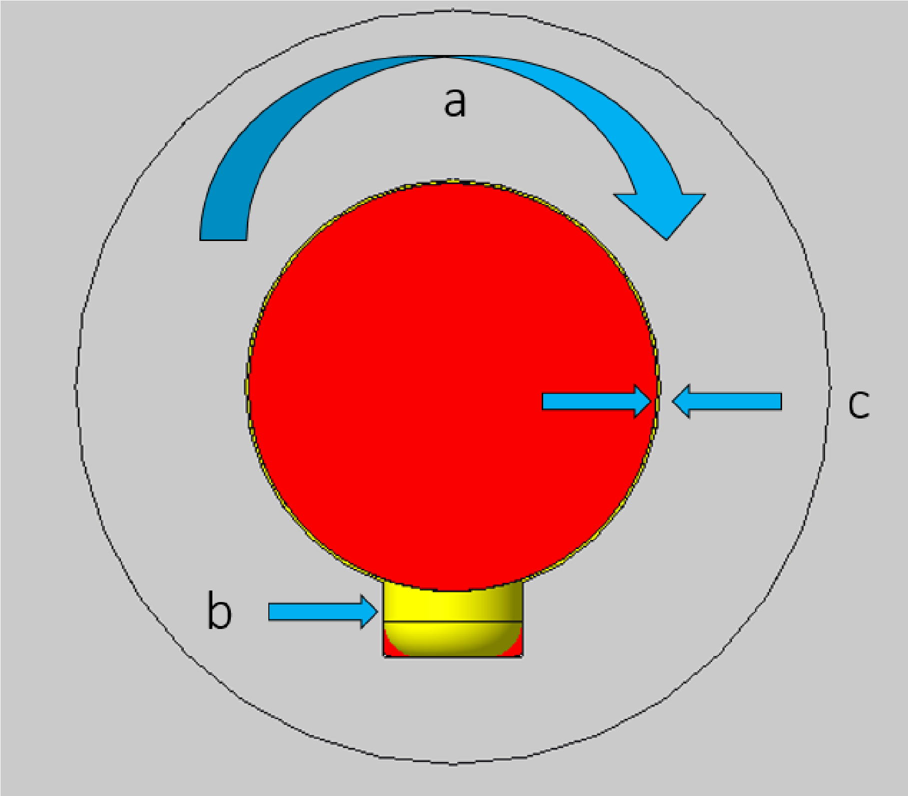


Figure 73 gear shaft and gearbox contact.

Figure 73 shows pin contact. When torque *a* is applied, slider pin contacts with bevel gearbox shaft key groove. This creates torque level arm that presses gear shaft against bevel gearbox shaft. The resulting loads are transferred trough edge b to gear shaft. This contact surface is relatively small. It can be expected that wearing of slider materials is the highest at this point. In addition, it is possible that slider pin, if made of harder material, starts to wear the bevel gearbox shaft also. This would prevent smooth movement of gearbox shaft.

In addition, the linearity of system was noted to be problematic. Coupling length and tolerance between axles did not produce good enough alignment. It could be possible that additional support bearing would be needed.

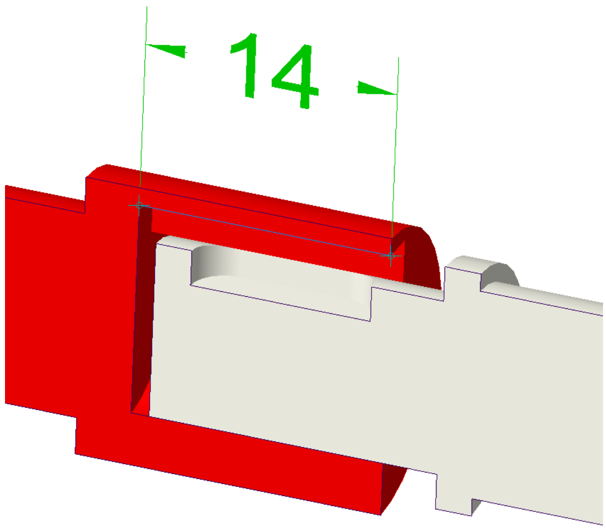


Figure 74 Coupling between gear shaft and propeller shaft.

Because of these issues, without test procedure, revision was changed to revision 2

9.3 Preliminary results of Revision 2 of thrust sensor

It was suspected that difference in measurements could be that sensitivity of FUTEK LTH350 131345 N (3000lb) was not adequate as shown in Selection of the measurement sensor, *3.5.* Because of this, new load cell for thrust sensor was acquired. Tests were run at constant speed and thrust load only. When simple speed tests were made, it was noted that thrust changed as rotation speed changed. Assumption was made that propeller axle movement was not sufficient. Based on these test results, it was decided to continue to revision 3.

9.4 Test bench results of revision 3 of thrust sensor

When measurements of propeller axis thrust sensor revision 3 where made, purpose was to analyze operation of thrust axis propeller sensor and to have understanding about suitability of mechanical structure for measurements. Because of this, reference level, y_0 was not collected frequently. This can cause difference in measured level against reference level. Still, measurement correction multiplier values, a, are comparable in real measurement values.

Calibration data shows that there are significant differences between static and dynamic data in propeller shaft measurement sensor. When comparing measurement data between static and dynamic calibration similar differences can be seen also. As thrust load rises, difference to mean target was more off with static calibration than dynamic calibration. Based on this data, static calibration is not suitable a method for propeller shaft measurement sensor. Based on measurement data, assumption was made that movement of propeller shaft was needed to be less restrict. It was decided to continue to revision 4.

9.5 Test bench results of revision 4 of thrust sensor

Data by propeller axis thrust sensor shows that linearity of sensor has improved. Although some variation did still exist, compared to KDN-250 and 56f reference sensor.

9.6 Open water test results.

Manufactured thrust sensor and 3D printed parts worked as expected in the open water tests.

Pollard pull test showed that propeller, which was made from four separate parts, was capable to produce thrust force of about 200 N.

The present results are in good agreement with the existing measurement system as well as with the CFD calculations.

10 CONCLUSION

Based on the conducted research, following recommendations are presented. To be able to investigate more relations between thrust and torque and to optimize space, it would be better to have custom-made straight teeth bevel gear box. This should give more repeatable result between positive and negative thrust directions when torque is applied. If gearbox body would be round, instead of standard cube, it would give possibility to use space more efficiently. One possibility to eliminate variations in measurement system would be elimination of rotational parts outside of the POD unit. If propulsion motor could be implemented inside propulsion unit, it would eliminate variations that are caused by gearbox. This could be achieved by electric or hydraulic motor directly at propeller shaft. However, this removes current torque measurement system and torque measurement is needed to implement into system.

Uncertainty analysis was not done. To be able to use measurements from propeller axis thrust measurement sensor in measurement report, uncertainty analysis according ITTC recommended procedures (ITTC 7.5-02-03-02.2 2002) is needed.

To be able to test more in test bench, it would be suggested to change test bench structure so that thrust and torque load sources are mechanically attached into propulsion unit allowing only axial movement. This would prevent any bending in measurement alignment. With the used structure, review of thrust and torque cross effect was not accurate enough.

Based on this research, it was not possible to make conclusions about preferred calibration method. It is recommended to use at least some rotation in the system, when measurement sensor is located or connected directly into rotating parts or between solid construction and rotating part. Calibration, regardless of calibration method, should be possible to carry out at towing tank when equipment is installed into measurement structure. Calibration accuracy corresponds to relation between sensor and measurement unit. Mounting the measurement unit into towing carriage or scaled model affects the slope sensitivity.

3D printed propeller and propulsion unit body needs some additional research. Some review of flexibility of propeller blade should be made to be able to analyze the propeller efficiency. Although printed propeller was capable to create sufficient thrust and

withstand torque forces, this shows that there is, at least with some limitations in thickness of the blades, possibility to use 3D printed propellers for ship model tests in a same way as current metal propeller. However, research about the strength of printed propeller should be done.

Based on the present research, measurement of thrust from propeller shaft, by using commercial thrust sensor is possible.

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Sensor pin arrangement and connection into DAQ

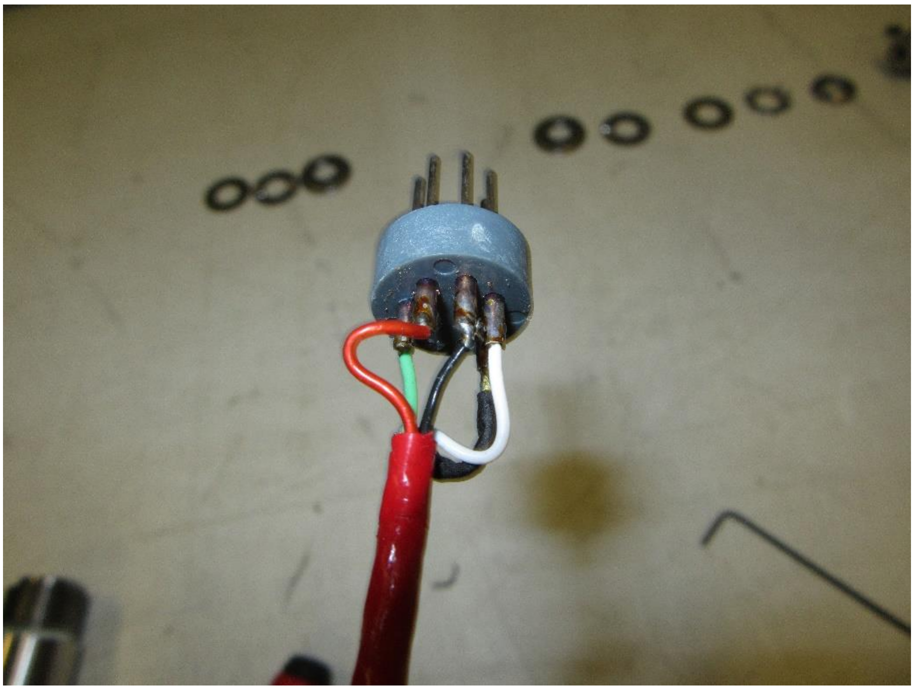


Figure 75 sensor cable soldered into 5-pin connector.

Sensor cable is connected by 5-pin connector.

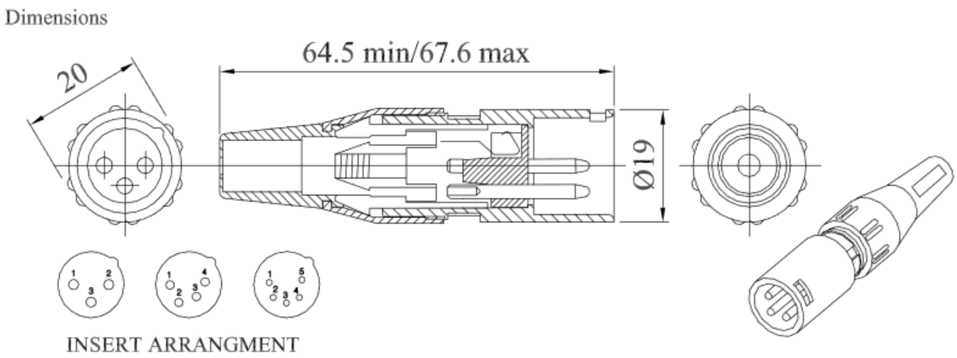
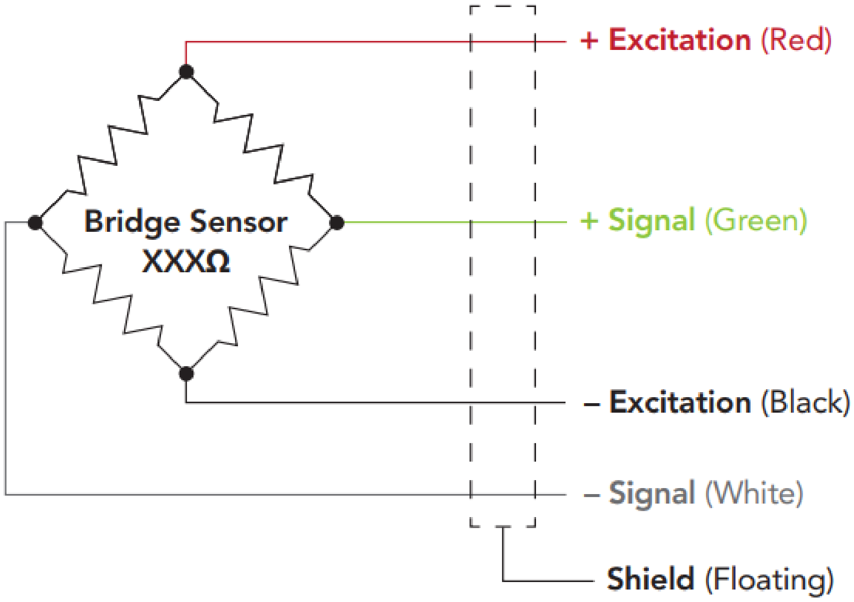


Figure 76 Deltron 7000 series connector (Deltron Components n.d.)

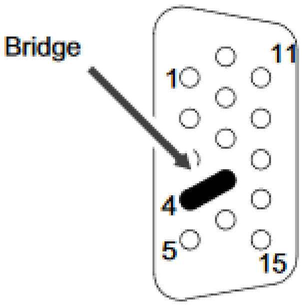
Current connectors are Deltron 7000 series. Compared to common Din 5 connector, from insert arrangement can be seen that arrange of pins are not symmetrical.

At HBM data acquisition unit connector type is 15-pin D sub. As 15 pin D subs are connected all same way, pin assignment for LTH350 is follow:



Signal	Deltron 700 pin
Signal +	1
Excitation +	2
Excitation -	3
Signal -	4
Shield	5

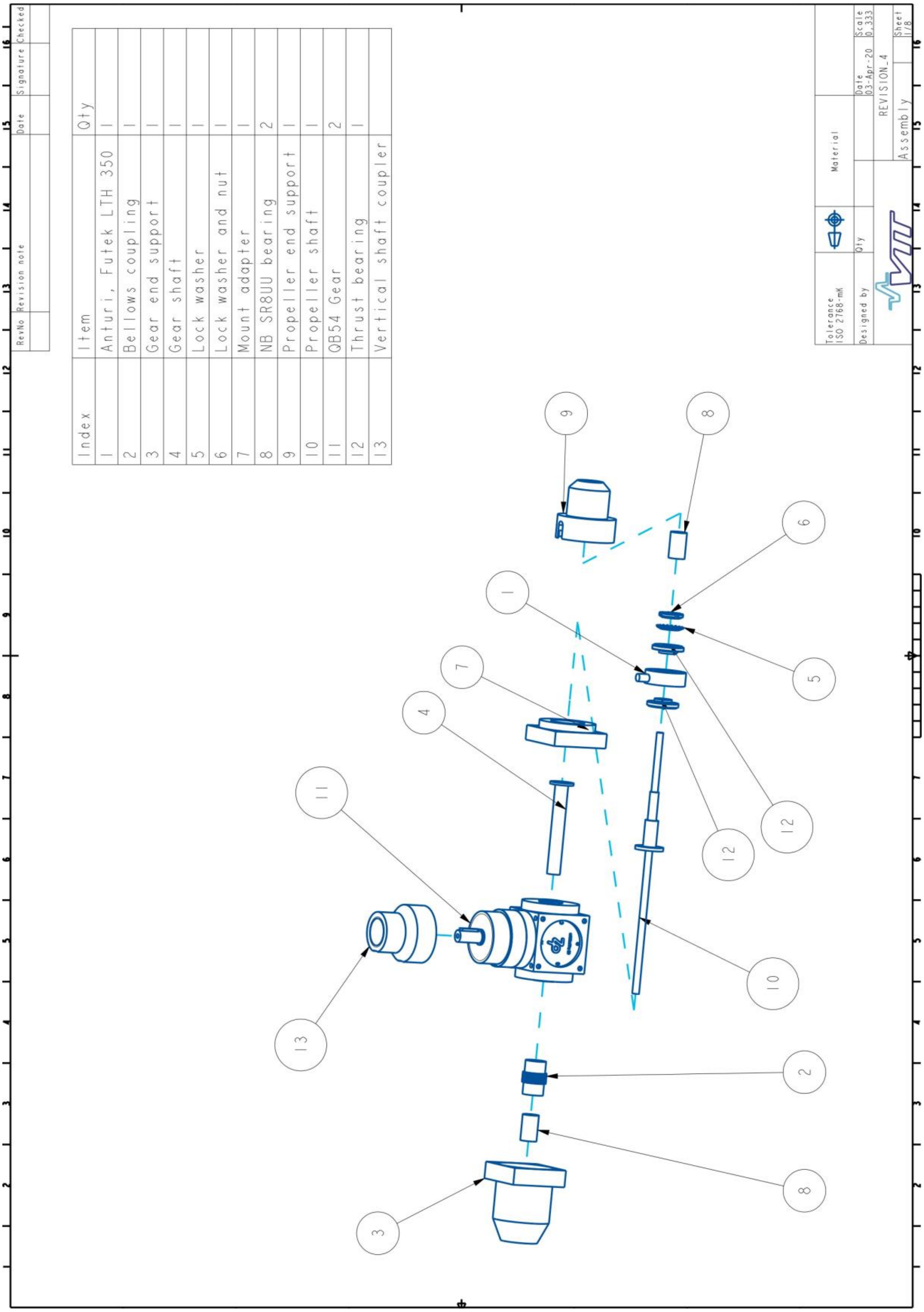
If sensor is connected directly into HBM MX840B data acquisition unit, pin arrangement for DE 15 connector is follow:



Signal	MX840B
Signal +	5
Excitation +	3
Excitation -	2
Signal -	10
Shield	Housing
Pin 4	Pin 9

It should be noted that pin 4 is needed to connect into pin 9. This is for plug-plug in detection and it is needed for data acquisition unit to recognize that plug is connected. In addition, this detection is used to activate saving measurements. Without this connection, data acquisition unit does not save sensors measurements.

DRAWINGS


Index | Item | Qty
1 | Anturi, Futek LTH 350 | 1
2 | Bellows coupling | 1
3 | Gear end support | 1
4 | Gear shaft | 1
5 | Lock washer | 1
6 | Lock washer and nut | 1
7 | Mount adapter | 1
8 | NB SR8UU bearing | 2
9 | Propeller end support | 1
10 | Propeller shaft | 1
11 | QB54 Gear | 2
12 | Thrust bearing | 1
13 | Vertical shaft coupler | 1
RevNo
Revision note
Date
Signature
Checked
Tolerance
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Designed by
Qty
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Date
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Assembly
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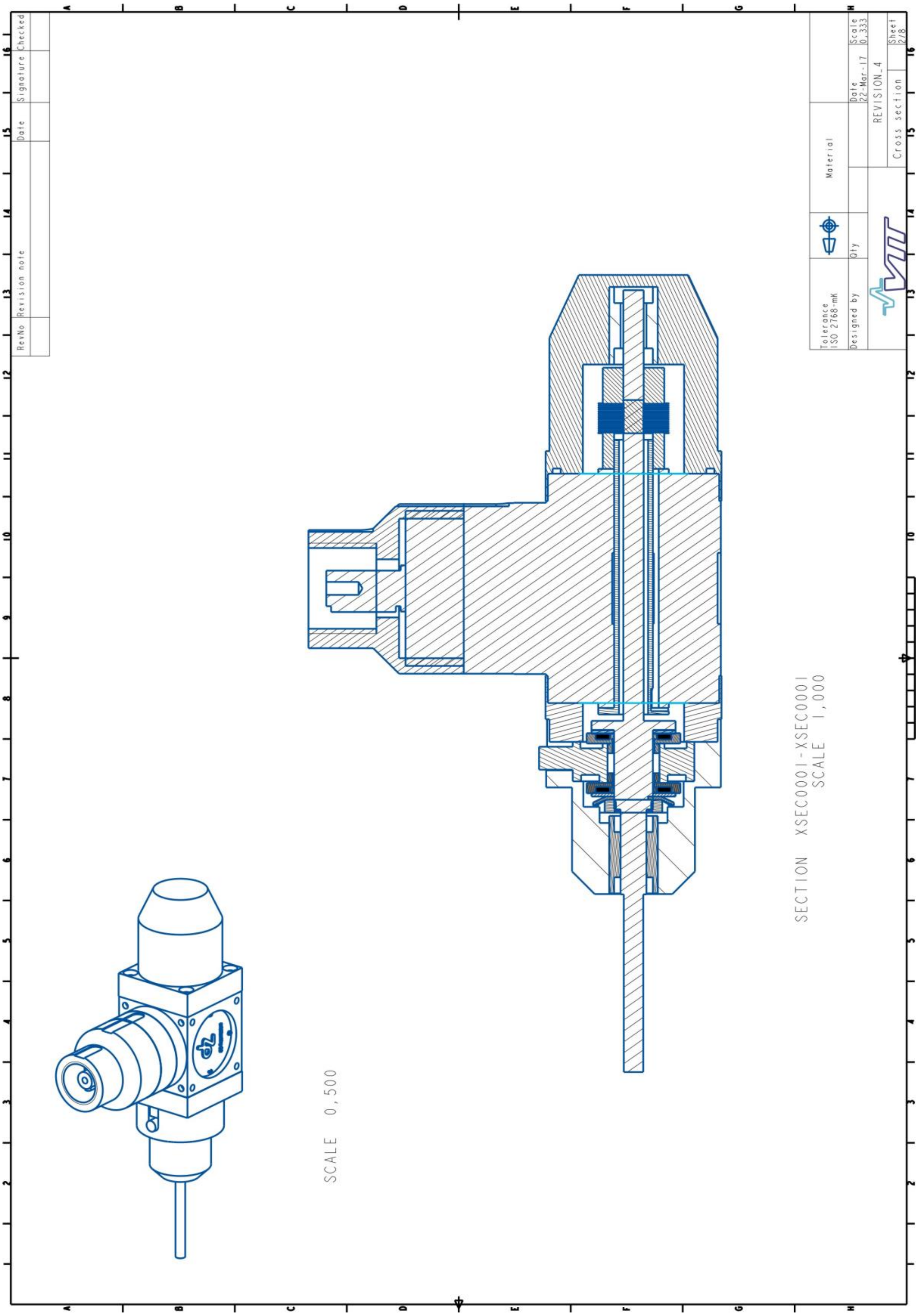
1/8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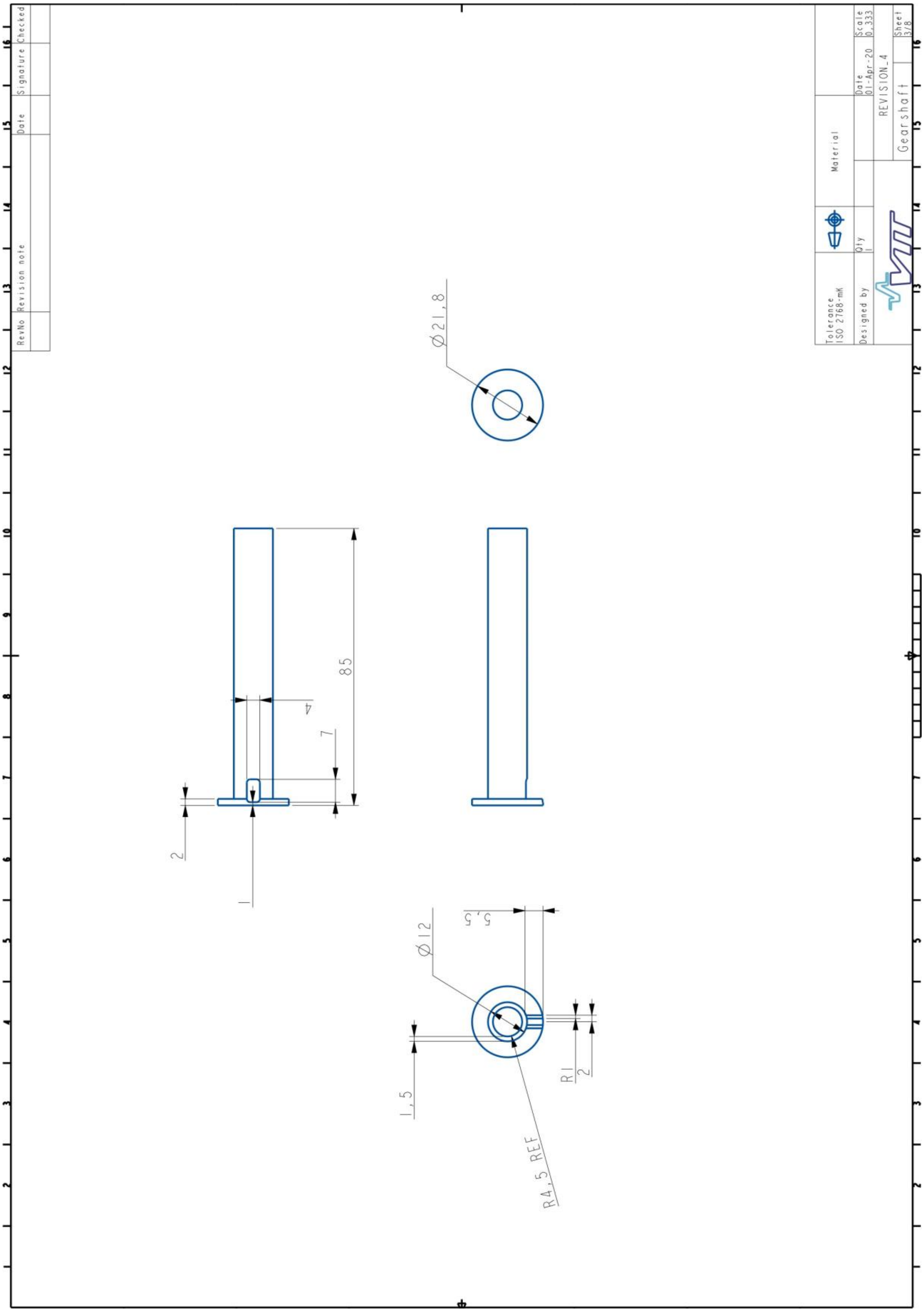
SCALE 0,500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Date
Signature
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Tolerance
ISO 2768-mK
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Qty
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Material
Date
01-Apr-20
Scale
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REVISION_4
Gearshaft
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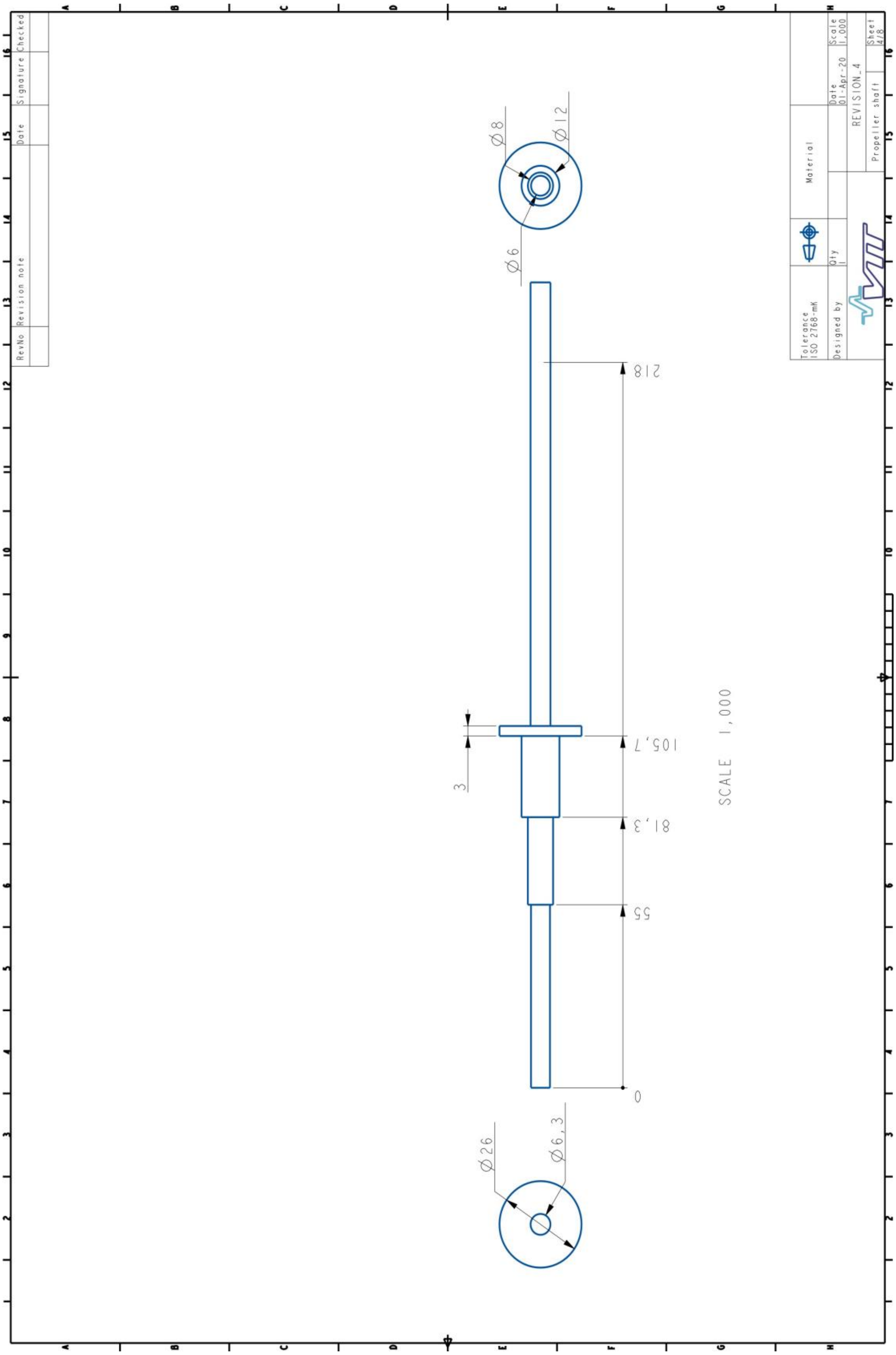
85
4
7
2
1
Ø12
5,5
1,5
R1
2
R4,5 REF



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Signature
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Tolerance
ISO 2768-mK
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Material
Date
01-Apr-20
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Propeller shaft
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Ø6
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Ø26
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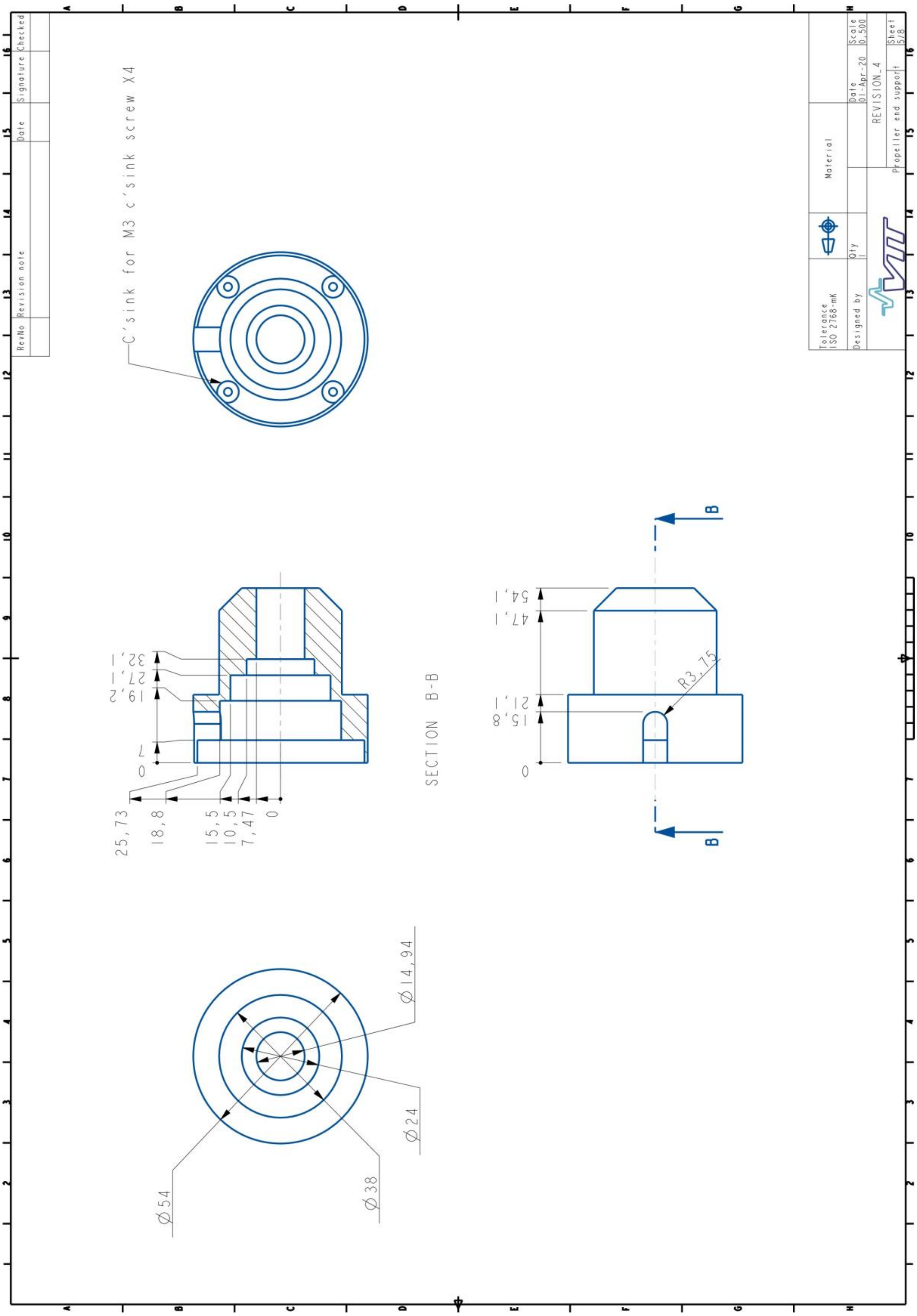
C'sink for M3 c'sink screw X4
SECTION B-B
Tolerance ISO 2768-mK
Designed by
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Material
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Propeller end support
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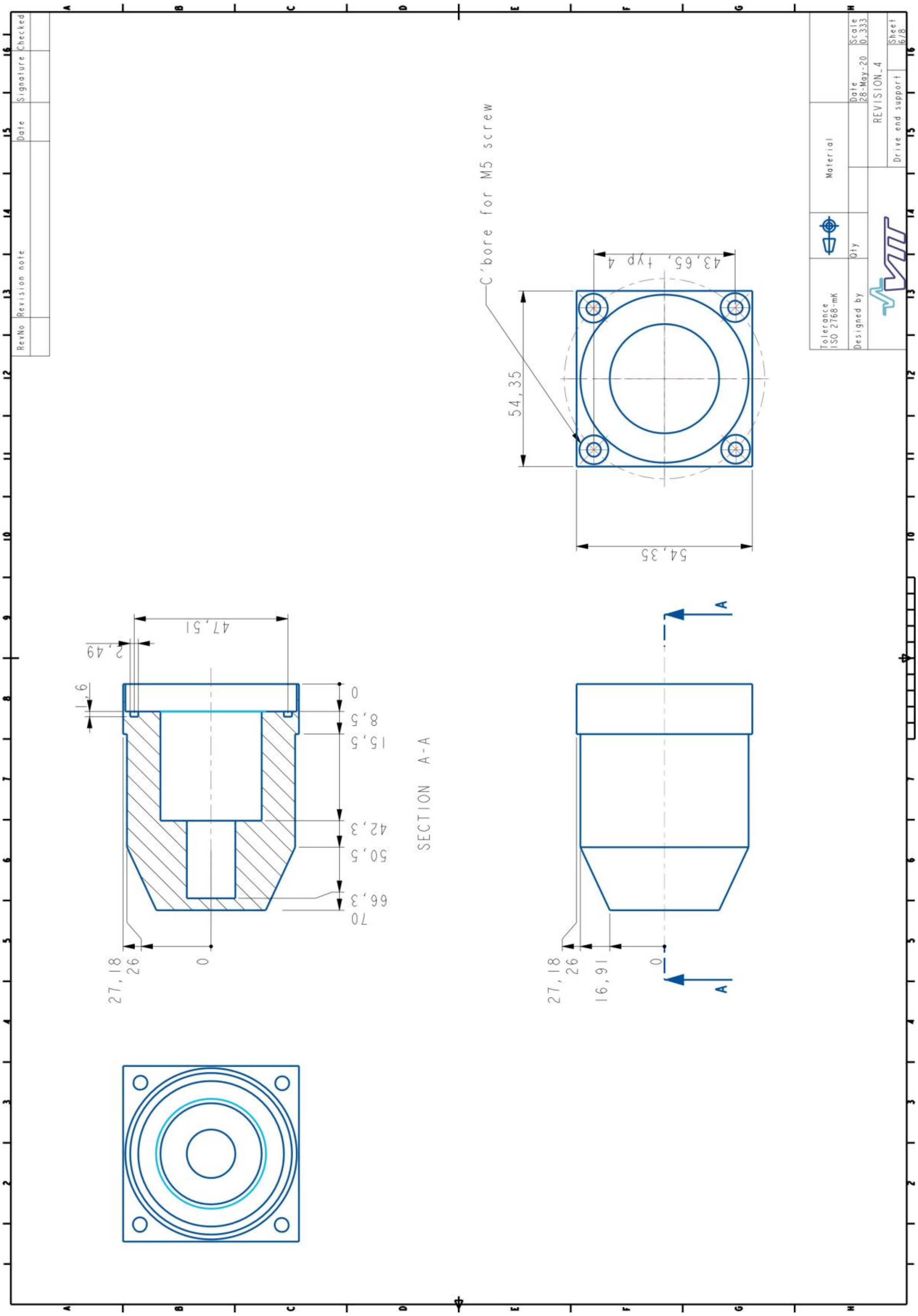
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C'bore for M5 screw
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42,3
50,5
66,3
70
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Drive end support
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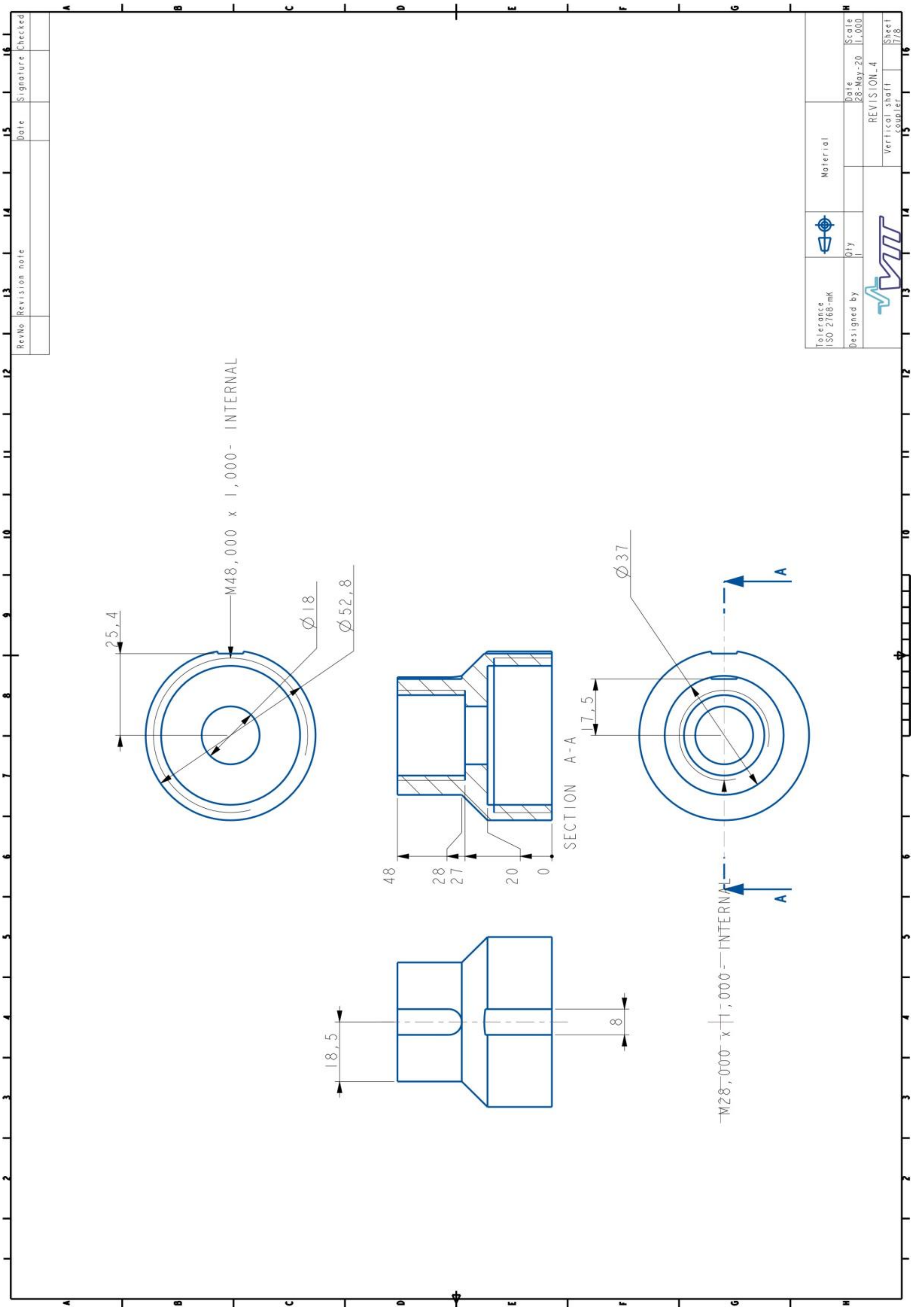

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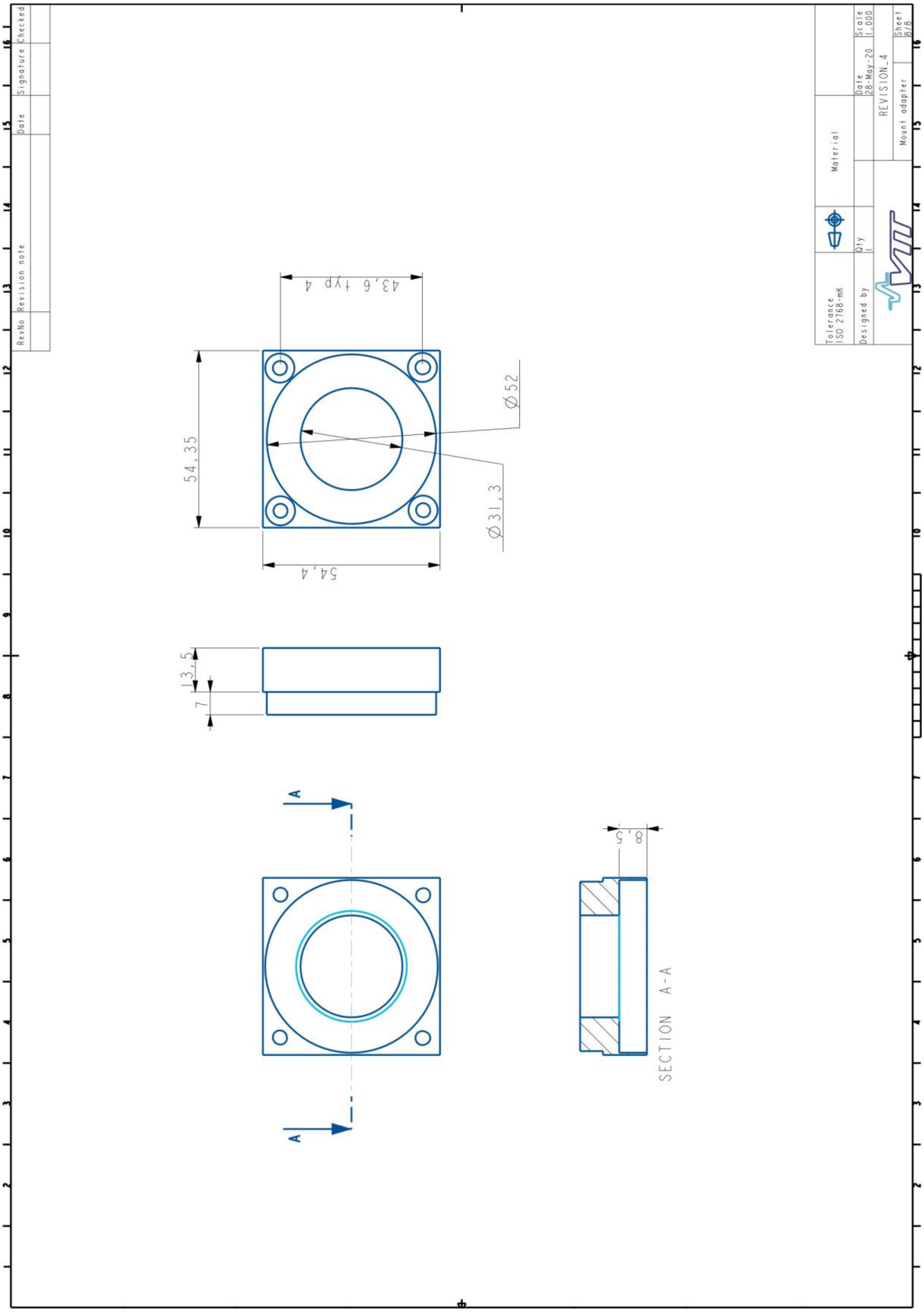
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Mount adapter
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43,6 typ 4
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Ø31,3
54,35
54,4
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7
8,5
A
A
SECTION A-A

Revision 3 measure bench measurement data

Static calibration								
Ref 56 T [kg]	Ref 56 Q [kpm]	KDN-250 T [kg]	KDN-250 Q [kpm]	FUTEK työntö [kg]	kierros [1/s]	Measurement	Comment 1	Comment 2
-0.007	0.072	-0.131	-0.157	0.029	1.000	Cal	CCW RPS	60
0.041	0.264	-0.409	-0.614	-0.451	6.171	Cal	CCW RPS	470
0.037	0.239	-0.377	-0.558	-0.426	5.032	Cal	CCW RPS	380
0.010	0.209	-0.393	-0.492	-0.087	4.054	Cal	CCW RPS	300
-0.009	0.171	-0.372	-0.405	-0.145	3.021	Cal	CCW RPS	220
-0.034	0.126	-0.338	-0.299	-0.196	2.014	Cal	CCW RPS	140
-0.050	0.074	-0.179	-0.173	-0.098	1.000	Cal	CCW RPS	60
16.084	-0.198	15.885	0.475	8.282	0.000	Cal	CW T suunta 2	15
13.040	-0.197	12.867	0.476	6.417	0.000	Cal	CW T suunta 2	12
11.017	-0.197	10.839	0.476	5.521	0.000	Cal	CW T suunta 2	10
8.057	-0.196	7.908	0.475	3.229	0.000	Cal	CW T suunta 2	7
6.068	-0.197	5.921	0.475	2.367	0.000	Cal	CW T suunta 2	5
3.068	-0.198	2.910	0.477	1.188	0.000	Cal	CW T suunta 2	4
-14.862	-0.055	-14.916	0.161	-10.367	0.000	Cal	CW T	15
-11.897	-0.054	-11.959	0.161	-8.456	0.000	Cal	CW T	12
-9.918	-0.053	-9.992	0.160	-7.033	0.000	Cal	CW T	10
-6.947	-0.053	-7.027	0.160	-4.945	0.000	Cal	CW T	7
-4.965	-0.053	-5.066	0.160	-3.630	0.000	Cal	CW T	5
-2.992	-0.052	-3.065	0.160	-2.189	0.000	Cal	CW T	2
-2.007	-0.052	-2.055	0.159	-1.428	0.000	Cal	CW T	2
-1.014	-0.051	-1.053	0.160	-0.887	0.000	Cal	CW T	1
-0.012	-0.051	-0.051	0.160	-0.395	0.000	Cal	CW T	0
-14.836	0.094	-14.653	-0.190	-10.751	0.000	Cal	CCW T	15
-11.861	0.093	-11.735	-0.190	-8.764	0.000	Cal	CCW T	12
-9.893	0.092	-9.792	-0.189	-7.308	0.000	Cal	CCW T	10
-6.940	0.091	-6.890	-0.187	-5.421	0.000	Cal	CCW T	7
-4.970	0.091	-4.916	-0.186	-3.950	0.000	Cal	CCW T	5
-2.984	0.091	-2.930	-0.185	-2.109	0.000	Cal	CCW T	3
-1.996	0.090	-1.947	-0.184	-1.289	0.000	Cal	CCW T	2
-0.991	0.085	-0.951	-0.175	-0.537	0.000	Cal	CCW T	1
0.008	0.084	0.051	-0.175	0.037	0.000	Cal	CCW T	0
-0.003	0.029	-0.011	-0.018	0.031	0.000	Cal	CCW Q	0
0.067	0.441	0.244	-0.988	0.051	0.000	Cal	CCW Q	2
0.052	0.346	0.209	-0.750	-0.008	0.000	Cal	CCW Q	1.5
0.036	0.227	0.159	-0.499	0.018	0.000	Cal	CCW Q	0.5
0.017	0.113	0.070	-0.250	0.084	0.000	Cal	CCW Q	0.5
0.005	0.019	-0.014	-0.015	0.143	0.000	Cal	CCW Q	0
-0.094	-0.418	-0.003	0.984	0.150	0.000	Cal	CW Q	2
-0.072	-0.303	0.009	0.735	0.088	0.000	Cal	CW Q	1.5
-0.055	-0.193	0.018	0.483	0.044	0.000	Cal	CW Q	1
-0.024	-0.090	0.002	0.234	0.068	0.000	Cal	CW Q	0.5
-0.009	0.000	0.004	0.001	0.050	0.000	Cal	CW Q	0

Dynamic calibration								
Ref 56 T [kg]	Ref 56 Q [kpm]	KDN-250 T [kg]	KDN-250 Q [kpm]	FUTEK T [kg]	R [1/s]	Measurement	Comment 1	Comment 2
-0.232414067	-0.286271067	-0.413899267	0.727460833	-0.032146753	12.06913	Cal	CW	12
-0.2138591	-0.2740507	-0.453437267	0.6932538	-0.2614995	9.909987333	Cal	CW	12
-0.211368233	-0.234317833	-0.4265395	0.5985143	-0.054967673	7.026460667	Cal	CW	12
-0.212268697	-0.187693033	-0.415154333	0.4936805	-0.032164323	5.014621333	Cal	CW	12
-0.196551624	-0.123311204	-0.397964355	0.349617206	0.055215415	3.010764922	Cal	CW	12
-11.96082361	-0.039254488	-12.09273758	0.162049283	-11.86856952	1.016204835	Cal	CW	12
-9.987449	-0.03895329	-10.13338667	0.161142267	-9.723461333	1.0142697	Cal	CW	10
-7.022580527	-0.03882929	-7.17822074	0.159915172	-6.698512171	1.022346282	Cal	CW	7
-5.036851333	-0.03857522	-5.214087333	0.159556667	-4.778528333	1.008532767	Cal	CW	5
-2.068614	-0.03848245	-2.228187667	0.158615267	-1.806348667	1.003479733	Cal	CW	2
-1.093358667	-0.038163473	-1.220860667	0.159245167	-0.783596567	1.010046067	Cal	CW	1
-0.225301443	-0.1908093	-0.364075677	0.491703033	-0.019734087	0.950290367	Cal	CW	Q level 9
-0.215187867	-0.1394355	-0.357205267	0.379223367	0.06435898	0.973955833	Cal	CW	Q level 7
-0.213108436	-0.10195067	-0.344236812	0.29685025	0.118848356	0.987926576	Cal	CW	Q level 5
-0.210420874	-0.06977949	-0.318419773	0.225748683	0.164506425	0.999634345	Cal	CW	Q level 3
-0.206956433	-0.042481917	-0.2964578	0.166894133	0.201682997	1.006348267	Cal	CW	Q level 1
-0.200109233	-0.039861543	-0.3451643	0.161641733	0.074016237	1.006956967	Cal	CW	Q level 0
-11.96082361	-0.039254488	-12.09273758	0.162049283	-11.86856952	1.016204835	Cal	CW	12
-9.987449	-0.03895329	-10.13338667	0.161142267	-9.723461333	1.0142697	Cal	CW	10
-7.022580527	-0.03882929	-7.17822074	0.159915172	-6.698512171	1.022346282	Cal	CW	7
-5.036851333	-0.03857522	-5.214087333	0.159556667	-4.778528333	1.008532767	Cal	CW	5
-2.068614	-0.03848245	-2.228187667	0.158615267	-1.806348667	1.003479733	Cal	CW	2
-1.093358667	-0.038163473	-1.220860667	0.159245167	-0.783596567	1.010046067	Cal	CW	1
-11.93555852	0.064478896	-12.0227009	-0.146836279	-11.717986	1.00409093	Cal	CCW	12
-9.956142667	0.064168927	-10.05346933	-0.145620167	-9.653565333	1.003542	Cal	CCW	10
-7.007566667	0.063933863	-7.111174	-0.143664533	-6.677831333	1.0071738	Cal	CCW	7
-5.033051333	0.06356344	-5.156796667	-0.142348933	-4.718309	1.009696533	Cal	CCW	5
-2.063918333	0.063529567	-2.169640333	-0.142133667	-1.820744333	1.008286667	Cal	CCW	2
-1.064280233	0.06348668	-1.136617133	-0.14173811	-0.927529633	1.0058274	Cal	CCW	1
-0.130588823	0.200825933	-0.36649663	-0.4407537	-0.02088596	0.964014833	Cal	CCW	Q
-0.136606303	0.1570488	-0.37053186	-0.344779233	-0.002788557	0.971422467	Cal	CCW	Q
-0.139856787	0.122001333	-0.35291788	-0.269912367	-0.00073927	0.982246067	Cal	CCW	Q
-0.149092277	0.091052483	-0.295114057	-0.2031179	0.00169169	1.005177467	Cal	CCW	Q
-0.148573827	0.076293593	-0.27453483	-0.170717267	0.016759787	1.008287333	Cal	CCW	Q
-0.152795163	0.064812597	-0.250313397	-0.143759	0.002548093	1.000554167	Cal	CCW	Q
-0.11649784	0.06352766	-0.27216462	-0.135974843	0.082935637	1.015233033	Cal	CCW	Q

CCW measurements							
Ref 56 T [k	Ref 56 Q [I	KDN-250 T	KDN-250 C	FUTEK T [k	RPS [1/s]	Measuren	Comment 1
-6.903	0.426	-7.057	-0.966	-8.083	12.038	Mittaus	CCW
-4.948	0.427	-5.127	-0.971	-5.826	12.041	Mittaus	CCW
-6.927	0.295	-7.055	-0.690	-7.724	12.061	Mittaus	CCW
-4.963	0.293	-5.131	-0.688	-5.561	12.061	Mittaus	CCW
-6.849	0.544	-7.055	-1.231	-8.569	9.851	Mittaus	CCW
-4.894	0.539	-5.113	-1.217	-6.283	9.857	Mittaus	CCW
-6.897	0.397	-7.054	-0.908	-7.845	8.635	Mittaus	CCW
-4.918	0.418	-5.091	-0.953	-5.856	9.880	Mittaus	CCW
-6.919	0.287	-7.054	-0.663	-7.827	9.904	Mittaus	CCW
-4.953	0.288	-5.083	-0.664	-5.506	9.907	Mittaus	CCW
-6.852	0.507	-7.039	-1.140	-8.306	6.984	Mittaus	CCW
-4.885	0.512	-5.084	-1.149	-6.002	6.982	Mittaus	CCW
-7.007	0.385	-7.182	-0.871	-7.862	7.006	Mittaus	CCW
-5.035	0.387	-5.202	-0.870	-5.572	6.987	Mittaus	CCW
-7.029	0.264	-7.181	-0.608	-7.486	7.020	Mittaus	CCW
-5.062	0.265	-5.228	-0.609	-5.264	7.020	Mittaus	CCW
-6.988	0.453	-7.184	-1.018	-7.778	4.986	Mittaus	CCW
-5.016	0.456	-5.213	-1.024	-5.768	4.954	Mittaus	CCW
-7.011	0.338	-7.174	-0.769	-7.289	4.996	Mittaus	CCW
-5.046	0.341	-5.230	-0.773	-5.465	4.992	Mittaus	CCW
-7.025	0.230	-7.174	-0.534	-6.817	5.027	Mittaus	CCW
-5.051	0.231	-5.213	-0.538	-5.167	5.019	Mittaus	CCW
-6.984	0.443	-7.187	-0.993	-7.683	2.978	Mittaus	CCW
-5.011	0.446	-5.218	-1.000	-5.610	2.969	Mittaus	CCW
-7.005	0.346	-7.181	-0.782	-7.570	2.993	Mittaus	CCW
-5.056	0.250	-5.229	-0.574	-5.162	3.000	Mittaus	CCW
-7.037	0.170	-7.167	-0.401	-7.051	3.022	Mittaus	CCW
-5.065	0.170	-5.199	-0.402	-4.964	3.026	Mittaus	CCW
-2.096	0.171	-2.328	-0.403	-2.096	3.013	Mittaus	CCW
-7.019	0.232	-7.197	-0.514	-7.118	0.934	Mittaus	CCW
-5.054	0.232	-5.248	-0.512	-5.081	0.945	Mittaus	CCW
-2.085	0.231	-2.333	-0.511	-2.194	0.945	Mittaus	CCW
-7.032	0.180	-7.197	-0.400	-6.999	0.952	Mittaus	CCW
-5.056	0.180	-5.232	-0.397	-4.978	0.967	Mittaus	CCW
-2.096	0.180	-2.285	-0.398	-2.116	0.962	Mittaus	CCW
-7.032	0.139	-7.190	-0.311	-6.981	0.976	Mittaus	CCW
-5.059	0.140	-5.208	-0.313	-4.963	0.977	Mittaus	CCW
-2.107	0.139	-2.272	-0.311	-2.044	0.995	Mittaus	CCW
-7.047	0.104	-7.138	-0.235	-6.881	0.986	Mittaus	CCW
-5.073	0.104	-5.212	-0.235	-4.838	0.986	Mittaus	CCW
-2.099	0.104	-2.263	-0.236	-1.934	0.984	Mittaus	CCW
-7.040	0.073	-7.120	-0.168	-6.826	0.996	Mittaus	CCW
-5.073	0.073	-5.141	-0.173	-4.807	0.993	Mittaus	CCW

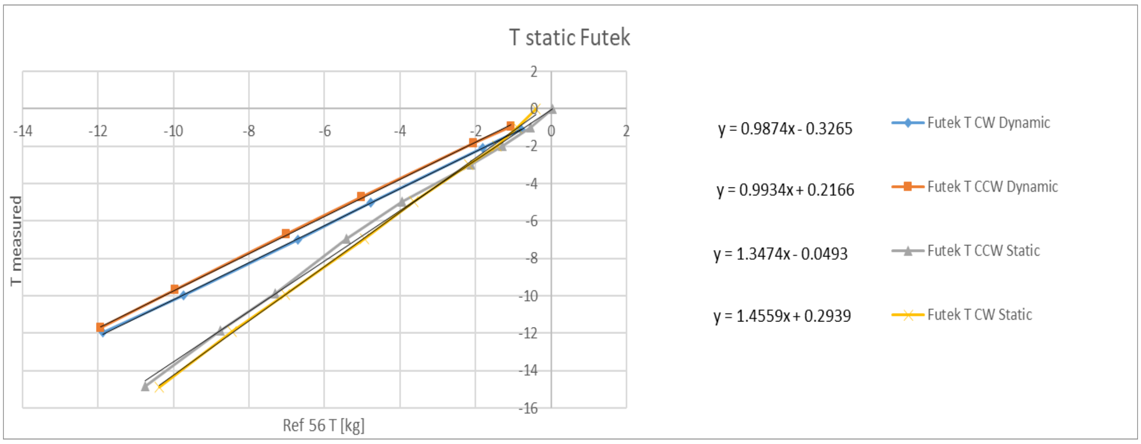

Figure 77 Calibration of thrust sensor revision 3.

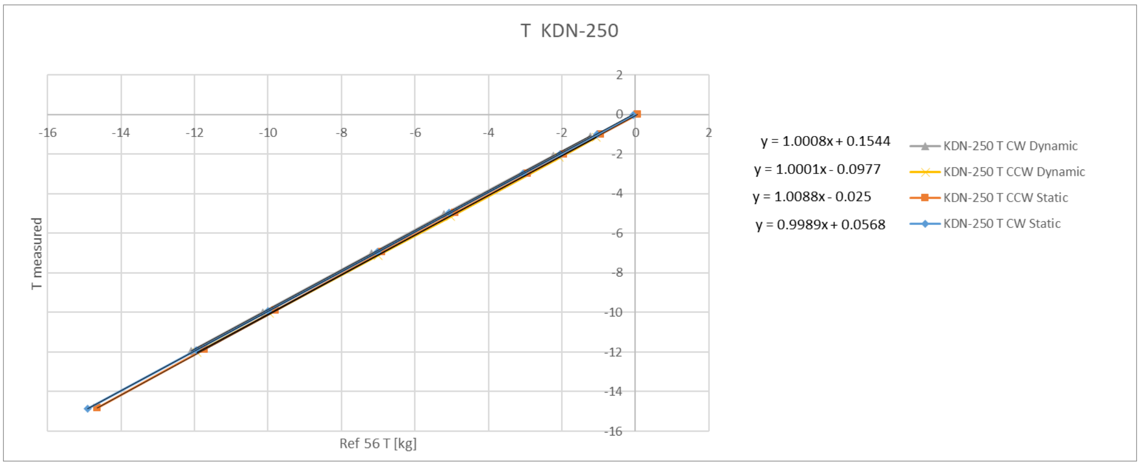

Figure 78 Calibration of KDN-250 with revision 3.

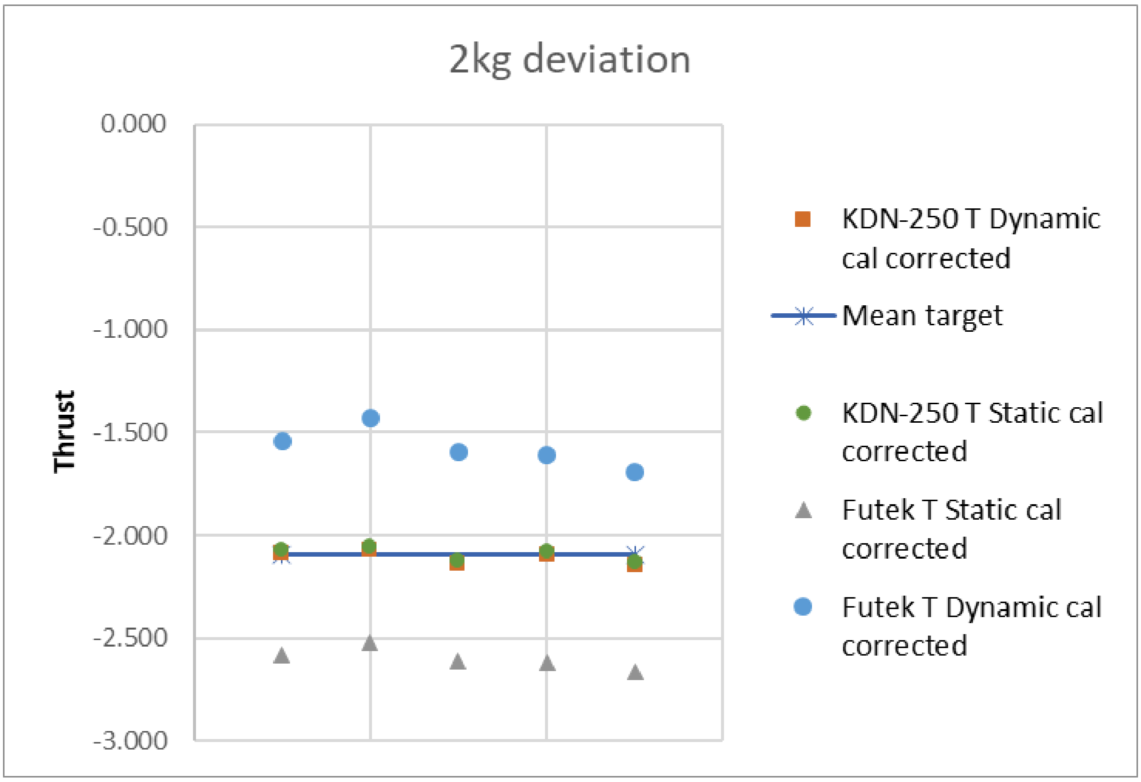

Figure 79 thrust load measurement, 2kg calibration weight as load, CCW direction.

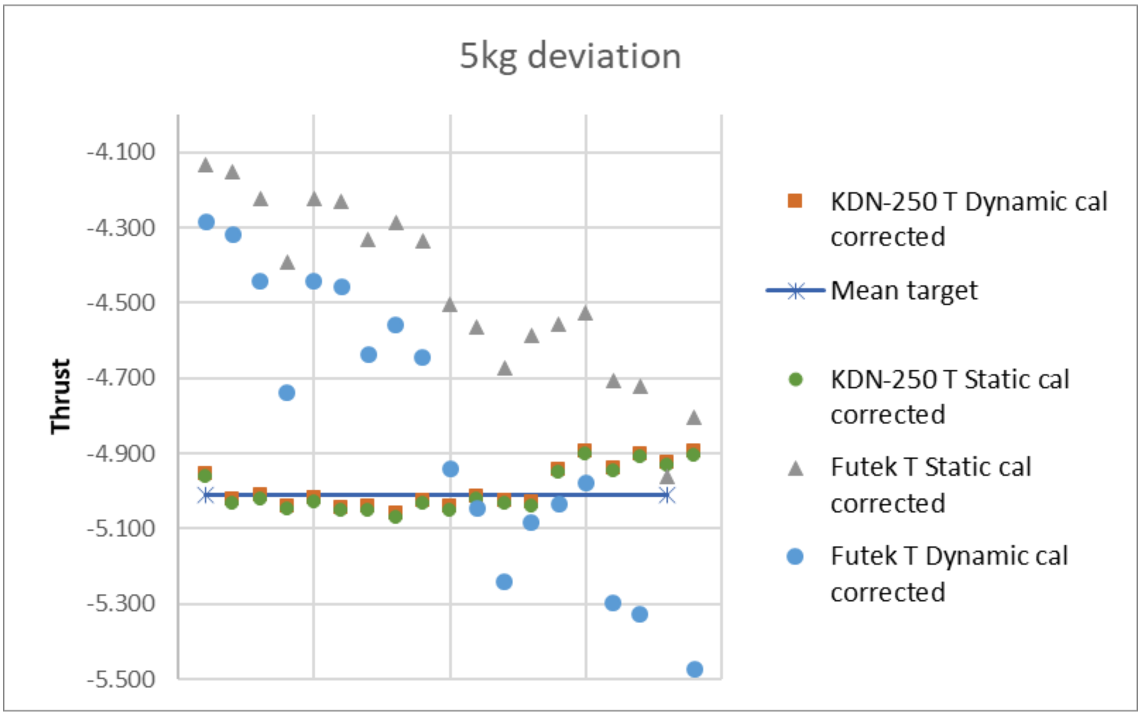

Figure 80 thrust load measurement, 5kg calibration weight as load, CCW direction.

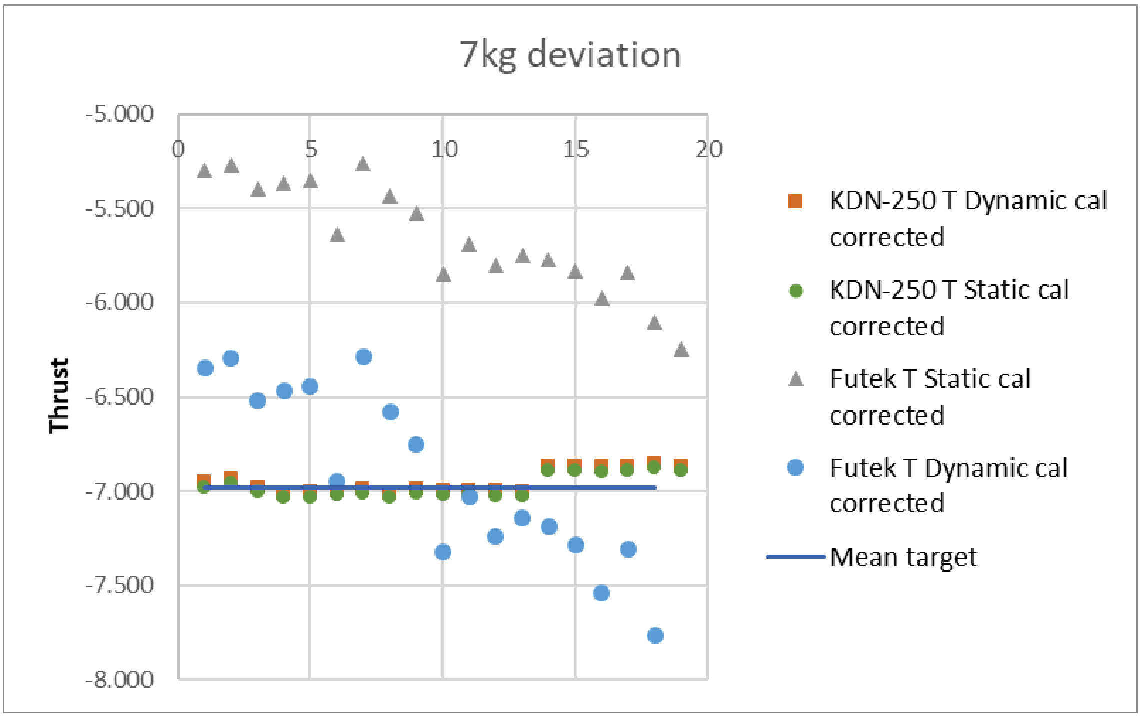

Figure 81, thrust load measurement 7kg calibration weight as load, CCW direction.

Revision 4 measure bench measurement data

Dynamic calibration								
Ref 56 T [kg	ef 56 Q [kp	DN-250 T [k	N-250 Q [k	FUTEK T [kg	RPS	Measurement	Comment	Comment
14.105	-0.091	14.455	-0.095	15.254	0.994	Cal	T CCW	15
11.266	-0.091	11.571	-0.094	12.078	0.995	Cal	T CCW	12
9.359	-0.091	9.635	-0.093	10.015	0.998	Cal	T CCW	10
6.499	-0.091	6.720	-0.093	6.965	0.995	Cal	T CCW	7
4.633	-0.091	4.832	-0.093	4.885	0.996	Cal	T CCW	5
1.798	-0.091	1.946	-0.094	1.930	0.994	Cal	T CCW	2
Ref 56 T [kg	ef 56 Q [kp	DN-250 T [k	N-250 Q [k	FUTEK T [kg	RPS	Measurement	Comment	Comment
14.118	0.065	14.408	0.117	15.198	0.994	Cal	T CW	15
9.365	0.065	9.583	0.115	9.942	0.993	Cal	T CW	10
6.503	0.065	6.684	0.115	6.957	0.993	Cal	T CW	7
4.639	0.064	4.794	0.114	4.861	0.993	Cal	T CW	5
1.809	0.064	1.910	0.115	1.893	0.998	Cal	T CW	2
Ref 56 T [kg	ef 56 Q [kp	DN-250 T [k	N-250 Q [k	FUTEK T [kg	RPS	Measurement	Comment	Comment
-0.086	-0.237	0.067	-0.247	-0.107	0.935	Cal	Q CCW	7
-0.094	-0.203	0.051	-0.213	-0.094	0.949	Cal	Q CCW	6
-0.099827	-0.17627	0.036564	-0.18488	-0.1047939	0.965956	Cal	Q CCW	5
-0.098	-0.15494	0.031	-0.16256	-0.1159169	0.97051	Cal	Q CCW	4
-0.103	-0.12951	0.016	-0.13572	-0.1219246	0.985629	Cal	Q CCW	3
-0.100	-0.10663	0.006	-0.11207	-0.1230086	0.985206	Cal	Q CCW	2
-0.099	-0.08927	-0.004	-0.09512	-0.1163775	0.993783	Cal	Q CCW	1
0.014	-0.02289	-0.028	-0.00254	0.094762	0	Cal	Q CCW	0
Ref 56 T [kg	Ref 56 Q [	KDN-250 T	KDN-250 (	FUTEK T [kg	RPS	Measurement	Comment	Comment
-0.06941	0.20773	0.07134	0.264146	-0.1209398	0.940125	Cal	Q CW	7
-0.081167	0.177103	0.052756	0.232087	-0.1276576	0.956624	Cal	Q CW	6
-0.083942	0.1506	0.033476	0.20431	-0.1420704	0.96646	Cal	Q CW	5
-0.088292	0.129317	0.018121	0.182051	-0.1467619	0.972955	Cal	Q CW	4
-0.094327	0.104305	0.000545	0.155811	-0.1393833	0.984472	Cal	Q CW	3
-0.100422	0.08268	-0.01582	0.132883	-0.143816	0.990638	Cal	Q CW	2
-0.098893	0.065589	-0.02567	0.11503	-0.1412674	0.996609	Cal	Q CW	1
0.0102913	-0.00032	-0.0114	0.000112	0.0648996	0	Cal	Q CW	0

Staitc calibration								
Ref 56 T [kg]	Ref 56 Q [kpm]	KDN-250 T [kg]	KDN-250 Q [kpm]	FUTEK T [kg]	RPS	Valinta	Comment 1	Comment 2
14.134	-0.007	14.345	-0.002	14.787	0.000	Cal	T	15
11.272	-0.005	11.466	-0.001	11.808	0.000	Cal	T	12
9.363	-0.005	9.536	0.000	9.833	0.000	Cal	T	10
6.513	-0.004	6.666	0.000	6.929	0.000	Cal	T	7
4.641	-0.003	4.780	0.001	4.887	0.000	Cal	T	5
1.846	-0.001	1.894	0.000	2.036	0.000	Cal	T	2
-0.001	0.000	0.000	0.000	-0.002	0.000	Cal	T	0
Ref 56 T [kg]	Ref 56 Q [kpm]	KDN-250 T [kg]	KDN-250 Q [kpm]	FUTEK T [kg]	RPS	Valinta	Comment 1	Comment 2
0.222271558	0.679953869	-0.111380302	0.744580553	-0.126701156	0	Cal	Q_CW	0.75
0.175	0.566	-0.060	0.621	-0.026	0	Cal	Q_CW	0.625
0.127	0.446	-0.051	0.497	0.037	0	Cal	Q_CW	0.5
0.086659749	0.326295276	-0.059069975	0.372660704	0.036917663	0	Cal	Q_CW	0.375
0.049296894	0.208519146	-0.056287141	0.247244121	-0.050727111	0	Cal	Q_CW	0.25
0.021256638	0.106558844	-0.053501261	0.125861508	0.014616513	0	Cal	Q_CW	0.125
Ref 56 T [kg]	Ref 56 Q [kpm]	KDN-250 T [kg]	KDN-250 Q [kpm]	FUTEK T [kg]	RPS	Valinta	Comment 1	Comment 2
0.042	-0.709	-0.112	-0.749	-0.026	0.000	Cal	Q_CCW	0.75
0.035	-0.608	-0.129	-0.627	-0.020	0.000	Cal	Q_CCW	0.625
0.030713528	-0.523298543	-0.137377	-0.506095226	-0.052624101	0.000	Cal	Q_CCW	0.5
0.016	-0.366935025	-0.076	-0.375089095	0.001331206	0.000	Cal	Q_CCW	0.375
0.014	-0.278519146	-0.093	-0.256253467	-0.058952216	0.000	Cal	Q_CCW	0.25
-0.002	-0.120150754	-0.057	-0.12489402	-0.109596382	0.000	Cal	Q_CCW	0.125

CCW measurements							
Ref 56 T [kg]	Ref 56 Q [kpm]	KDN-250 T [kg]	KDN-250 Q [kpm]	FUTEK T [kg]	RPS	Measuren	Comment
-0.050520329	-0.141951208	0.010774289	-0.181058188	0.389387852	1.004912617	Mittaus	CCW
-0.049320235	-0.157320336	0.025050201	-0.19709651	0.397450134	0.999653221	Mittaus	CCW
-0.048596416	-0.199587651	0.056494658	-0.241279329	0.391290336	0.983766309	Mittaus	CCW
-0.047322235	-0.14175745	0.011105054	-0.180595302	0.405988188	1.004432349	Mittaus	CCW
1.857922819	-0.14136094	1.948752349	-0.180527047	2.369345638	1.007007181	Mittaus	CCW
1.856579195	-0.156258389	1.958187248	-0.196058389	2.366612752	0.996274228	Mittaus	CCW
1.854867785	-0.198355034	1.983799329	-0.240236577	2.368414765	0.980306174	Mittaus	CCW
-0.052162671	-0.141168859	0.009023174	-0.180016376	0.413165638	1.001041208	Mittaus	CCW
4.69486443	-0.141032148	4.815665101	-0.180287181	5.474867785	1.000917987	Mittaus	CCW
4.699387248	-0.155329799	4.81824698	-0.195334497	5.474678523	0.996836711	Mittaus	CCW
4.695934899	-0.19755745	4.837597987	-0.239438725	5.479803356	0.980896309	Mittaus	CCW
-0.046099564	-0.140435705	0.007929329	-0.179486846	0.419655369	1.004127584	Mittaus	CCW
9.434936242	-0.140378054	9.624387248	-0.179931611	10.63275839	1.001305101	Mittaus	CCW
9.431672483	-0.154673289	9.628314765	-0.195042752	10.62618792	1.000181007	Mittaus	CCW
9.435544295	-0.19759	9.637704698	-0.239921342	10.62044295	0.98832698	Mittaus	CCW
-0.05057143	-0.138551141	-0.004178215	-0.177511007	0.480874027	1.00111047	Mittaus	CCW
14.21434899	-0.138552617	14.47101342	-0.178861544	15.85586577	1.000046913	Mittaus	CCW
14.20990604	-0.152464497	14.46379866	-0.193777987	15.84849664	1.00408349	Mittaus	CCW
14.20396644	-0.192091074	14.4703557	-0.235280336	15.71993289	0.98967094	Mittaus	CCW
-0.044340047	-0.137056711	0.013982248	-0.17651255	0.461987181	1.001990738	Mittaus	CCW
-0.025438946	-0.242701275	0.086900148	-0.289212416	0.637307691	3.079339597	Mittaus	CCW
-0.025438946	-0.242701275	0.086900148	-0.289212416	0.637307691	3.079339597	Mittaus	CCW
-0.024537966	-0.283509799	0.09684198	-0.331617852	0.643133342	3.075275839	Mittaus	CCW
-0.017812799	-0.398895302	0.118565899	-0.450365168	0.640127295	3.05239396	Mittaus	CCW
-0.045346523	-0.136640336	0.003231161	-0.175642148	0.46378651	1.016272617	Mittaus	CCW
1.866720805	-0.241190738	2.000698658	-0.288001342	2.463644966	3.079234899	Mittaus	CCW
1.864805369	-0.28165047	2.005420805	-0.329905235	2.461744966	3.07175906	Mittaus	CCW
1.857875168	-0.396294161	2.021518792	-0.447671611	2.431603356	3.0542	Mittaus	CCW
-0.050907819	-0.136013423	0.009267805	-0.175491007	0.459662685	1.005616443	Mittaus	CCW
4.692908054	-0.239591812	4.858105369	-0.286364564	5.532767785	3.079651678	Mittaus	CCW
4.692590604	-0.278770671	4.858510738	-0.32696302	5.534520805	3.076062416	Mittaus	CCW
4.694869799	-0.392913624	4.875218121	-0.444510604	5.552284564	3.050322148	Mittaus	CCW
-0.048605034	-0.135439396	0.002380631	-0.174574094	0.448770872	0.999547987	Mittaus	CCW
9.466263758	-0.23805953	9.679461074	-0.284794362	10.53102013	3.083095302	Mittaus	CCW
9.466463758	-0.276234966	9.682319463	-0.324510134	10.57727517	3.07229396	Mittaus	CCW
9.470545638	-0.389137584	9.700567114	-0.440966644	10.57304698	3.050157047	Mittaus	CCW
-0.04619349	-0.135036443	0.017336081	-0.174027584	0.444832953	1.002081141	Mittaus	CCW
14.22102013	-0.236761275	14.46642953	-0.283851141	15.75314765	3.079356376	Mittaus	CCW
14.22107383	-0.275218591	14.4656443	-0.323720604	15.73016779	3.076751007	Mittaus	CCW
14.21824832	-0.384460604	14.47252349	-0.436422886	15.88738255	3.060334899	Mittaus	CCW
-0.043887007	-0.133010738	0.006405993	-0.172744899	0.554564832	1.005684631	Mittaus	CCW
-0.013678685	-0.336358188	0.111140584	-0.39015094	0.466451477	6.021583893	Mittaus	CCW
-0.009379678	-0.397292013	0.115995738	-0.452915705	0.541093557	6.013691946	Mittaus	CCW
-0.013368356	-0.578722282	0.140621383	-0.641027047	0.523815503	5.984918121	Mittaus	CCW
-0.047962691	-0.133176107	0.006909678	-0.172279195	0.495486174	1.004874765	Mittaus	CCW
1.862985906	-0.336151611	2.007594631	-0.390407181	2.470131544	6.024796644	Mittaus	CCW
1.868465101	-0.396591477	2.011849664	-0.452255302	2.452811409	6.021086577	Mittaus	CCW
1.869139597	-0.57885557	2.033269128	-0.641961007	2.402138926	5.982150336	Mittaus	CCW

-0.031598248	-0.132318658	0.006457812	-0.171458926	0.545961074	1.005968993	Mittaus	CCW
4.690234899	-0.331735436	4.860805369	-0.385662013	5.554012752	6.034404027	Mittaus	CCW
4.695957718	-0.392772819	4.86352349	-0.448075772	5.549969128	6.015104027	Mittaus	CCW
4.708260403	-0.577053423	4.889519463	-0.639795839	5.526410738	5.981632215	Mittaus	CCW
9.459424161	-0.33093906	9.656627517	-0.384933154	10.63021477	6.022863758	Mittaus	CCW
-0.034008725	-0.131890336	-0.007412081	-0.171600805	0.533438792	1.00387604	Mittaus	CCW
9.459424161	-0.33093906	9.656627517	-0.384933154	10.63021477	6.022863758	Mittaus	CCW
9.461321477	-0.393686376	9.664675168	-0.449260201	10.61157047	6.01116443	Mittaus	CCW
9.478271812	-0.573189262	9.687908725	-0.636918121	10.59795302	5.988411409	Mittaus	CCW
-0.041684154	-0.131582148	-0.002190389	-0.171417383	0.561035302	1.002702148	Mittaus	CCW
14.22062416	-0.328321342	14.48685906	-0.383290604	15.92395302	6.033310738	Mittaus	CCW
14.22213423	-0.390840336	14.4979396	-0.447746242	15.74048993	6.017657718	Mittaus	CCW
14.22969128	-0.56127396	14.52934899	-0.625067785	15.65765101	6.008185906	Mittaus	CCW
-0.029545537	-0.128992013	0.013148617	-0.168705235	0.31430845	1.009873356	Mittaus	CCW
-0.008105302	-0.381440134	0.109894221	-0.43688349	0.64481651	9.030995302	Mittaus	CCW
-0.002126154	-0.458104362	0.123498383	-0.516406711	0.626253691	9.013132886	Mittaus	CCW
-0.003735926	-0.662277852	0.152800497	-0.728549866	0.63084953	8.978715436	Mittaus	CCW
-0.02790349	-0.130171745	-0.00258304	-0.169440671	0.632240336	1.011014161	Mittaus	CCW
1.885409396	-0.384002215	2.008087248	-0.440898658	2.622445638	9.034951678	Mittaus	CCW
1.882834228	-0.461076242	2.018956376	-0.521003758	2.621291946	9.027740268	Mittaus	CCW
1.875067785	-0.669202081	2.043384564	-0.736594228	2.55962349	8.988689933	Mittaus	CCW
4.700195302	-0.383953557	4.864881208	-0.44074698	5.582639597	9.038	Mittaus	CCW
4.705832886	-0.45639255	4.87720604	-0.515885705	5.508251007	9.023187919	Mittaus	CCW
4.709608725	-0.674090738	4.899244295	-0.741635302	5.479814765	8.978048322	Mittaus	CCW
14.23226846	-0.386026779	14.48357047	-0.444188389	15.93116107	9.029005369	Mittaus	CCW
14.23344966	-0.462344564	14.49614094	-0.523591477	15.86725503	9.027651678	Mittaus	CCW
14.23824161	-0.675563423	14.52727517	-0.744310201	15.75461745	8.985254362	Mittaus	CCW
0.003848228	-0.416057315	0.118945671	-0.477333356	0.584537785	12.07800671	Mittaus	CCW
0.005030275	-0.505642148	0.125843195	-0.57063	0.598087315	12.06022148	Mittaus	CCW
0.000642148	-0.727549262	0.142388671	-0.800284765	0.538726242	12.02481879	Mittaus	CCW
1.871689262	-0.419368725	2.010384564	-0.481414362	2.522866443	12.0770604	Mittaus	CCW
1.87013557	-0.509630671	2.016246309	-0.575460134	2.487814094	12.06105369	Mittaus	CCW
1.869804698	-0.732932081	2.035134228	-0.806880067	2.460471141	12.02536242	Mittaus	CCW
4.687243624	-0.424490403	4.854598658	-0.487816779	5.609953691	12.07555705	Mittaus	CCW
4.695977181	-0.514569799	4.872596644	-0.582668993	5.586555705	12.06074497	Mittaus	CCW
4.704355034	-0.744354362	4.894531544	-0.820824295	5.50810604	12.02289262	Mittaus	CCW
9.440510067	-0.430906309	9.656494631	-0.496632416	10.77307383	12.07859732	Mittaus	CCW
9.444421477	-0.522311208	9.669915436	-0.592338792	10.73491275	12.05933557	Mittaus	CCW
9.453624161	-0.752791141	9.701245638	-0.832572685	10.65841611	12.02244966	Mittaus	CCW
14.19983893	-0.440063356	14.48242953	-0.510066577	15.96757718	12.07414765	Mittaus	CCW
14.20724832	-0.533118725	14.49765772	-0.607621074	15.89800671	12.05938255	Mittaus	CCW
14.21374497	-0.76403094	14.53330872	-0.848949597	15.8114094	12.02161745	Mittaus	CCW

Ref 56 T [kg]	Ref 56 Q [kpm]	KDN-250 T [kg]	KDN-250 Q [kpm]	FUTEK T [kg]	RPS	Measuren	Comment
0.434289396	-0.007277376	0.431998792	-0.013787134	0.605466376	1.001551946	Mittaus	CW
1.866794631	0.007595463	1.904562416	0.001897403	2.166383221	0.996282617	Mittaus	CW
1.87387047	0.049746074	1.92984698	0.046269282	2.14666443	0.980912215	Mittaus	CW
1.878277181	0.087748772	1.957285235	0.086442523	2.141958389	0.968557114	Mittaus	CW
0.437602617	-0.008028255	0.434832953	-0.01464455	0.622114027	1.00409349	Mittaus	CW
4.699710738	0.006697537	4.789153691	0.000793544	5.276718792	1.001170336	Mittaus	CW
4.703147651	0.047957906	4.802175168	0.044100141	5.271055034	0.983342081	Mittaus	CW
4.71145302	0.085712047	4.813691275	0.084455	5.230008054	0.967709597	Mittaus	CW
0.439680134	-0.008895436	0.430140872	-0.015803087	0.624674832	0.998951477	Mittaus	CW
9.426069128	0.005415584	9.601175839	-0.000197725	10.43299329	0.998501074	Mittaus	CW
9.428754362	0.046537463	9.616779195	0.043160013	10.40218121	0.986302685	Mittaus	CW
9.429879195	0.083005557	9.631177181	0.081750315	10.37962416	0.968798859	Mittaus	CW
0.439566376	-0.009574369	0.431013423	-0.016706597	0.629712953	1.003015772	Mittaus	CW
14.19781879	0.004827302	14.43018792	0.000236826	15.5884698	1.003594362	Mittaus	CW
14.19795302	0.044873893	14.43321477	0.042099497	15.47608054	0.979912349	Mittaus	CW
14.20055705	0.080554725	14.439	0.079961705	15.43248993	0.969363289	Mittaus	CW
-0.017668248	0.093396	0.060047	0.095890638	0.153658752	3.079102685	Mittaus	CW
-0.017668248	0.093396	0.060047	0.095890638	0.153658752	3.079102685	Mittaus	CW
-0.012942503	0.132526309	0.080686698	0.136686846	0.149326664	3.076791275	Mittaus	CW
0.007500315	0.240764497	0.122004993	0.249482685	0.149945322	3.051602013	Mittaus	CW
0.02482755	0.336221409	0.148553221	0.349604497	0.172025248	3.030289262	Mittaus	CW
4.712032886	0.089847235	4.842937584	0.092380195	5.323481208	3.079983893	Mittaus	CW
4.714439597	0.127073893	4.852967785	0.133615638	5.320869128	3.073877852	Mittaus	CW
4.727765772	0.232767919	4.883022819	0.242431812	5.293742282	3.061593289	Mittaus	CW
4.74148255	0.325337584	4.924296644	0.338532617	5.25716443	3.037616779	Mittaus	CW
9.435683221	0.088474718	9.645351007	0.09102794	10.40886577	3.088591946	Mittaus	CW
9.441501342	0.125740671	9.653726174	0.131907785	10.40705973	3.07764094	Mittaus	CW
9.444606711	0.229095503	9.685228859	0.238117852	10.36165705	3.055987248	Mittaus	CW
9.459677852	0.320643423	9.729363087	0.333654497	10.35006174	3.034101342	Mittaus	CW
14.23462416	0.086150819	14.47597315	0.089237268	15.58034899	3.084100671	Mittaus	CW
14.23712081	0.12157094	14.47922148	0.126461946	15.55710067	3.082079866	Mittaus	CW
14.2457651	0.224935101	14.51116107	0.234108658	15.46161745	3.057526174	Mittaus	CW
14.25488591	0.314027987	14.5427047	0.327199664	15.52520134	3.043208054	Mittaus	CW
0.003149557	0.177595772	0.115933631	0.186651611	0.244287987	6.022344966	Mittaus	CW
0.009591443	0.23173953	0.129096282	0.243675436	0.225209597	6.023967785	Mittaus	CW
0.035907134	0.371559664	0.155181711	0.389369664	0.221873557	5.995108725	Mittaus	CW
0.056788685	0.497442886	0.161199597	0.521510268	0.208172752	5.972921477	Mittaus	CW
1.89524698	0.177441879	2.031909396	0.185941342	2.267257718	6.030984564	Mittaus	CW
1.903937584	0.229292685	2.04964698	0.239843356	2.240531544	6.030059732	Mittaus	CW
1.93114094	0.369925839	2.077289262	0.387678054	2.217590604	5.985997315	Mittaus	CW
1.950338926	0.496414094	2.085632215	0.520462752	2.19011745	5.973013423	Mittaus	CW
4.728241611	0.174956711	4.889220134	0.18383	5.396991946	6.024319463	Mittaus	CW
4.738109396	0.229109732	4.912732886	0.240644564	5.384096644	6.025632886	Mittaus	CW
4.760553691	0.367191477	4.941718792	0.384634698	5.363757718	5.999655705	Mittaus	CW
4.783721477	0.492784094	4.947537584	0.516749933	5.315400671	5.966871141	Mittaus	CW
9.452340268	0.175360537	9.666521477	0.185360201	10.50736913	6.023979195	Mittaus	CW
9.457295973	0.229484765	9.678390604	0.241914362	10.48225503	6.017626174	Mittaus	CW
9.474004027	0.367683893	9.704500671	0.386219329	10.46234899	6.004371141	Mittaus	CW
9.493745638	0.489311074	9.715925503	0.514665973	10.36155906	5.974848993	Mittaus	CW
14.22231544	0.175103289	14.48257718	0.185741007	15.68303356	6.028156376	Mittaus	CW
14.23096644	0.229128121	14.48812752	0.242976107	15.5752349	6.020728859	Mittaus	CW

14.24722148	0.367457315	14.51607383	0.386794497	15.49951007	5.988026846	Mittaus	CW
14.27059732	0.486633691	14.53100671	0.511764295	15.46897987	5.981520134	Mittaus	CW
0.021272463	0.223465302	0.135139497	0.237079933	0.268561879	9.034357718	Mittaus	CW
0.029363201	0.287711208	0.150975933	0.303431544	0.252276174	9.019069799	Mittaus	CW
0.055285047	0.447797651	0.178765436	0.471339128	0.236244564	8.993778523	Mittaus	CW
0.088506899	0.592733691	0.162725208	0.622537919	0.196244805	8.973826846	Mittaus	CW
1.913411409	0.224688859	2.046742282	0.239052013	2.321618792	9.039087248	Mittaus	CW
1.925555705	0.288295503	2.060221477	0.305058725	2.297180537	9.032199329	Mittaus	CW
1.953434228	0.449415503	2.090855034	0.472094497	2.244142953	9.006657047	Mittaus	CW
1.979285906	0.59499651	2.075054362	0.624433826	2.192275839	8.975672483	Mittaus	CW
4.734280537	0.226511141	4.895741611	0.240592416	5.42596443	9.030302013	Mittaus	CW
4.743614094	0.290811409	4.918233557	0.308827785	5.39230604	9.030275839	Mittaus	CW
4.769132215	0.451610134	4.950892617	0.475326846	5.347060403	9.005012752	Mittaus	CW
4.797477852	0.59919745	4.943110738	0.629175772	5.279078523	8.975593289	Mittaus	CW
9.455661074	0.219298389	9.673260403	0.23282906	10.62371812	9.035134228	Mittaus	CW
9.465371812	0.281115168	9.688651678	0.297084564	10.57943624	9.033089262	Mittaus	CW
9.490979195	0.437884295	9.722042282	0.460652349	10.52647651	9.003777852	Mittaus	CW
9.51297651	0.578681141	9.719769128	0.608120067	10.41630201	8.975474497	Mittaus	CW
14.23426174	0.219598725	14.48089262	0.234321611	15.81700671	9.031938255	Mittaus	CW
14.23797987	0.281303423	14.49427517	0.298512416	15.75611409	9.028359732	Mittaus	CW
14.25783221	0.43825443	14.52353691	0.462212685	15.72391946	9.002910738	Mittaus	CW
14.28642282	0.583166913	14.53281879	0.613152953	15.68151678	8.980766443	Mittaus	CW
0.040104537	0.248592148	0.105402302	0.266173356	0.409704832	12.0784698	Mittaus	CW
0.046747544	0.316163893	0.121568946	0.33633	0.402865436	12.06610738	Mittaus	CW
0.076989248	0.483466711	0.162595839	0.509885369	0.445038188	12.03834899	Mittaus	CW
0.098084826	0.616085034	0.164968034	0.650174228	0.378857315	12.01411409	Mittaus	CW
1.920597315	0.25269698	2.024157718	0.270967919	2.405809396	12.07798658	Mittaus	CW
1.933120805	0.323156107	2.046298658	0.345181879	2.369386577	12.06657718	Mittaus	CW
1.95785906	0.48997	2.1004	0.518754295	2.277151007	12.03674497	Mittaus	CW
1.988611409	0.624700403	2.12042953	0.660329933	2.195914094	12.01487248	Mittaus	CW
4.73921745	0.259198725	4.877140268	0.279781409	5.540957718	12.07763087	Mittaus	CW
4.745397987	0.331297651	4.888120805	0.355166779	5.507969128	12.06287919	Mittaus	CW
4.777765772	0.501661812	4.899914765	0.533435638	5.434324161	12.0344094	Mittaus	CW
4.793736913	0.626211946	4.900283221	0.665942685	5.339406711	12.01365772	Mittaus	CW
9.462313423	0.265650805	9.651012752	0.289709799	10.71314765	12.07542282	Mittaus	CW
9.464881879	0.338815034	9.662483893	0.36673604	10.70314094	12.06046309	Mittaus	CW
9.493084564	0.509108121	9.672681208	0.54443651	10.62863087	12.03296644	Mittaus	CW
9.506263087	0.627840403	9.651218121	0.671019664	10.5369396	12.01212081	Mittaus	CW
14.22420134	0.272828389	14.44563758	0.302377651	15.99746309	12.07506711	Mittaus	CW
14.22711409	0.348905168	14.45532215	0.382578792	15.91622819	12.06089262	Mittaus	CW
14.25210738	0.516517584	14.47014765	0.558767383	15.84032215	12.03273154	Mittaus	CW
14.26499329	0.601618188	14.44595302	0.651134295	15.7930604	12.01924161	Mittaus	CW

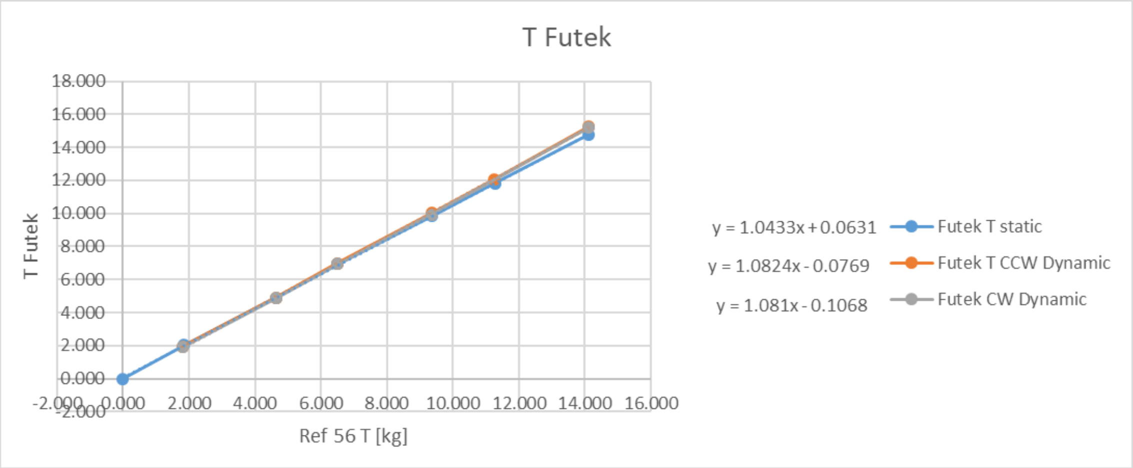

Figure 82 Calibration of thrust sensor revision 4.

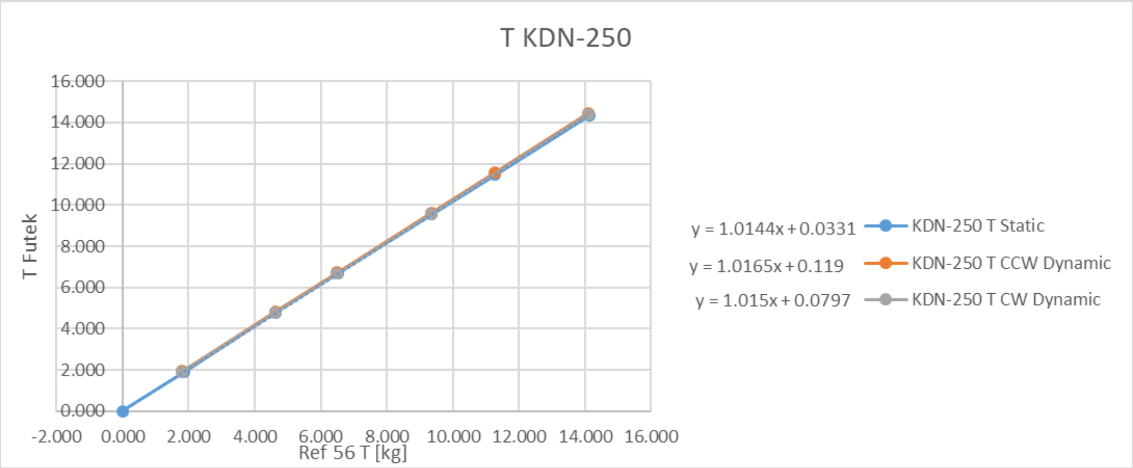

Figure 83 Calibration of KDN-250 with revision 4.

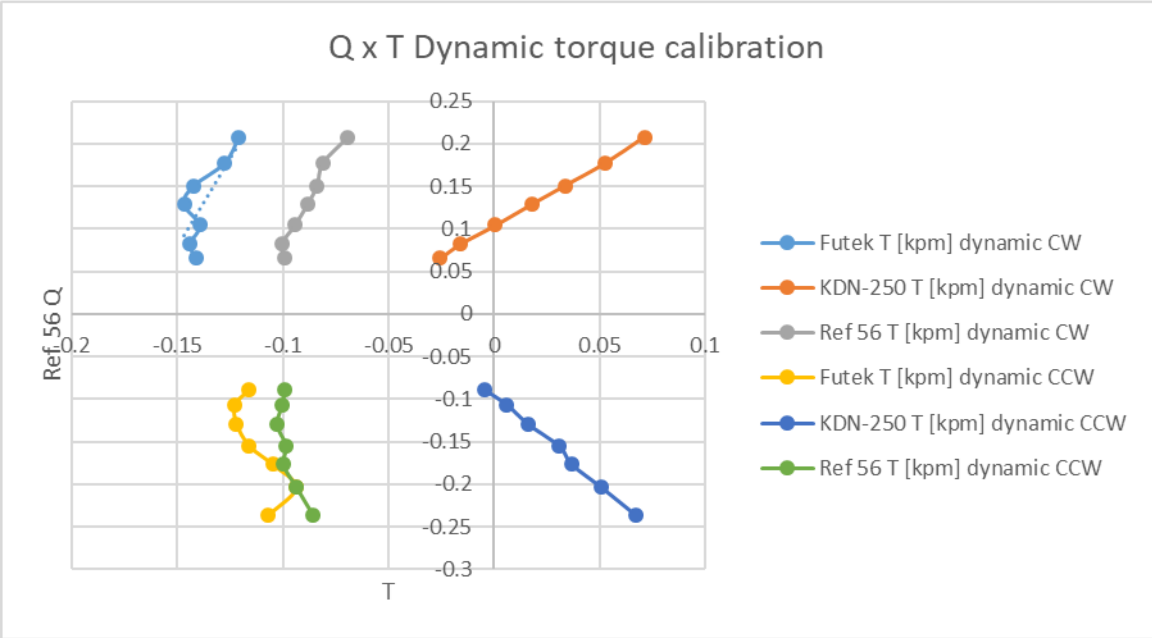

Figure 84 torque against thrust, revision 4 calibration measurements.

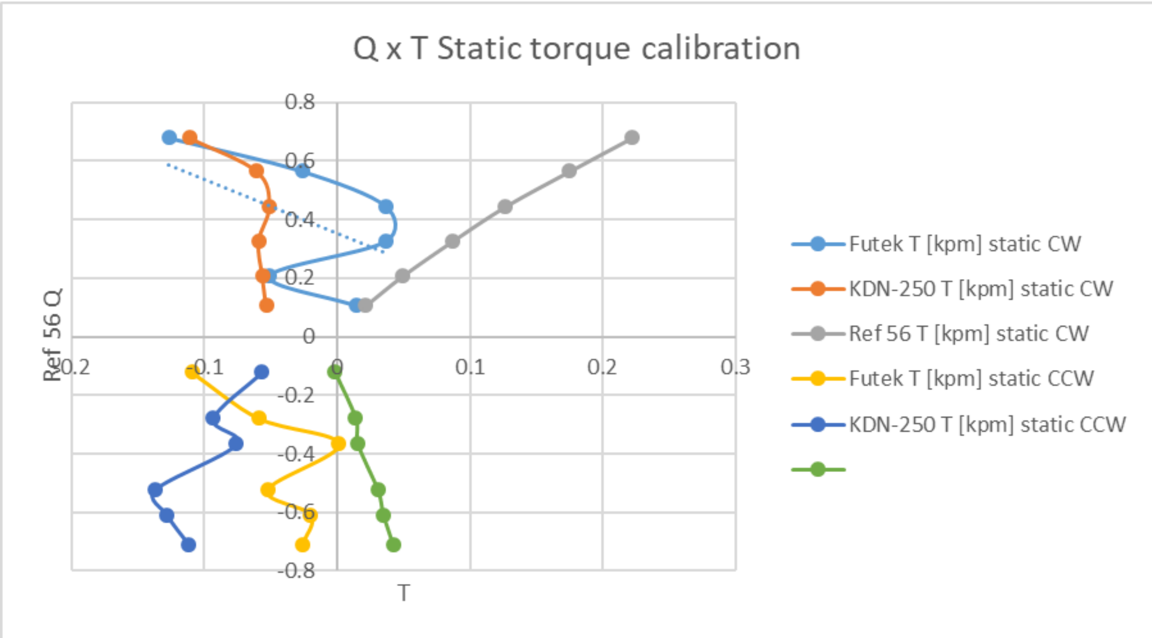

Figure 85 torque against thrust revision 4 calibration measurements.

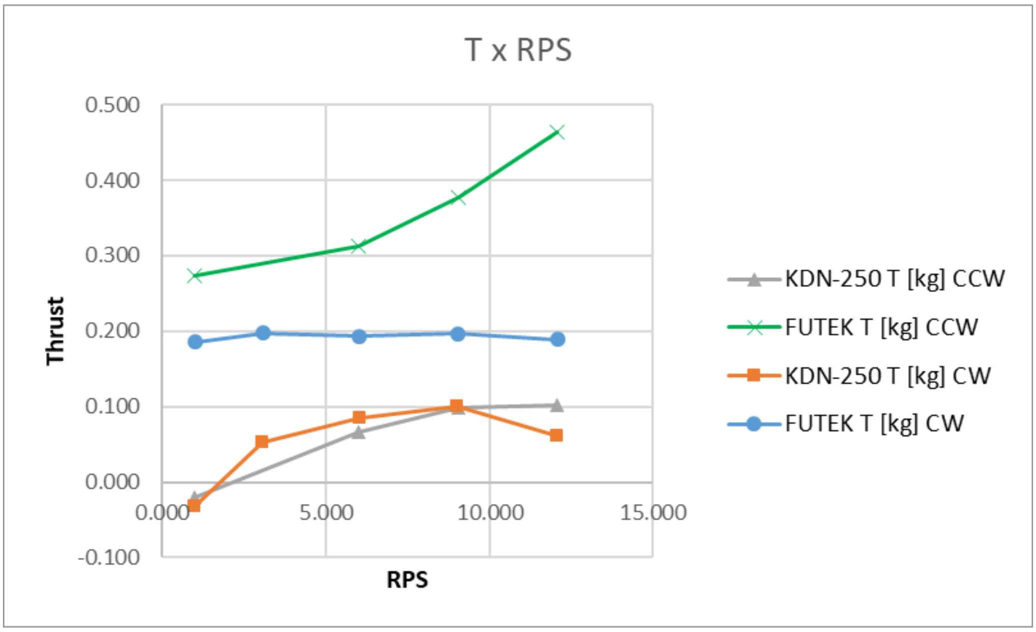

Figure 86 thrust against RPS revision 4 calibration measurements.

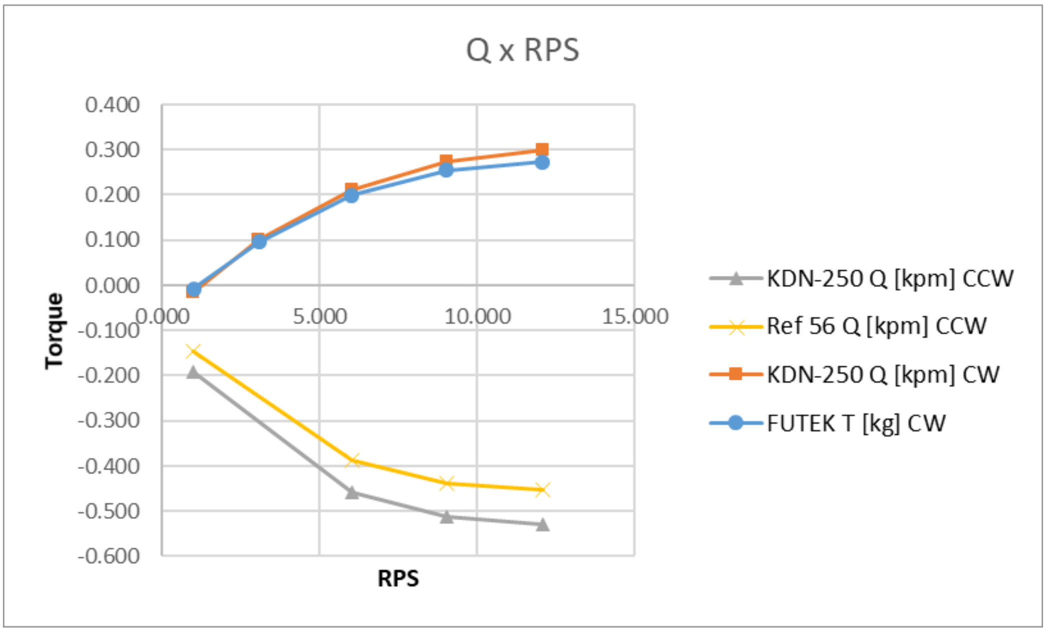

Figure 87 torque against RPS, revision 4 calibration measurements.

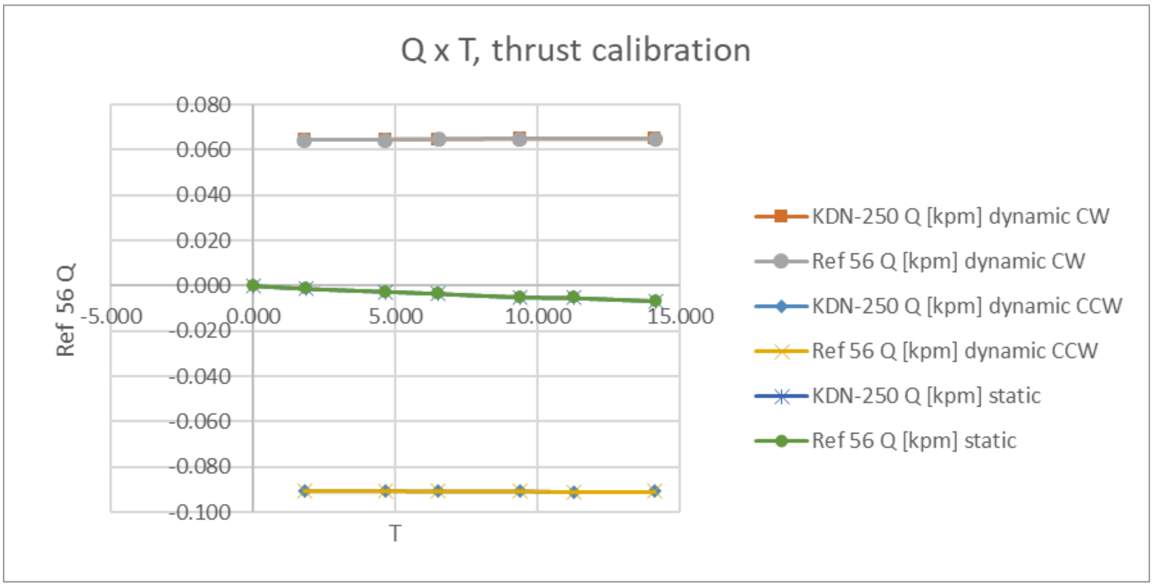

Figure 88 torque against thrust, revision 4 calibration measurements.

Table 7 thrust sensor revision 4 calibration table.

Revision 4 calibration table									
			Futek		KDN-250				Note
			T		Q		T		
Cal type	Direction of rotation		a	y0	a	y0	a	y0	
Static	CW		0.9584	-0.0599	0.9368	-0.0222	0.9858	-0.0324	
Static	CCW				0.9353	-0.0177			
Dynamic	CW		0.9249	0.0997	0.8032	-0.0145	0.9852	-0.0785	
Dynamic	CCW		0.9237	0.0719	0.8887	0.0119	0.9838	-0.1171	

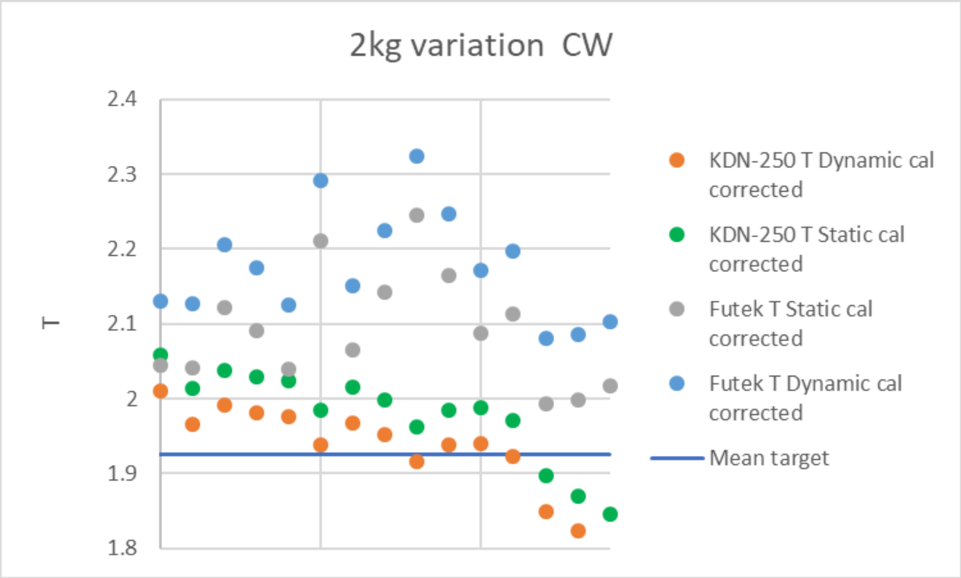

Figure 89 thrust load measurement, 2kg calibration weight as load.

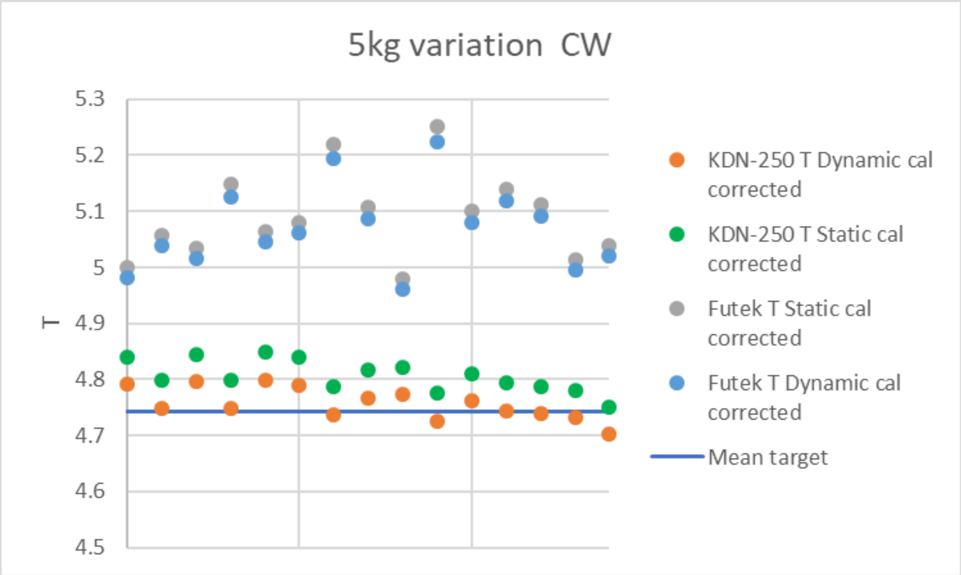

Figure 90 thrust load measurement, 5kg calibration weight as load.

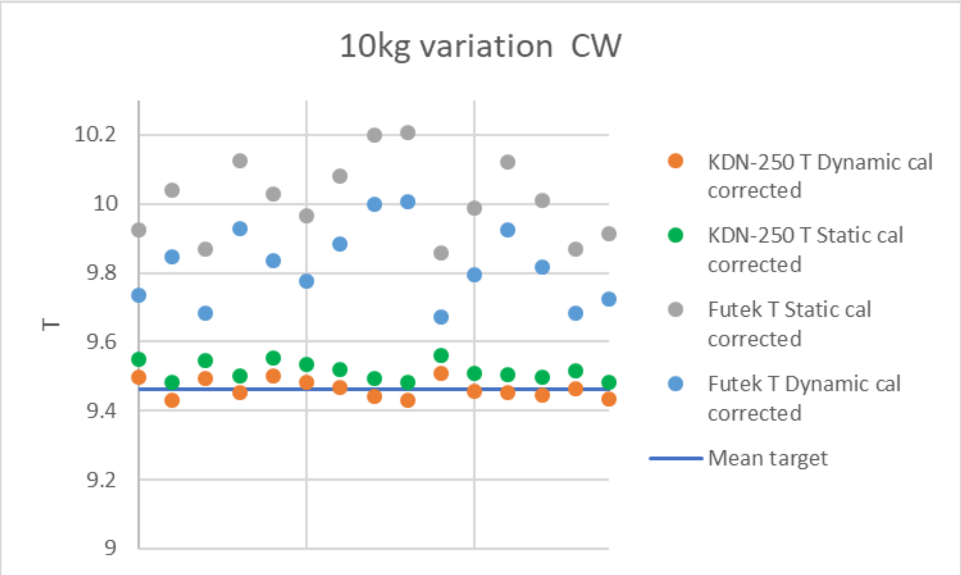

Figure 91 thrust load measurement, 10kg calibration weight as load.

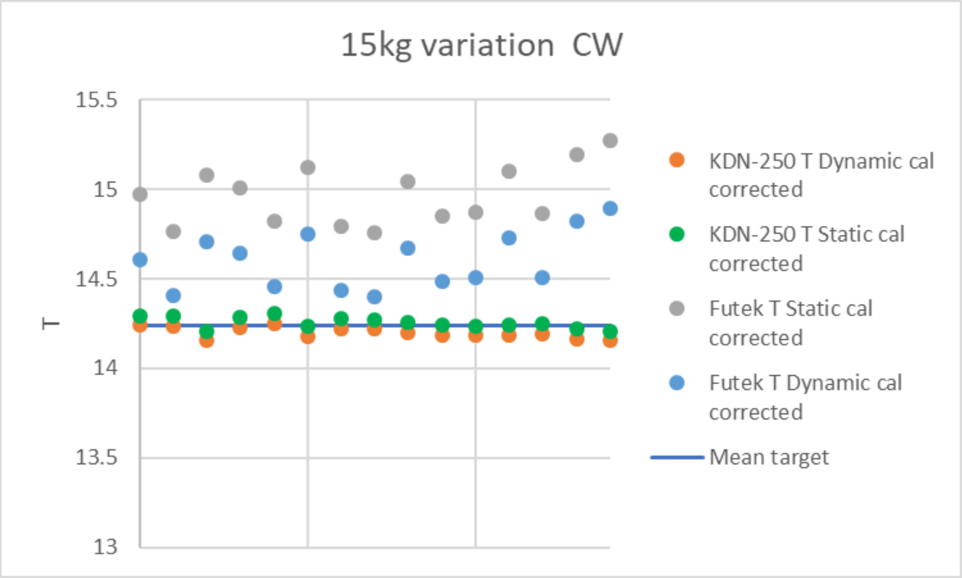

Figure 92 thrust load measurement, 15kg calibration weight as load.

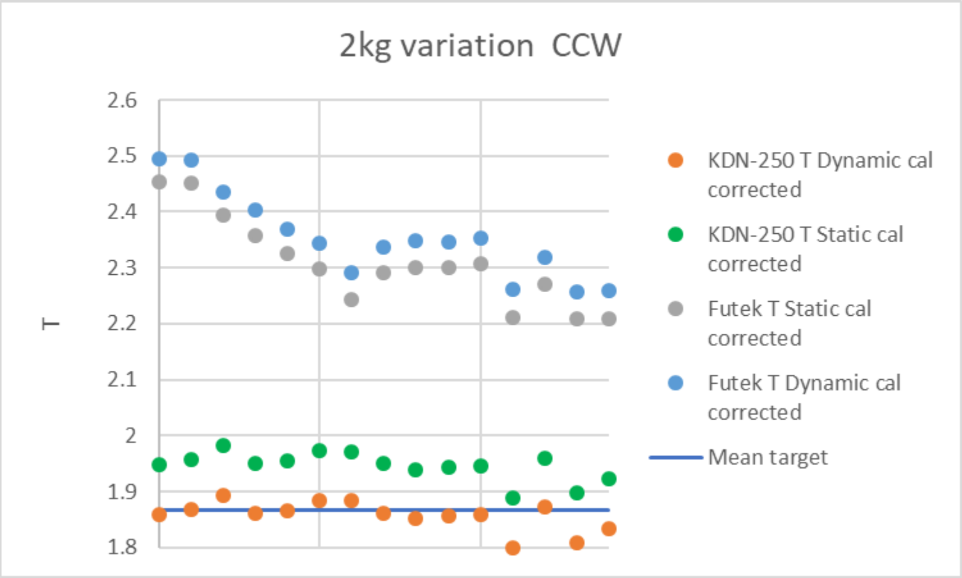

Figure 93 thrust load measurement, 2kg calibration weight as load.

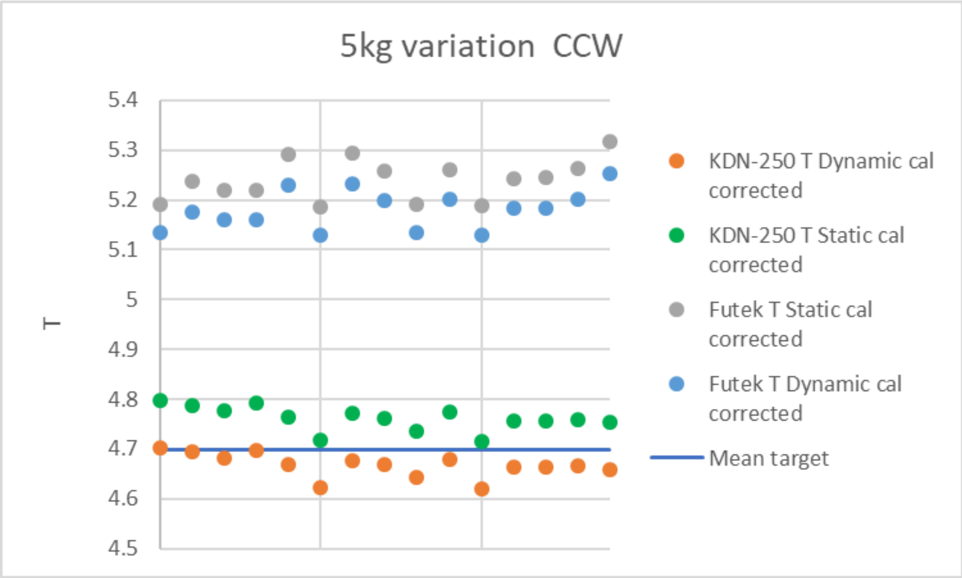

Figure 94 thrust load measurement, 5 kg calibration weight as load.

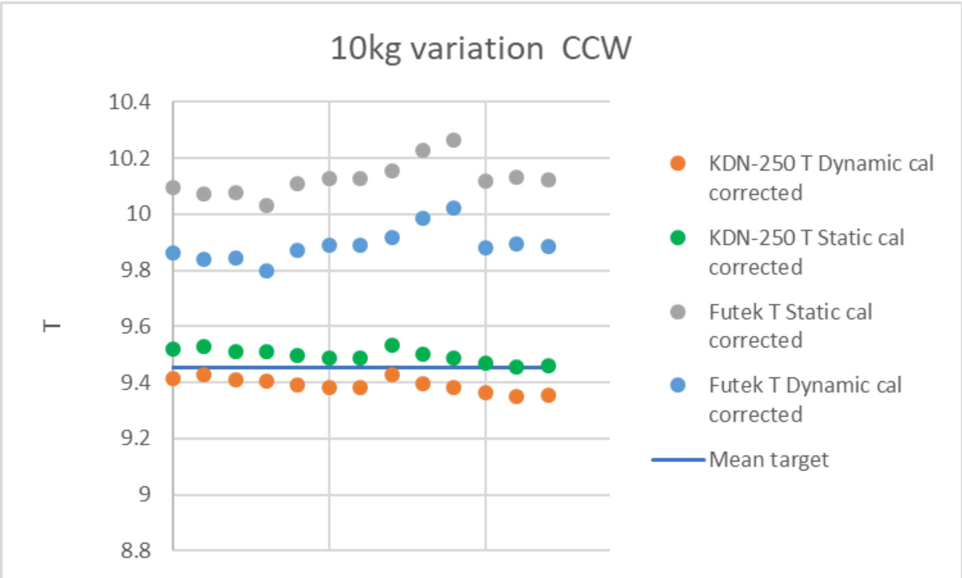

Figure 95 thrust load measurement, 10kg calibration weight as load

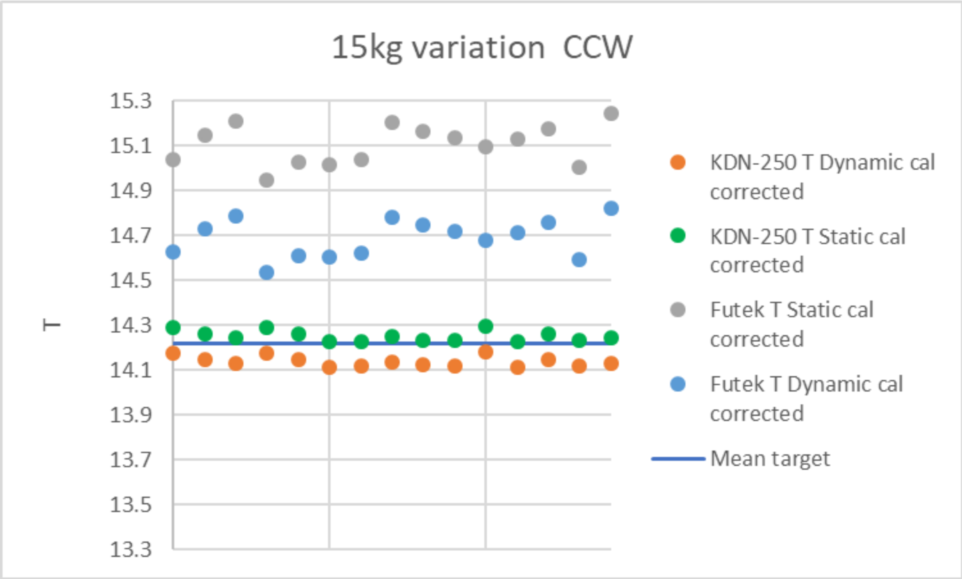

Figure 96 thrust load measurement, 15kg calibration weight as load.

Open water measurement data

Calibration data				
Speed	n [kHz]	KDN-250 T [kg]	KDN-250 Q [kpm]	Futek T [kg]
0.000	0.000	-0.743	0.505	-0.441
0.000	0.000	-0.724	0.378	-0.739
0.000	0.000	-0.670	0.253	-0.816
0.000	0.000	-0.627	0.125	-0.398
0.000	0.000	-0.547	-0.001	-0.787
0.000	1.055	15.047	-0.023	14.989
0.000	1.056	12.057	-0.022	12.016
0.000	1.057	10.060	-0.022	10.011
0.000	1.057	7.039	-0.022	7.014
0.000	1.058	5.015	-0.022	5.019
0.000	1.058	1.997	-0.022	1.997
0.000	1.058	0.000	-0.022	0.001

N= 16 open water				
Speed	n [kHz]	KDN-250 T [kg]	KDN-250 Q [kpm]	Futek T [kg]
0.319	15.914	11.092	-0.350	11.348
0.638	15.921	9.753	-0.324	10.042
0.958	15.929	8.127	-0.296	8.428
1.276	15.938	6.440	-0.265	6.707
1.435	15.946	5.581	-0.249	5.840
2.551	16.000	-1.297	-0.106	-1.104
2.392	15.992	-0.196	-0.131	0.039
2.233	15.980	0.825	-0.154	1.092
2.073	15.971	1.815	-0.175	2.078
2.073	15.974	1.854	-0.176	2.105
1.913	15.962	2.743	-0.194	3.038
1.754	15.955	3.696	-0.213	3.964
1.993	19.952	7.340	-0.351	8.262
1.594	15.951	4.588	-0.231	4.871

Pollard pull				
1.754	15.955	3.696	-0.213	3.964
1.993	19.952	7.340	-0.351	8.262
1.594	15.951	4.588	-0.231	4.871
0.797	8.012	1.170	-0.071	0.596
0.000	0.651	-0.045	0.025	-0.879
0.000	0.650	0.008	-0.015	-0.819
0.000	0.650	0.000	-0.015	-0.883
0.000	0.648	-0.052	0.025	-0.992
0.000	19.934	19.971	-0.594	21.096
0.000	18.038	16.097	-0.483	16.809
0.000	16.002	12.520	-0.380	12.898
0.000	14.050	9.590	-0.296	9.737
0.000	11.990	6.915	-0.219	6.790
0.000	10.100	4.867	-0.160	4.573
0.000	8.001	3.039	-0.107	2.522
0.000	5.987	1.740	-0.067	1.045
0.000	4.060	0.801	-0.040	0.045
0.000	2.033	0.212	-0.023	-0.572
0.000	0.653	0.022	-0.013	-0.742
0.000	0.655	-0.034	0.023	-0.820