Traceable Torque Measurement under Rotation in Nacelle Test Benches

– A Good Practice Guide –

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This guide has been produced within the EURAMET project entitled *Torque Measurement in the MN m*[1] *range*. More information about this collaborative research project can be found on the project's website https://www.ptb.de/emrp/ind14-home.html. The aim of this guide is to provide practical information and advice about torque measurement and especially about torque calibration in nacelle test benches for nacelle test bench operators.

Disclaimer

Any mention of commercial products within this guide is for information only; it does not imply recommendation or endorsement by the partners in this project.

The views expressed in this guide are those of the authors and of the EMPIR 14IND14 project team.

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Authorship

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[1] The unit for torque can also be written as MN·m.

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1 Introduction

Prior to the market launch of wind turbines (also called nacelles), large gearboxes and generators, extensive tests, which can be performed on a nacelle test bench, are of great importance. One such test is the efficiency determination of the device under test. For direct efficiency determination, the mechanical input directly at the flange of the device under test and the electrical or mechanical output of the device under test are to be measured. While the output can already be measured with a sufficient uncertainty, measuring the input consisting of torque and rotational speed poses a problem. A broad variety of measuring instruments is available for measuring rotational speeds. The torque that appears in nacelle test benches, however, ranges up to several MN m and cannot easily be determined due to the lack of traceability possibilities. This good practice guide introduces a method for tracing large torque measurement up to 5 MN m in nacelle test benches using a torque transfer standard.

This good practice guide comprises the following sections. A list of the general requirements on the performance of a torque calibration in nacelle test benches including the calibration set-up is given in section 2. A description of the preparatory work, tests and instructions on a quasi-static torque calibration and a torque calibration using so-called *characterisation maps* to cover the entire operation range of a nacelle test bench as part of the performance of a torque calibration are outlined in section 3. Guidelines for the evaluation of the calibration results including the determination of a measurement uncertainty are introduced in section 4. Section 5 again states the benefits of traceable torque measurement in nacelle test benches for the operators of the test benches and the feasibility of the calibration results.

Further information about understanding measurement and measurement uncertainty can be found in the Guide to the expression of uncertainty in measurement (GUM) [7] and the International Vocabulary of Metrology (VIM) [5]. General information about operating procedures in calibration laboratories is given in DIN 17025 [2], while information about static torque calibration can be taken from EURAMET cg-14 [6], one of the European calibration guidelines.

1.1 Glossary

We have provided a glossary of technical terms that arise in the following description of a torque calibration in nacelle test benches at the end of this document.

1.2 Symbols and their meaning

Important symbols and their meaning regarding torque calibration in nacelle test benches are listed in Table 1.

Table 1 Symbols and their meaning.

Symbol	Unit	Meaning
a	%	Relative resolution of the torque measuring instrument in the test bench
a_F	%	Relative resolution of the torque measuring instrument in the test bench under load
a_Z	%	Relative resolution of the torque measuring instrument in the test bench after load release
b	%	Relative repeatability of the torque measuring instrument in the test bench
f_{sample}	Hz	Sampling frequency of the DAQ
$H_{\text{NTB/TTS}}$	% rH	Relative humidity measured close to the torque measurement instrument in the test bench (NTB) and close to the torque transfer standard (TTS)
k	-	Amplification factor to calculate the expanded uncertainty based on the combined uncertainty
l	-	Integer number of revolutions that are averaged over
M	kN m	Increasing torque load indicated by the torque transfer standard
M'	kN m	Decreasing torque load indicated by the torque transfer standard
M_i	kN m	Increasing torque load indicated by the torque measuring instrument in the test bench

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M_i'	kN m	Decreasing torque load indicated by the torque load in the test bench
$\overline{M_\mathrm{i}},\overline{M}$	kN m	Arithmetic mean of several measurements of M_i and M at the same load step
$M_\mathrm{i,0}$	kN m	Residue indication of the torque measurement instrument in the test bench after load release
M_L	kN m	Torque load step
n_max	min^{-1}	Maximum rotational speed of the test bench considering the device under test
n_NTB	min^{-1}	Rotational speed measured in the test bench
$\bar{n}_\mathrm{NTB}$	min^{-1}	Arithmetic mean of the measurement of rotational speed
$\bar{q}$	%	Relative indication deviation of the torque measuring instrument in the test bench averaged over several repetitions
q_j	%	Relative indication deviation of the torque measuring instrument in the test bench per load cycle
q_max	%	Maximum value of q at each load step
q_min	%	Minimum value of q at each load step
r	kN m	Resolution of the torque measuring instrument in the test bench
r_rot	°	Envisioned signal resolution per rotation
S	mV/V	Measurement signal
$S_\mathrm{zero.rot}$	mV/V	Rotational torque zero signal
$S_\mathrm{zero,stat}$	mV/V	Static torque zero signal
t_dwell	s	Dwell time before measurement
t_heat	s	Time to heat up all components until stable conditions are reached
t_meas	s	Measurement time depending on the minimum rotational speed and the number of revolutions that are averaged over
t_ramp	s	Time to ramp up or down torque or rotational speed
t_step	s	Total measurement time per torque step
u_c	%	Combined absolute measurement uncertainty
u_i	%	Uncertainty component
u_rep	%	Uncertainty component due to the repeatability
u_res	%	Uncertainty component due to the resolution
u_std	%	Uncertainty component due to the deployed torque transfer standard
U	%	Expanded absolute measurement uncertainty
v	%	Relative reversibility of the torque transducer in the test bench
$\vartheta_\mathrm{NTB/TTS}$	°C	Temperature measured close to the torque measurement instrument in the test bench (NTB) and close to the torque transfer standard (TTS)

2 Calibration set-up

Due to several constraints on nacelle test benches, the operators use different methods in different places to measure the input torque to the device under test. An example of a nacelle test bench including the possible positions for measuring torque is depicted in Figure 1.

In nacelles, the main axis is the x-axis. Consequently, the main torque measured in nacelle test benches is M_x. Although the main axis of torque measurement in metrology is the z-axis, in the following description and instructions, the main axis is the x-axis and the main torque to be measured is M_x since this good practice guide is directed at test bench operators.

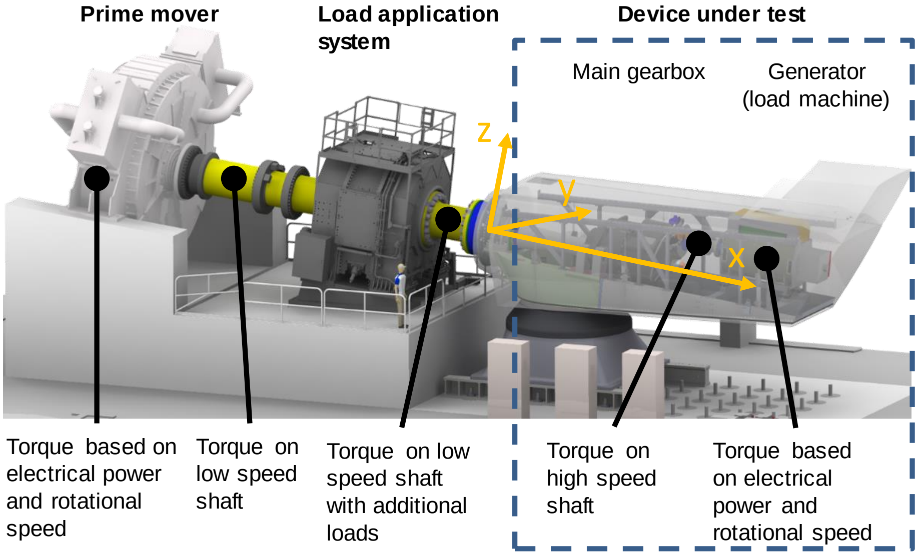

Figure 1 Examples of torque measurement options in test benches and the coordinate system of a nacelle and, therefore, the test bench [9].

2.1 Place to measure the reference torque

To determine the efficiency of a device under test using the direct measurement method by determining the input and output of the device under test, the torque should ideally be measured directly at the connection flange between the test bench and the device under test. In most test benches, specially designed adapters are required to install this additional torque transducer to measure the reference torque. A calibration of the test bench is not possible without a device under test, because only then is a torque generation possible. For a calibration of the typical testing range (torque and rotational speed) of the test bench, a suitable test object representing frequently tested objects is to be installed on the test bench. Ideally, this test object provides full access to its control system to allow the initiation of several control scenarios dependent on the controlled change of electrical braking power asserted by the generator.

All torque transducers, the reference torque transducer as well as the torque transducer in the test bench, must be aligned very precisely to minimise *parasitic permanent loads* such as longitudinal and lateral forces (F_x, F_y and F_z) and bending moments (M_y and M_z) on the torque transducer. Possible *misalignments* are caused by a lack of *planarity* on the adapters, a lack of *concentricity* of the entire drive train, and a *wrong distance* between the load application system and the device under test.

2.2 Torque transfer standard

For measuring the reference torque, to which the torque measurement in a test bench is then compared, a so-called *torque transfer standard* is needed. A transfer standard is a measurement gauge that bears a defined relation between a physical quantity, which in this case is torque, and a unit of measurement, here kN m. This torque transfer standard is to be calibrated according to EURAMET cg-14 [6], a European calibration guide or DIN 51309 [3], the German torque standard.

A torque transfer standard has to meet several requirements. First, the transfer standard must have a *sufficient measurement range* to cover the operational torque range of the test bench, and it is to be calibrated over this measurement range. The best physical principle working in the MN m torque range is the detection of strains by means of alternating electrical resistance using strain gauges. The strain gauges are glued to a deformation body made of steel. To gain the required stiffness of the transfer standard's deformation body and a sufficient sensitivity at the same time, a hollow shaft-type deformation body is best (project result taken from [10]).

Moreover, the transfer standard must withstand the occasionally occurring *additional mechanical loads* created by the load application system as it is installed directly at the hub flange of the device under test and is, therefore, exposed to all simulated wind loads caused by the load application system. Even when no explicit additional loads are applied to the drive train, the load application system deploys loads to stabilise the drive train, leading to power losses and additional friction torque along the drive train during rotation. For information about these additional loads and for surveillance reasons, the transfer standard should be equipped with additional measuring bridges to sense bending moments, and longitudinal and lateral forces. Additional knowledge about the behaviour of the transfer standard under alternating temperature (and humidity) is advantageous, since the ambient conditions in a test bench do not comply with the laboratory conditions during the calibration of the transfer standard.

In general, the transfer standard has to meet special requirements regarding its *dimensions* and *weight*. These requirements are not only limited by the test benches, but also by the available torque calibration machine that is used to characterise the torque transducer and lead to it being a transfer standard. In order to induce the torque load up to several MN m correctly and to ensure the easy mounting of the transfer standard, a flange with bore holes for bolts is an appropriate type of connection. As mentioned above, this might call for specially designed adapters to install the transfer standard in the test bench.

2.3 Data acquisition

A *timewise synchronised* data recording of the torque measured by the transducer of the test bench and by the transfer standard can be realised either by one shared or by two synchronised data acquisition systems.

Regardless of the data acquisition system used, all recorded data should be timestamped, and both the start and end time of the measurement are to be documented. Other than for static calibrations, the signals are to be recorded continuously to enable an investigation of the angular acceleration and its impact on the torque signals. The quantities to be measured during a calibration are listed in Table 2.

Table 2 Quantities to be measured for a torque calibration in test benches.

Quantity to be measured	Symbol	Reading	Unit
Torque measured by the transducer in the test bench	M_i	mV/V	kN m
Rotational speed measured by instruments in the test bench or the TTS	n_NTB	V	min^{-1}
Torque measured by the transfer standard	M	mV/V	kN m
Temperature measurement close to the test bench transducer and the transfer standard (temp. meas. inside the transfer standard)	ϑ_NTB, ϑ_TTS	V	°C
Humidity measurement close to the test bench transducer and the transfer standard (humid. meas. inside the transfer standard)	H_NTB, H_TTS	V	% rH

Temperature ϑ and *humidity* H are to be measured as close to both torque transducers as possible. Ideally, temperature and humidity are measured inside the transfer standard, where the strain gauges are located, and not only certain temperature points but also the temperature gradients over the transducers and the adjacent components are to be recorded. All transducer measurement signals should be corrected for changes in the environmental conditions.

2.3.1 Amplifier and filter settings

All signals should be recorded using an adequate sampling frequency taking the rotational speed n_NTB and the envisioned resolution r_rot of both torque signals and the rotational speed into account. The resolution aimed at is $r_\mathrm{rot} = 1°$ for the maximum rotational speed n_max .

The lowest limit of the sample frequency f_sample can be calculated accordingly:

$$f_\mathrm{sample} \geq n_\mathrm{max} / r_\mathrm{rot} \cdot 360° \quad , \tag{1}$$

where the sampling frequency f_sample is in Hz and the rotational speed n_max is in s^{-1}. Furthermore, a low pass filter should be implemented to avoid aliasing effects.

2.3.2 Timewise synchronisation of different data sets

To synchronise all components of one data acquisition system or two different data acquisition systems including all their components, either a collective time server, where all associated components use the same network time protocol or a simple synchronisation signal, which is recorded and timestamped by the different components and data acquisition systems, can be deployed. Concerning the accuracy, both methods are sufficient.

When assigning the square-wave method to synchronise the data sets, the square-wave signal is used to shift the data in post-processing and to erase the temporal shift between the two data sets. The square-wave can have, e.g., an amplitude of $\hat{u}_{\text{sync}}$=±5 V and a frequency of f_{square} = 0.2 Hz. While a rough alignment of the data sets is achieved by the logged start time and by distinctive signal changes as shown in Figure 2a), the fine synchronisation is based on the square-wave signal, which is depicted in Figure 2b).

An advantage of the timewise synchronisation using a square-wave signal is its easy implementation in different test benches with all kinds of data acquisition systems.

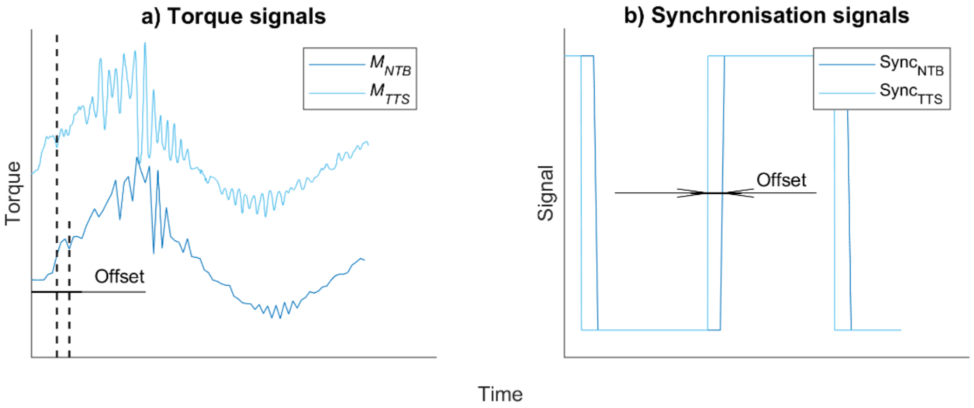

Figure 2 Timewise synchronisation of the data sets of the torque transfer standard and the nacelle test bench using an ideal square-wave signal, which is recorded by both data acquisition systems, for a precise alignment of the different data sets.

2.4 Example of a set-up

In the example of a calibration set-up in Figure 3, the torque transfer standard that measures the reference torque is placed directly at the hub flange of the device under test as required.

Moreover, an overview of the requirements on the transfer standard based on a survey of test bench operators within the EMPIR 14IND14 project is listed in Table 3, while the general requirements regarding the dimensions and the weight of the transfer standard are listed in Table 4.

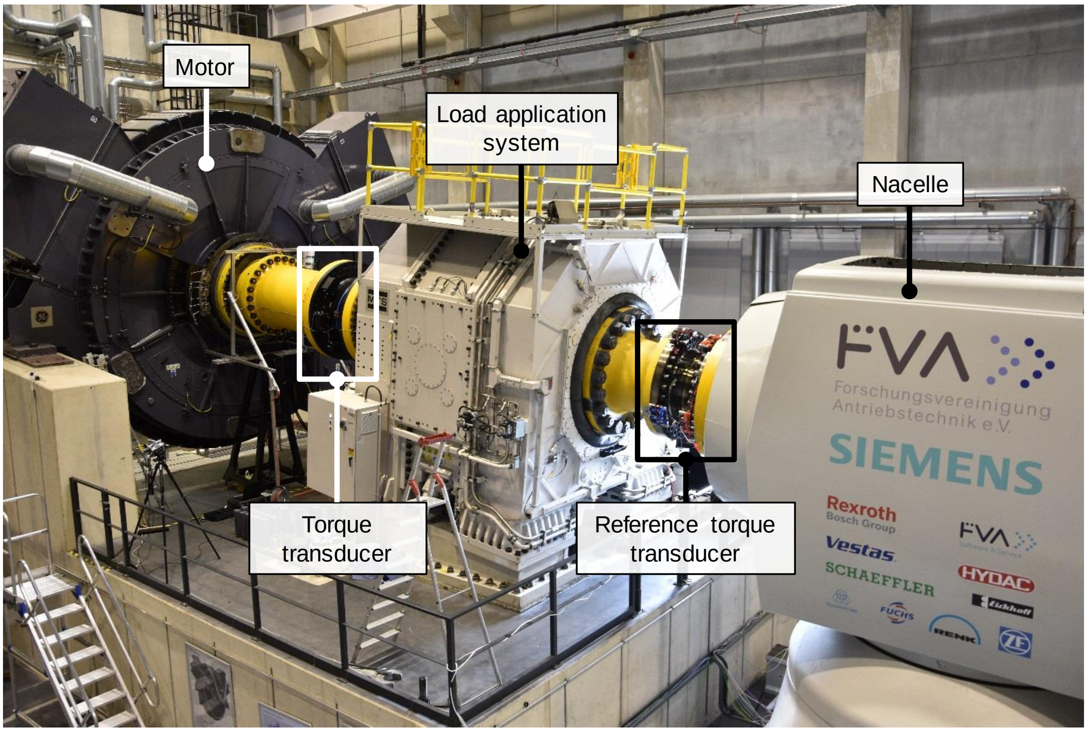

Figure 3 The reference torque transducer to calibrate the torque measurement in a nacelle test bench is installed directly at the hub flange of the device under test, where the mechanical input to the device under test is to be determined (4 MW nacelle test bench of the Center for Wind Power Drives at RWTH Aachen).

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Table 3 Requirements of the RWTH Aachen test bench on torque transfer standards for calibrating nacelle test benches regarding the carrying capacity taken from [8].

Torque			
Nominal torque	kN m	± 6000	
Maximal torque	kN m	± 7000	
Torque measurement accuracy	%	0.1	
Forces and moments		**Parasitic loads**	**Operating loads**
Forces (F_x, F_y, F_z)	kN	± 100, ± 100, ± 100	± 1450, ± 2000, ± 2000
Maximum forces (F_x, F_y, F_z)	kN	± 100, ± 100, ± 100	± 2000, ± 3000, ± 3000
Moments (M_y, M_z)	kN m	± 100, ± 100	± 7500, ± 7500
Maximum moments (M_y, M_z)	kN m	± 100, ± 100	± 15000, ± 15000
Forces/moments must be transmitted		Requirement	
Measurement of forces/moments		Optional	
Lifecycles			
Static stress assessment (cycles @ max. torque)		5000	
Fatigue stress assessment (cycles @ max. torque)		Failsafe	10^{12}
Kinematic			
Nominal rotational speed	min^{-1}	12	
Maximum rotational speed	min^{-1}	25	
Measurement during rotation		Requirement	
Measurement in both rotational directions		Requirement	

Table 4 Dimensional requirements of PTB's 1.1 MN m torque standard machine on a torque transducer to be calibrated and, afterwards, to be deployed to calibrate the torque measurement instrument in the nacelle test benches of RWTH Aachen.

Dimensions			
Maximum flange diameter for calibration machine	m	1.25	
Maximum flange diameter for test bench	m	4.5	
Minimum length for calibration machine	m	0.6	
Maximum length for calibration machine	m	2.2	
Maximum weight for calibration machine	t	2	
Flanges: through-hole			Requirement
• 30 x M36 on bolt circle Ø 900 mm			Requirement
• For test benches, an adapter is required			Optional

Additionally, there is a list of metrological requirements on the behaviour of the transfer standard in Table 5.

Table 5 Metrological requirements on a torque transfer standard to become an adequate torque transfer standard.

Metrological parameters	
Non-linearities	≤ ± 0.05 %
Hysteresis	$\leq 2.9 \cdot 10^{-5}$ mV/V
Interpolation deviation	≤ |0.019| %
Drift over time	$\leq 8 \cdot 10^{-3}$ %
Creep (short term creep)	$\leq \lvert 3 \cdot 10^{-3} \rvert$ %

An example of a torque transfer standard for nacelle test bench calibration is shown in Figure 4. This transfer standard is owned by PTB, the national metrology institute of Germany, and was produced by Hottinger Baldwin Messtechnik GmbH. It has a measurement range of 5 MN m and is statically calibrated up to 1.1 MN m with an expanded relative uncertainty of $8.8 \cdot 10^{-4}$ ($k = 2$) according to DIN 51309 (which is comparable to EURAMET cg-14) using the world's largest torque standard machine located at PTB. Due to the very small non-linearities of the torque transfer standard, a linear regression curve was ascertained for clockwise torque load applied in increasing and decreasing steps:

$$M = 3851.1 \text{ kN m/(mV/V)} \cdot S \quad . \qquad (2)$$

Above 1.1 MN m, a calibration is not possible. To predict the relation between the output signal and the applied torque, including a predicted measurement uncertainty taking the prediction itself into account, an extrapolation method was developed.

The current drift, the sensitivity deviation over time between the periodically repeated calibrations of the transducer, is given at $-3.10 \cdot 10^{-5}$ kN m/(mV/V). The torque transfer standard is to be recalibrated at least every two years and also between test bench calibrations. All assignments and the prevalent temperature and humidity are to be documented at all times, even during transportation.

Besides two redundant bridges for measuring the applied torque, the transducer is equipped with measurement bridges to sense longitudinal and lateral forces and bending moments as required. However, these bridges are not calibrated.

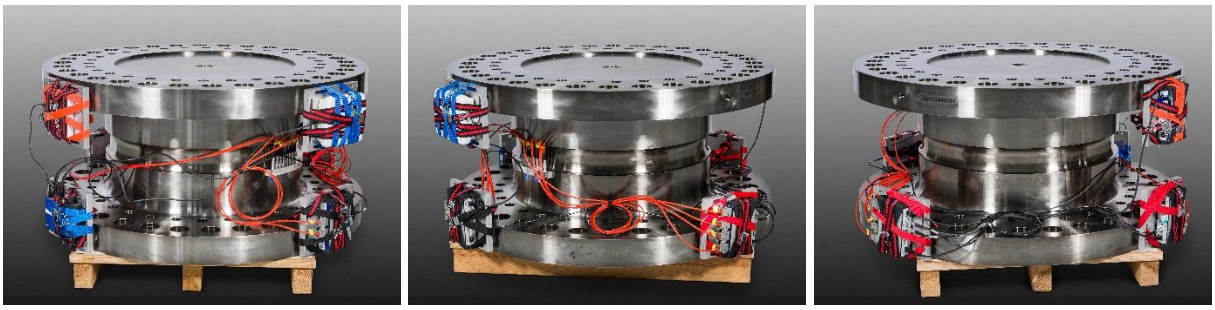

Figure 4 360° view of the torque transfer standard with a 5 MN m measuring range equipped with a data acquisition system and a telemetry system to transmit the acquired measurement data.

The data acquisition system of this transfer standard is independent and self-sufficient and consists of a very precise carrier frequency amplifier (225 Hz) for the two torque bridges, two more carrier frequency amplifiers (600 Hz) for the additional measuring bridges, a battery pack, and an access point communicating via a wireless local area network with a non-rotating access point on the ground to transmit the measurement data.

In this set-up, two independent but timewise synchronised data acquisition systems were used. As a consequence, the data acquisition of the transfer standard had to be self-sufficient with wireless data transmission. For that reason, a battery pack was needed as an independent power supply during rotation. To ensure appropriate wireless data transmission, the measurement signals had to be amplified and digitalised directly at the transducer and they had to be transmitted afterwards. The required signal amplifiers, the battery pack and the transmitter were distributed symmetrically on the flange of the transfer standard to avoid objectionable torque/force shunt.

3 Performing a torque calibration

The torque calibration procedure developed is based on static torque calibration, which is regulated in EURAMET cg-14 [6]. However, static torque calibration does not consider the effects of torque measurement under rotation. To remedy this, a new procedure for torque calibration under rotation was developed, in particular, for test benches and is introduced in this good practice guide. Further information about the development approach and about the first calibrations can be found in the following publications:

G. Foyer, S. Kock 2017 Measurement uncertainty evaluation of torque measurements in nacelle test benches in TC3 IMEKO in Helsinki, Finland

G. Foyer, S. Kock, P. Weidinger 2018 *Influences in nacelle test benches, their effects on the measurement uncertainty and consequences for a calibration* submitted to ACTA IMEKO (15/08/2018)

P. Weidinger, G. Foyer, S. Kock, J. Gnauert and R. Kumme 2018 Development of a torque calibration procedure under rotation for nacelle test benches in IOP Conf. Series 1037

3.1 Preparatory operations and tests

Before each calibration, several important preparatory operations and tests are to be performed:

- warming up of all electrical components
- noting the influences of warming up the mechanical components in the test bench
- preloading the torque transducers after the first mounting to minimise time effects (e.g. creep)
- investigating the mechanical behaviour with the transfer standard being part of the drive train
- testing for electro-magnetic compatibility.

Prior to every measurement, all electrical components, such as amplifiers and strain gauges, are to be heated up for at least $t_{\mathrm{heat}} = 20$ min. Moreover, the effects caused by warming up the mechanical components of the test bench, such as the drive train suspension and possible gearboxes, are to be analysed by monitoring the torque and rotational speed measurement and the oil temperature of lubricated mechanical components while operating the test bench at nominal speed and torque for about 30 min.

To ensure relatively stable ambient conditions, to investigate the behaviour of the calibration set-up considering additional components (e.g. the transfer standard plus adapters) and to get rid of time effects after the first installation, the test bench should be operated in its current operational range. This operational range depends on the device under test and the boundary conditions of the transfer standard. The dwell time t_{dwell} for the following measurements is to be determined based on the settling time of the set-up in the aftermath of a rotational acceleration or deceleration or an increase or decrease of the torque load. Both torque and rotational speed can be increased or decreased either in a defined unit step, a single or partitioned ramp or a sine as shown in Figure 5.

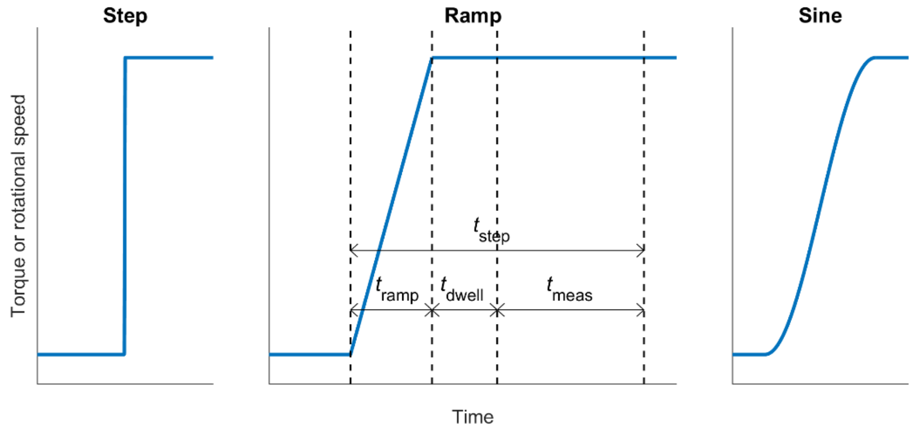

Figure 5 Schematic depiction of the torque or rotational speed increase or decrease possibilities in a test bench and the time sequences for the calibration measurements.

The form of torque and rotational speed application should be considered for the determination of both the time to ramp up t_{ramp} and the dwell time t_{dwell}, while the measurement time t_{meas} highly depends on the minimum rotational speed n_{min}, the number of revolutions I that are averaged over, which is explained in section 3.3, and the control behaviour of the entire set-up. The required holding time per load step t_{step} can be calculated as follows:

$$t_{\text{step}} = t_{\text{ramp}} + t_{\text{dwell}} + t_{\text{meas}}(n_{\text{min}}, l) \quad . \tag{3}$$

Furthermore, the amplifiers and the data transmission system(s) are to be tested prior to the calibration measurement campaign for electro-magnetic compatibility because of the high-powered machines in a test bench, e.g., prime mover, generator, frequency transformer. Especially the transfer standard and its data acquisition system are to be examined for purposely caused interferences, while the electro-magnetic compatibility of the measurement instruments in the test bench is to be ensured.

3.2 Ambient and boundary conditions

During the calibration measurements, attention is to be paid to the ambient and boundary conditions, which include:

- the alignment of the torque measurement instruments (the internal torque transducer and the torque transfer standard),
- the maximum constraint forces (depending on the deployed torque transducers, the device under test and the test bench itself),
- the temperature and humidity range along the test set-up, and
- the direction of the rotation under torque load.

The torque transducers are to be aligned very precisely regarding the concentricity of the transducers and all adapters. Moreover, it is important that all connected components are planar and assembled without any tilting. Any misalignments can cause parasitic permanent loads, e.g., axial and lateral forces and bending moments. During the calibration process, the test bench conditions, such as couplings, bearings and bolted connections, must remain unchanged.

Any parasitic or additional loads evoked by misalignments, the test bench control system or the load application system must be less than the maximum constraint forces and moments as stated in section 0, considering the superposition of applied forces and moments.

Ideally, not only temperature and humidity at both torque measurement instruments, but also the temperature gradients along the test set-up are measured. The ambient temperature during the calibration process is to be between 10°C and 35°C and is to be documented. Furthermore, all mechanical and electrical components are to be acclimatised before the calibration process. The mechanical components, such as the torque transfer standard, need to be installed and taken into operation one day prior to the calibration measurements. Furthermore, the electronic components need to be stored with the supply power for at least $t_{\text{heat}} = 20$ min prior to every single measurement to ensure that they are heated sufficiently. If the temperature of the torque measurement instruments changes by more than 5 K per calibration measurement, the indicated torque value is to be corrected depending on temperature. Because of the hermetical sealing of the strain gauges of most torque measurement instruments, an alteration in humidity is uncritical, as are the pressure influences, which are not measurable on torque transducers using strain gauges.

Most nacelle test benches have a preferential direction of rotation under the torque load which is to be calibrated. In the case that the test bench can be loaded with clockwise as well as with anti-clockwise torque, both possibilities should be calibrated, and the direction of application is to be documented.

3.3 Signal evaluation

As for calibrations of all kinds, the raw data should always be kept in case specific sequences need to be analysed further after the calibration. For the calibration, all signals should be corrected for alternations in the ambient conditions.

To account for dead-weight effects on the output signals $S_{\text{meas,i}}$, all signals are to be averaged over a multiple integer, but at least over one full rotation of the main drive train where the torque is measured. An averaging over a larger number of revolutions results in a filtering of mechanical noise, but it also makes time-dependent effects, such as creep or an instable test bench control, invisible. The definition of one revolution is based on the averaged measurement signal of the rotational speed $\bar{n}_{\text{NTB}}$ ($\bar{n}_{\text{NTB}}$ is to be averaged over the measurement time t_{meas}). Consequently, to minimise errors due to the data evaluation, the resolution of the rotational speed is to be adjusted as explained in section 2.3.1. It is advised to keep the number of rotations l that are averaged over constant for all evaluations of a calibration. Attention might have to be paid to the deployed measurement time per load step especially for lower speeds of rotation as these might grow quite large. The signals are averaged as follows:

$$\bar{S} = \frac{1}{m} \cdot \sum_{i=1}^{m} S_{\text{meas},i} \quad , \qquad (4)$$

with

$$m = \frac{l}{n_{\text{NTB}} \cdot 1\,\text{min} \cdot (60\,\text{s})^{-1}} \cdot f_{\text{sample}} \quad , \qquad (5)$$

and

$$l \in \mathbb{Z}_{>0} \quad . \qquad (6)$$

For further analysis, all measurement signals $\bar{S}_{\text{NTB/TTS}}$ are to be corrected for the offset signal $\bar{S}_{\text{zero}}$ of the transducers without loads applied and in the initial position. This offset is called the zero signal and its determination will be explained in detail in section 3.4. In the case of a hard-taring possibility of any measuring instruments in the test bench, these mechanisms should be locked before starting the calibration and are not to be manipulated in future. A manual taring of any measurement instruments during or after the calibration might end up making the calibration useless.

$$S_{\text{NTB/TTS}} = \bar{S}_{\text{NTB/TTS}} - S_{\text{zero,NTB/TTS}} \quad . \qquad (7)$$

Since hitting eigenfrequencies of a higher order cannot be avoided, the measurement data has to be checked for possible dynamic influences. These resonance effects should not be considered in the evaluation.

3.4 Determination of the zero signal

A crucial parameter for any calibration is the zero-point determination. Its quality and correctness affect all other results of the calibration since it is used to eradicate the signal offset caused by tension due to the assembly in all measurement data of the load cycle that follows.

In EURAMET cg-14 [6] and other common calibration standards, the zero signal is to be taken in an unloaded condition where $M = 0$ kN m. In the case of a test bench with a horizontally aligned drive train and torque transducers, this would be a signal in only one position of the transducer including influences caused by the dead-weight and possible misalignments of the transducer and the drive train. This means the transducers are always loaded with a bending moment and a lateral force due to their own weight and any misalignments, which may be different for each relatively rotated position, and this does not comply with the operation mode of the test bench under rotation. Thus, a simple zero signal in an unloaded condition is not sufficient for the application in a test bench.

To overcome this issue, two options are possible: i) static zero-signal determination with static measurements equally allocated over one full rotation as depicted in Figure 6a) and explained in section 3.4.1; and ii) zero-signal determination under rotation with minimum rotational speed illustrated in Figure 6b) and outlined in detail in section 3.4.2. Both approaches have to tackle one main issue; neither the transfer standard nor the test bench transducer can be dismounted after each load cycle for zero-signal determination. For this reason, the zero signal has to be captured with the entire set-up.

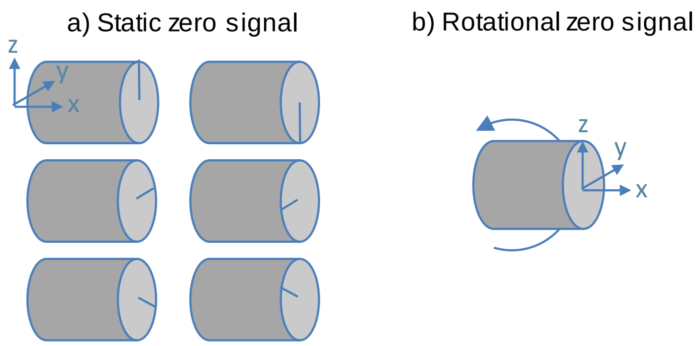

Figure 6 Two different approaches to zero-point determination: a) static and b) rotational.

3.4.1 Static zero-point determination

For static zero-signal determination, the zero-torque signal is to be measured over incrementally rotated positions relative to the main axis of the drive train. It is important that the entire drive train is rotated without mounting or dismounting any components before or afterwards. The number of distinct positions *p* per full revolution depends on the measurement system of the transducer deployed. For direct torque measurement using a deformation body with strain gauges, 3·120° measurements are sufficient, while for a force lever system, 6·60° (Figure 6a)) measurements should be gathered. In general, the number of measurement positions should reflect the specific test set-up and its effects. More or fewer measurement positions are possible, but a full rotation and an equal distribution of the measurements should be ensured. Per position, the signal $\overline{S}_\mathrm{i}$ is to be averaged over t_meas = 20 s after a dwell time t_dwell, which corresponds to the dwell time for all other loading steps. The static zero signal $S_\mathrm{zero,stat}$ is then the mean of the averaged signals $\overline{S}_\mathrm{i}$ of one full rotation:

$$S_\mathrm{zero,\,stat} = \frac{1}{p} \cdot \sum_{j=1}^{p} \overline{S}_j \quad , \tag{8}$$

with $$\overline{S}_j = \frac{1}{n} \cdot \sum_{k=1}^{n} S_k \quad , \tag{9}$$

and $$n = t_\mathrm{meas} \cdot f_\mathrm{sample} \quad . \tag{10}$$

This method, depending on the number of measurement positions, can be very time-consuming. It could be used as an alternative one-off zero-point determination when a new drive train is set up to monitor the tension state of the drive train. Furthermore, an additional static zero-point determination once a week makes it easier to assess the stress state of the torque transducers and the drive train, and it could reveal additional, unanticipated influences on the system.

3.4.2 Rotational zero-point determination

The rotational zero signal can be determined either before connecting the transfer standard to the device under test or afterwards with the entire test bench set-up. As for all measurements, the signals are to be recorded continuously. The advantage of performing the rotational zero-signal determination before connecting the drive train to the device under test is that no friction torque caused by the generator exists. On the other hand, it is disadvantageous that the set-up does not match the final calibration set-up, where the drive train is connected to the device under test, and that disconnecting the drive train between the different load cycles is related to a certain amount of effort.

The friction influence could be overcome by switching on the generator and its control system, which may act as an additional motor and, consequently, may compensate for the torque losses due to friction. To be able to proceed in this way, full access to the device under test's control system is essential. If a control to M = 0 kN m is unstable or not possible at all, the zero signal is to be determined with the generator control switched off.

For this zero-signal determination, the test bench is to be operated at the minimum rotational speed possible n_min. The output signals are to be averaged over an integer number of revolutions *l*. Ideally, the same number *l* as for the averaging of the signals under load later is used.

$$S_\mathrm{zero,\,rot} = \frac{1}{m} \cdot \sum_{i=1}^{m} S_i \quad , \tag{11}$$

with $$m = \frac{l}{n_\mathrm{NTB} \cdot 1\ \mathrm{min} \cdot (60\ \mathrm{s})^{-1}} \cdot f_\mathrm{sample} \quad , \tag{12}$$

and $$l \in \mathbb{Z}_{>0} \quad . \tag{13}$$

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It is most suitable to proceed as stated in EURAMET cg-14, where the zero signal is determined before and after each load cycle with no load applied ($M = 0$ kN m), as represented in Figure 7.

This zero-signal determination could also be incorporated into the general test routine of the implementation of a new device under test to get a reliable zero signal.

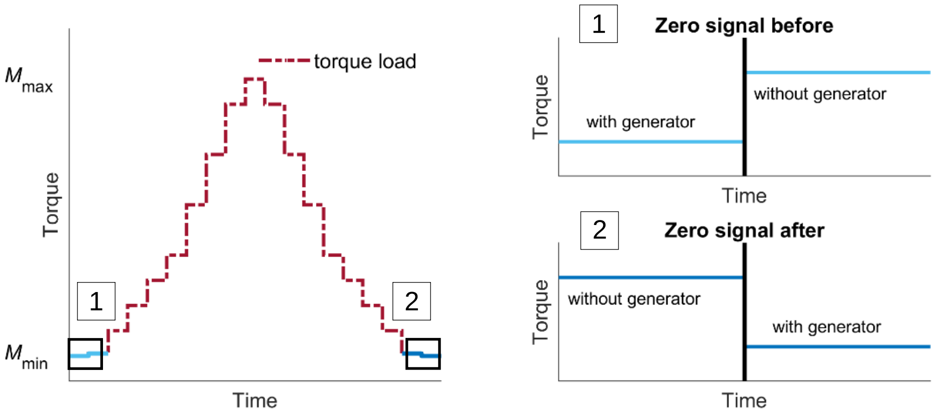

Figure 7 Schematic figure of a stepwise increase and decrease of the torque load at 6.5 min^{-1} and the rotational zero-point determination before and after the load cycle with generator switched off (without generator) and on (with generator).

3.5 Quasi-static torque calibration

Since the torque transfer standard cannot be calibrated under rotation, a first comparison measurement under minimum rotational speed $n_{\min}$ is to be performed comparing the results to the static calibration of the transfer standard. This quasi-static calibration is to be executed according to EURAMET cg-14 with the same load steps as during the static calibration of the torque transfer standard if possible. Due to the additional loads permanently applied by the load application system for control reasons and the continuous rotation, it is not necessary to mount the transducers in three different mounting positions as defined in EURAMET cg-14. However, it is requested to repeat the load cycle at least three times to ensure the determination of the measurement repeatability. For a statistical evaluation of the calibration, at least three repetitions of the load cycle are required.

While rotating under a constant minimum rotational speed, the torque is to be applied stepwise in defined increments and decrements up to the maximum load of the static calibration as illustrated in Figure 8. The torque can either be applied in a ramp or as a step or a sine. In the case that the test bench operates in both directions, this quasi-static calibration is to be executed for both directions. As stated before, the zero signal is to be determined before performing the load cycle.

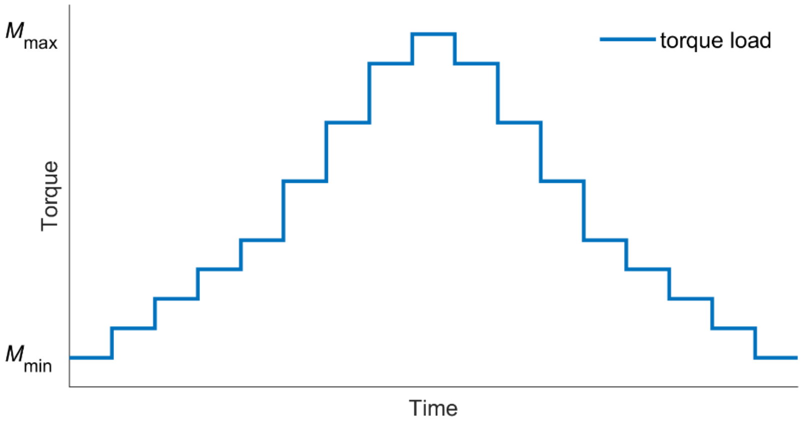

Figure 8 Schematic figure of a quasi-static torque calibration with defined increasing and decreasing torque steps.

3.6 Characterisation maps

Nacelles and other devices under test have device-specific operating points as a combination of torque and rotational speed, which vary from device to device. When calibrating a test bench, all these operating points are to be mapped by applying different combinations of torque and rotational speed.

So-called *characterisation maps* provide a simple solution for rectifying this problem. A similar procedure to this has been suggested for rotatory power measurement [1].

Most test benches have a defined main direction of rotation. For these test benches, only one direction of torque load is to be calibrated. However, if downwind nacelles are tested on the test bench, both torque application directions are to be calibrated. Moreover, since negative torque can appear during braking scenarios, the effect of applying negative torque on the hysteresis behaviour and the zero return should be analysed for all nacelle test benches.

To define the measurement points of the *characterisation maps*, the typical operating range of the test bench, depending on the commonly tested devices, is to be listed. The typical operating range is depicted in Figure 9 in the form of a blue rectangle. It should be pointed out that the range of the *characterisation map* is limited by the installed device under test during the calibration measurements. For that reason, the device under test is to be picked accordingly.

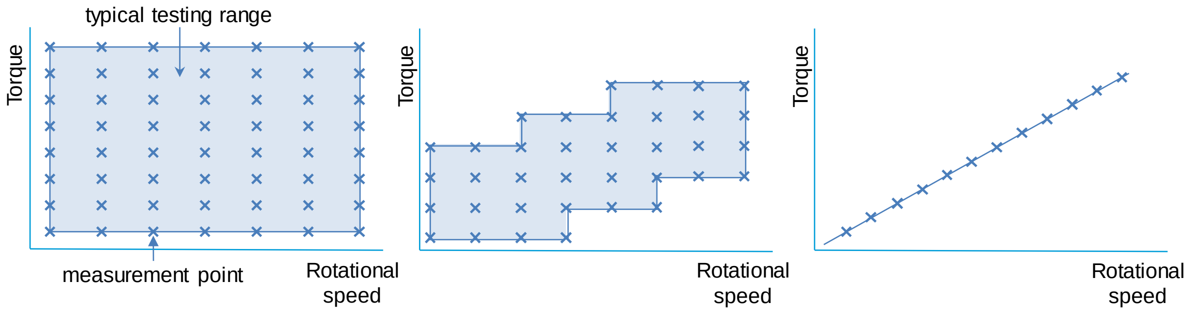

Figure 9 Schematic depiction of a characterisation map based on the typical testing range of a nacelle test bench with a uniform distribution of the measurement points.

When there are no particular points within the operating range which need to be calibrated explicitly, such as typical maximum torque loads for certain devices under test, the load steps should be spread evenly as shown in Figure 9 in the form of the *X*s. In general, the calibration should cover the entire operating range of the test bench by repeating the standard calibration with different combinations of torque load and rotational speed (Figure 10). To investigate the influence of rotational speed on the torque measurement, there are two different categories of *characterisation maps*: for CM1 (CM1a and CM1b in Figure 10), the torque is periodically fixed while the rotational speed is altered stepwise; and for CM2 (CM2a and CM2b in Figure 10), the rotational speed is kept constant periodically while the torque load is increased and decreased. All forms of the *characterisation map* have the same operating range. To determine the hysteresis of the test bench torque transducer, each calibration point should be met twice during one load cycle: first when raising the increment and second when attenuating it again. Attention is to be paid to omitting rotational speed steps close to eigenfrequencies of the system, which would lead to undesired dynamic effects.

Here again, both the torque and rotational speed can be increased or accelerated respectively stepwise as a ramp, a step or a sine, whereby the ramp is the most common one. Moreover, if this type of combined calibration is not sufficient, single calibrations for each typical load, so-called partial range calibrations, can be performed. For a statistical evaluation of the calibration measurements, each *characterisation map* is to be repeated twice or each load step is to be passed at least four times. Should a calibration like this not be possible at all due to a lack of access to the control system of the device under test, the calibration has to be performed in the median of the typical testing range (see Figure 9c)) with a suitable standard device under test. Because of the set-up and the permanently acting control systems in a test bench, the determination of the transducer creep is not possible, which should not pose a problem.

At least one map per category (CM1 and CM2) is to be performed in order to investigate the influence of the rotational speed on the torque measurement. If a closed loop control is not possible, then performing only CM2 is sufficient, since the reproducibility of CM1 would not be good without a closed loop control anyway.

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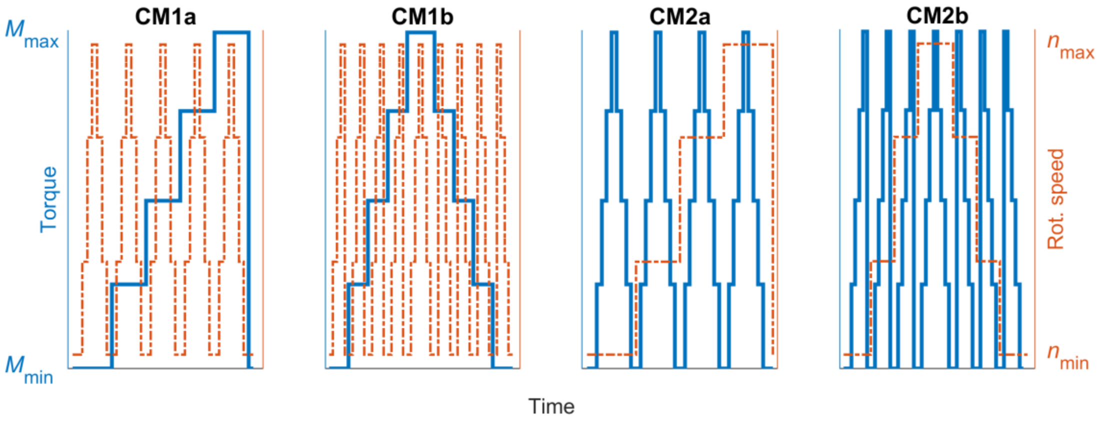

Figure 10 Example of different load step sequences for a calibration with torque being increased (and decreased) and rotational speed being accelerated and decelerated at each torque step and vice versa.

3.7 Crosstalk effects

The assembly process and the integration of the nacelle into the test bench are challenging, because of the large masses and dimensions of nacelles. For example, a 5 MW nacelle has the following dimensions: 6.5 m height, 6.5 m width and 17 m length and a total mass of 290 t. Even a very accurate assembly leads to an axis *misalignment* between the main shaft of the test bench and the hub of the nacelle. This axis misalignment may be in the range of up to 0.5 mm and, thereby, it may generate parasitic loads in the form of forces (F_x, F_y, and F_z) and bending moments (M_y and M_z) under rotation.

The control system of the load application system tries to keep these parasitic loads to zero. However, due to the inaccuracy of the control system, the perfect limitation of the parasitic loads to zero is not possible in most cases. Consequently, an application of pure torque during the calibration is not possible. Figure 11 shows examples of the additional loads on the torque transfer standard within the averaging sequence over an integer number of distinct rotations (here six rotations).

Additional influences on the torque transducer are not desired as they not only have an influence on the intended measuring bridges but also on the other measuring bridges, which causes an unintentional signal alteration.

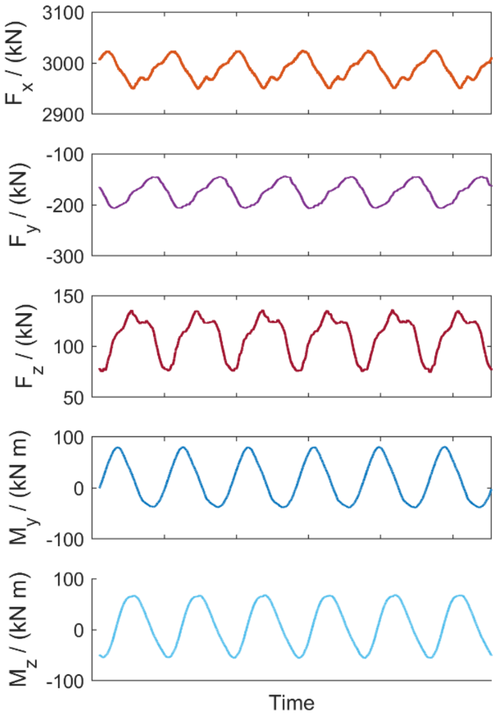

Figure 11 Parasitic loads during the calibration at the torque step of 1000 kN m and rotational speed of 6.5 min^{-1}.

The close surveillance of additional loads is, therefore, necessary to avoid unwanted influences on the torque measurement. However, most periodic influences of additional loads can be neglected due to the averaging of the torque signal.

To purposely study crosstalk influences on the torque signal, *characterisation maps* similar to Figure 12 are suggested.

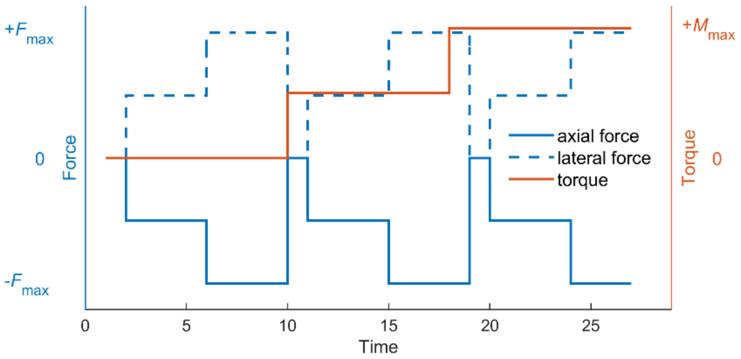

Figure 12 Schematic principle for investigating the crosstalk influence on the torque signal caused by additional loads.

3.8 Calibration interval

For test benches involved in development tests of test benches in general or in the development of the devices under test, the calibration interval should not exceed 12 months.

The calibration interval of the torque measurement instrument in the test bench highly depends on the set-up and the usage of the test bench and the quality procedure in the test bench. For test benches, which are mainly used to determine the efficiency of the device under test, the recommendation for the calibration interval is rather long at up to 24 months.

After every change of the underlying regression curve or any maintenance or alignment concerning the torque measurement instrument, a recalibration is required.

Ideally, a calibration at the beginning and at the end of a device under test being assembled and tested would be preferable. In reality, however, the utilisation and activity of the test bench need to be considered as well.

4 Evaluation of the calibration result including a measurement uncertainty

The set-up for calibrating a torque transducer in a test bench by using a torque transfer standard is comparable to a reference torque calibration machine. In a reference torque calibration machine, a calibrated and very well-known torque transducer is deployed to calibrate another torque transducer. Due to the similarity of the set-up, the effects during the calibration are analogous.

Other than the load cycles, which are based on EURAMET cg-14, the evaluation of the calibration result is based on ISO 7500-1 [4]. ISO 7500-1 describes the calibration of a force measurement system in material testing machines. Here, the deployed method does not necessarily demand that the exact load steps are met. Instead, an indication deviation between the transducer to be calibrated and the transfer standard is calculated.

For the torque calibration in test benches, the calibration result is adapted to the calibration result in ISO 75100-1 and consists of:

- the relative indication deviation q,
- the measurement uncertainty u_c for the indication deviation, and
- the reversibility (in case increasing and decreasing torque load was applied).

The calibration result is not a classification of the transducer calibrated as is common for calibrations.

The calibration result can be used in the form of:

- a look-up table (to correct the result by consulting the table),
- a regression curve (to correct the result in post-processing), or
- a correction of the underlying regression curve of the test bench transducer (requires a second calibration of the test bench transducer using the corrected regression curve to determine the measurement uncertainty).

The evaluation of an example of a torque calibration under constant rotation can be found in the following publications:

P. Weidinger, G. Foyer, S. Kock, J. Gnauert, R. Kumme 2018 *Procedure for torque calibration under constant rotation investigated on a nacelle test bench* in Proc. of Sensoren & Messsysteme 2018, Nuremberg, Germany

P. Weidinger, G. Foyer, S. Kock, J. Gnauert, R. Kumme *Calibration of torque measurement under constant rotation in a wind turbine test bench* submitted to JSSS.

4.1 Evaluation of the transducer to be calibrated

The performance of the torque transducer to be calibrated can be evaluated by the relative indication deviation q, the relative repeatability b, the relative resolution a, and the determination of the relative reversibility v when a calibration of decreasing torque is desired. All the following subsections are adapted from ISO 7500-1.

4.1.1 Relative indication deviation

The relative indication deviation $q_j(M_\mathrm{L})$ is the deviation of the torque measurement instrument in the test bench from the torque transfer standard relative to the real torque value measured by the torque transfer standard per load step M_L. It is to be calculated for each of the at least two repeated load cycles j (1 and 2) or *characterisation maps*:

$$q_j(M_\mathrm{L}) = \frac{M_{\mathrm{i},j}(M_\mathrm{L}) - M_j(M_\mathrm{L})}{M_j(M_\mathrm{L})} \cdot 100\% \quad , \qquad (14)$$

with $j = 1,\ldots,\mathrm{n}$,

where M_i is the increasing torque load indicated by the torque measuring instrument in the test bench, and M is the increasing torque load indicated by the torque transfer standard.

The calibration result is represented as a relative indication deviation $\bar{q}(M_\mathrm{L})$, which is the arithmetic mean of the relative indication deviation per repetition $q_j(M_\mathrm{L})$:

$$\bar{q}(M_\mathrm{L}) = \frac{1}{n}\sum_{j=1}^{n} q_j(M_\mathrm{L}) \quad . \qquad (15)$$

Figure 13 is an example of a depiction of the relative indication deviation for a quasi-static load cycle under constant rotation. To assess the calibration result and the interrelation between the applied torque and the rotational speed, not only is the relative indication deviation to be calculated, but also the standard deviation for this value. Depending on the standard deviation for the repeated measurements, a distinction between the torque deviations contingent on the different applied rotational speeds can be made.

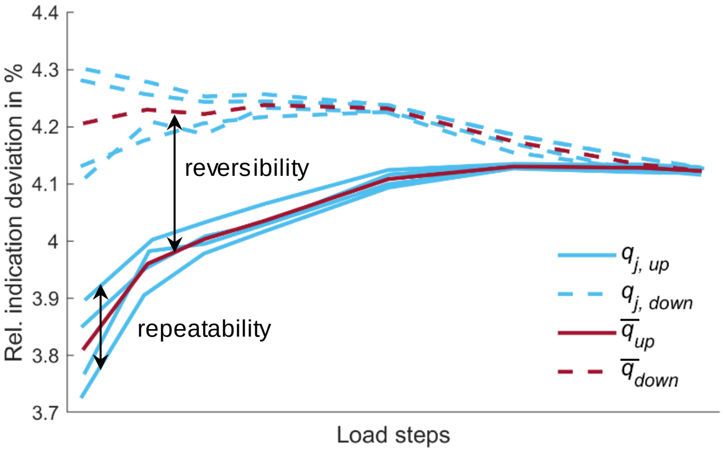

Figure 13 Example of indication deviation for four repetitions and averaged indication deviation.

4.1.2 Relative repeatability

The quality of repeating the torque measurements in the test bench is described by the relative repeatability *b*. This relative repeatability is calculated for each load step separately and is the difference between the maximum indication deviation $q_{\max}$ and the minimum indication deviation $q_{\min}$ per load step:

$$b(M_{\mathrm{L}}) = \max_{j}\left(q_j(M_{\mathrm{L}})\right) - \min_{j}\left(q_j(M_{\mathrm{L}})\right) \quad . \qquad (16)$$

The relative repeatability is an important contribution to the measurement uncertainty and an example of this is illustrated in Figure 13.

4.1.3 Relative resolution

Most test benches are state of the art and display the applied load digitally. Therefore, the focus regarding the resolution *r* lies on digital torque displays. In general, the resolution depends on the resolution of the amplifier's A/D converter and the data saving format. However, if the indication fluctuation exceeds this resolution, the resolution is to be summed up by half the span of the indication fluctuation. The indication fluctuation is to be determined with the prime mover and the device under test switched on, but with no load applied. To determine the indication fluctuation, the signal is to be averaged per revolution over the averaging sequence as depicted in Figure 14, then the minimum and maximum of the averaged signals per revolution are to be found and the difference is calculated.

Subsequently, the relative resolution *a* is to be determined for each load step depending on the applied load:

$$a(M_{\mathrm{L}}) = \frac{r(M_{\mathrm{L}})}{M(M_{\mathrm{L}})} \cdot 100\% \quad , \qquad (17)$$

with

$$r\,(M_{\mathrm{L}}) = \frac{\max_{l} \mathrm{r}_l(M_{\mathrm{L}}) - \min_{l} \mathrm{r}_l(M_{\mathrm{L}})}{2} \quad , \qquad (18)$$

where *M* is the torque load for the observed load step (averaged values of all repetitions). The resolution is to be represented in the same unit as the measured torque.

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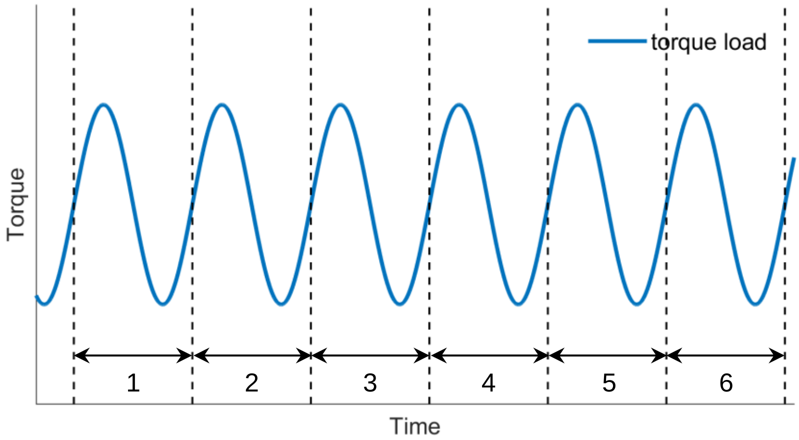

Figure 14 Schematic figure on how to determine the indication deviation per load step.

4.1.4 Relative reversibility

For the special case that a regression curve for decreasing torque load is demanded, the relative reversibility *v* for the decreasing load can be determined. However, it is to be emphasised that the reversibility highly depends on the maximum torque load applied beforehand. To determine the relative reversibility, the deployed torque transfer standard must be calibrated for decreasing torque load. Moreover, for the reversibility measurements, only one decreasing load cycle is to be performed.

Based on the deviation between the torque measurement values for increasing and decreasing load steps (Figure 13), the relative reversibility is calculated:

$$v = \frac{M - M'}{\bar{M}} \cdot 100\% \qquad (19)$$

4.2 Measurement uncertainty

As mentioned above, the prevailing calibration set-up is comparable to a reference calibration machine, where the transducer to be calibrated is compared to a national standard. Thus, in general, for an NTB calibration, the influences on the transducer to be calibrated are the same as those in a reference torque standard machine but even larger.

The measurement uncertainty itself is based on the aforementioned factors and consists of the following uncertainty contributions:

- the resolution,
- the repeatability, and
- the torque transfer standard.

All this results in the best expected value for the indication deviation and the corresponding expanded measurement uncertainty. The following evaluations are based on ISO 7500-1 and are adapted for a torque calibration under rotation.

4.2.1 Measurement conditions

In general, the influences on the torque transducer to be calibrated are the same as those in a reference torque standard machine but even larger. The Ishikawa diagram in Figure 15 lists examples of possibly occurring influences affecting the calibrated torque measurement in a nacelle test bench.

Most influences can be quantified and categorised by the aforementioned preparatory operations and tests. Additionally, all set-up-specific effects, i.e., misalignments and friction in different components are directly part of the calibration result and have already been considered in the measurement uncertainty by determining the repeatability.

Emergency braking, which may occur and is to be tested under normal testing conditions, should be avoided during the calibration process. After emergency braking, the test bench is to be operated with maximum torque load in the driving direction for at least 3 min and a new zero signal is to be determined. In doing so, the hysteresis effect due to the opposite torque load is minimised.

In the case that different amplifiers were used for the calibration of the torque transfer standard than for the calibration in the nacelle test bench, the difference between the diverse amplifiers is to be accounted for in the measurement uncertainty or even the indicated torque value.

Because of the signal averaging over a certain number of revolutions, the dead-weight influence on the torque signal can be neglected.

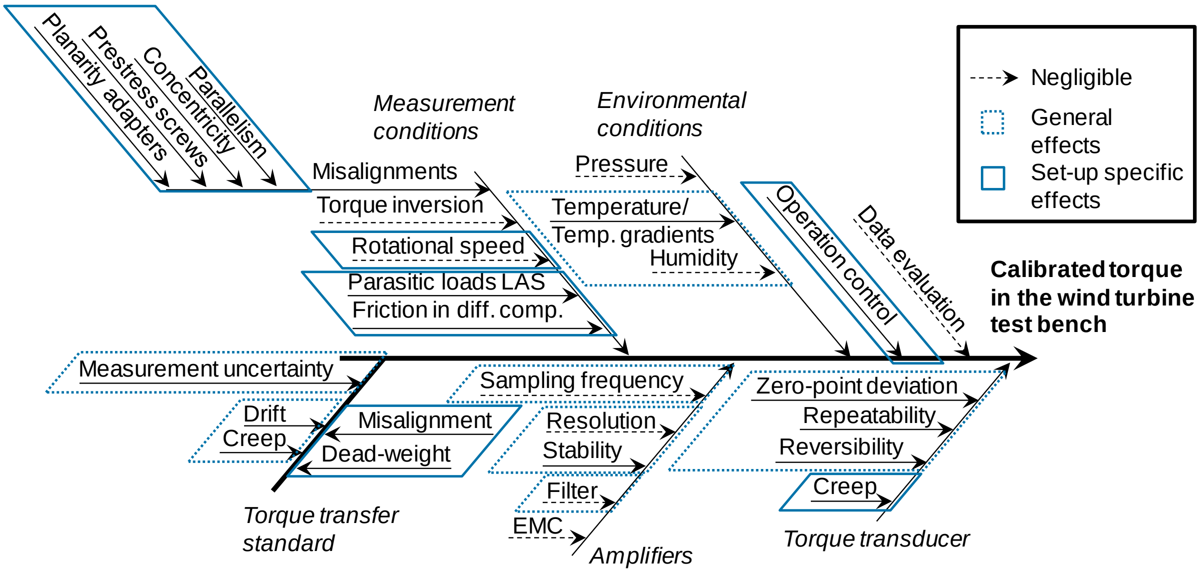

Figure 15 Ishikawa diagram listing the influences during the calibration of the torque measurement in nacelle test benches.

4.2.2 Uncertainty contribution of the resolution

The uncertainty contribution of the relative resolution of the torque measurement instrument in the test bench u_{res} for each examined load step is the square root of the sum of the following components squared:

- the uncertainty component due to the relative resolution of the torque measurement instrument in the test bench under load, which is denoted as a_{M} divided by $2\sqrt{3}$ because of the assumption of a rectangular distribution,
- the uncertainty component due to the relative resolution of the torque measurement instrument in the test bench after load release, which is denoted as a_{Z} divided by $2\sqrt{3}$ (same assumption of a rectangular distribution). The relative resolution of the torque measurement after load release is part of the indication deviation of every load step because of the aforementioned taring of the torque values for every load step.

The uncertainty contribution of the relative resolution can be calculated for every load step as follows:

$$u_{\mathrm{res}}(M_{\mathrm{L}}) = \sqrt{\left(\frac{a_{\mathrm{M}}(M_{\mathrm{L}})}{2\sqrt{3}}\right)^2 + \left(\frac{a_{\mathrm{Z}}}{2\sqrt{3}}\right)^2} \qquad (20)$$

As the relative resolution a is expressed in the unit %, the absolute uncertainty contribution of the relative resolution u_{res} is expressed in % as well.

4.2.3 Uncertainty contribution of the repeatability

As mentioned before, the relative repeatability is considered as an uncertainty contribution to the total uncertainty for the indication deviation. The uncertainty contribution of the repeatability u_{rep} is the standard deviation of the best expected value q_{i} in % and the relative mean indication deviation $\bar{q}$ in %, where n is the number of repetitions per load step:

$$u_{\mathrm{rep}}(M_{\mathrm{L}}) = \sqrt{\frac{1}{n\,(n-1)} \sum_{j=1}^{n} \left(q_j(M_{\mathrm{L}}) - \bar{q}(M_{\mathrm{L}})\right)^2} \qquad (21)$$

4.2.4 Uncertainty contribution of the transfer standard

The uncertainty contribution of the torque transfer standard u_{std} is given by the relative calibration uncertainty of the transfer standard u_{cal}, which is stated in its calibration certificate, and additional possible uncertainty contributions (A, B, and C) due to deviating temperature and humidity during the calibration measurements, drift over time, and deviations because of the deployed combined linear regression curve for increasing and decreasing torque load. The uncertainty contribution of the torque transfer standard is calculated according to the following:

$$u_{\mathrm{std}}(M_{\mathrm{L}}) = \sqrt{(u_{\mathrm{cal}}(M_{\mathrm{L}}))^2 + A^2 + B^2 + C^2} \quad . \tag{22}$$

As the uncertainty contribution of the torque transfer standard is shown as a relative uncertainty, it is expressed as a percentage (%).

4.2.5 Expected value for the indication deviation

The result of the torque calibration is the best expected value for the mean relative indication deviation $\bar{q}(M_{\mathrm{L}})$ of the torque measurement instrument in the test bench. Moreover, an expanded measurement uncertainty $U(M_{\mathrm{L}})$ belongs to this relative indication deviation, which is the product of the coverage factor k and the combined uncertainty $u_{\mathrm{c}}(M_{\mathrm{L}})$:

$$U(M_{\mathrm{L}}) = k \cdot u_{\mathrm{c}}(M_{\mathrm{L}}) = k \cdot \sqrt{\sum_{j=1}^{n} (u_j(M_{\mathrm{L}}))^2} = k \cdot \sqrt{(u_{\mathrm{res}}(M_{\mathrm{L}}))^2 + \left(u_{\mathrm{rep}}(M_{\mathrm{L}})\right)^2 + (u_{\mathrm{std}}(M_{\mathrm{L}}))^2} \quad . \tag{23}$$

Additional uncertainty contributions may be influences of the deployed amplifiers of the torque transfer standard or significant influences of the friction torque.

It is recommended to use a coverage factor of $k = 2$. In certain cases, k can also be calculated based on the number of effective degrees of freedom as stated in the GUM.

Annotation: the measurement uncertainty is an absolute measurement uncertainty of the relative indication deviation, which is represented in the unit %. The absolute measurement uncertainty has the same unit as its reference value. Consequently, the unit of the absolute measurement uncertainty is %.

4.2.6 Example of an uncertainty calculation

An example of a calculation of the measurement uncertainty for torque calibration under constant rotation is given in P. Weidinger, G. Foyer, S. Kock, J. Gnauert, R. Kumme *Calibration of torque measurement under constant rotation in a wind turbine test bench* submitted to JSSS.

This paper covers a complete consideration of a torque calibration under constant rotation in a nacelle test bench including the measurement uncertainty budget and the temperature difference between the calibration laboratory, where the torque transfer standard was calibrated, and the conditions during the nacelle test bench calibration. Moreover, a detailed calculation of the relative indication deviation for four measurement repetitions is given. The expanded ($k = 2$) absolute measurement uncertainty $U(M_{\mathrm{L}})$ for the best expected value for the relative indication deviation is calculated including the uncertainty contribution of the torque transfer standard, which comprises the drift of the transducer, the temperature influence and the uncertainty of the amplifier calibration (special case).

5 Calibration output and benefit for the test bench operator

The result of a torque calibration in nacelle test benches can be expressed in different forms:

- a look-up table (post-processing),
- a regression curve (post-processing), or
- a correction of the torque transducers underlying the transfer curve (additional calibration required afterwards).

In general, the possibly occurring indication deviations in the torque measurement of a nacelle test bench can be corrected by all the different forms of the calibration result. Moreover, the calibration gives a measurement uncertainty for the calibrated range, which is again a contribution to the measurement uncertainty of the efficiency determination.

Test bench operators can benefit from knowing the deviation between their internal torque measuring instrument and a traced national torque standard and correcting this deviation to obtain a more accurate torque measurement result. Furthermore, after a calibration, the precision including the repeatability of the torque measurement instrument in the nacelle test bench is determined. Based on this, not only can the efficiency of devices under test be determined more reliably, but also the data to validate simulations and the repeatable component testing gain credibility.

With the standardised calibration of torque measurements in nacelle test benches, efficiencies of devices tested on different test benches can be compared to each other reliably.

Glossary

- *Calibration*: operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication (VIM 2.39).
- *Characterisation map*: load cycle covering the typical operation range of a nacelle test bench. The *characterisation map* is limited by the device under test installed during the calibration.
- *Crosstalk effect*: influence of additional multi-axial loads not only on the respectively intended measuring bridges but also on the other measuring bridges, which causes an unintentional signal alteration.
- *Load cycle*: range of applied load on a measuring instrument during calibration.
- *Measurement uncertainty*: non-negative parameter characterising the dispersion of the quality values being attributed to a measurand, based on the information used (VIM 2.26).
- *Torque transfer standard*: calibrated and very well-known torque transducer, which is used to trace torque measurement to the national standard.
- *Zero signal*: offset value of a transducer in non-loaded condition. The zero signal is used to tare all measurement signals of the following load cycle.

6 References

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