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Torque calibration in the MN m range under rotation in a nacelle test bench

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Abstract

Mechanical torque M is the most important parameter for the power transmission of wind turbines in general and on nacelle test benches. However, torque measurement in nacelle test benches is not yet traceable to national standards, consequently neither its precision nor its measurement uncertainty is known. To rectify this, a calibration method for torque measurement under varying rotational speed n using a torque transfer standard was developed. The result of this calibration procedure is the relative indication deviation $\overline{q}(M_\mathrm{L})$ between the torque measuring device in the nacelle test bench and the torque transfer standard, which amounts to about 4.3 %, and the associated expanded measurement uncertainty of less than 0.26 %.

Keywords: Torque calibration, torque transfer standard, calibration procedure, nacelle test benches

Introduction

The European commission and the European countries work together to accelerate the transition of energy production with a shift to cleaner and more efficient energy systems [12]. In 2017, the wind energy sector has overtaken coal in power generation capacity with a coverage of 11.6 % of the EU's electricity demand [8]. With a capacity installation of 15.6 GW, wind power covered 55.2 % of all renewable power installations one year later and was, thus, the leading renewable energy source [8].

To support this tendency, Nacelle Test Benches (NTBs) have been taken into operation. The crucial parameter for the power transmission of wind turbines is mechanical torque M_x, called M in the following. With wind turbines having scaled up to 4 to 10 MW, the torque input rose to a new level in the multi-MN m range. However, traceable torque measurement is only feasible up to 1.1 MN m so far [11]. Moreover, the existing calibration standards, such as DIN 51309 [4] and EURAMET cg-14 [6], are not applicable to calibrate torque measurement under rotation.

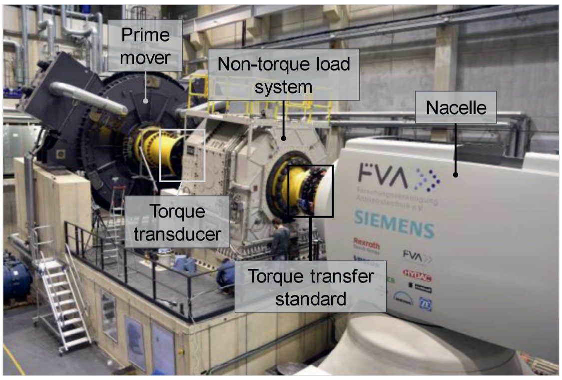

Fig. 1: Experimental set-up to calibrate the torque measurement in the NTB of the Center for Wind Power Drives (CWD) at RWTH Aachen by a TTS.

To rectify this, a procedure for torque calibration under rotation was developed [13–15]. The procedure considers two correlated input variables; torque M and rotational speed n. This paper presents the successful implementation of the calibration procedure using a 5 MN m Torque Transfer Standard (TTS) on the NTB of the Center for Wind Power Drives (CWD) at RWTH Aachen (Fig. 1).

Experimental set-up

The calibration procedure was tested and validated on the renowned NTB of CWD Aachen. As a reference standard, the 5 MN m torque transducer, which was established to be a TTS, was used.

Nacelle test bench

The main set-up of the NTB consists of a prime mover or Load Application System (LAS), the Device Under Test (DUT), and electrical power supply equipment [2]. In the field, the wind acts on the wind turbine's rotor and causes reaction loads on the drive train of the wind turbine. In NTBs, these loads are simulated by so-called Non-Torque Load systems (NTLs).

The NTB at CWD Aachen has a nominal capacity of 4 MW generated by a direct drive with a permanent-magnet motor. Moreover, the NTB is directly coupled with the DUT. The torque is measured by an internal torque transducer with a nominal range of M_{nom} = 2.7 MN m, which is permanently installed between the prime mover and the NTL. The DUT, that is required as a counter reactor to generate torque during the calibration process, was the research nacelle owned by Forschungsvereinigung Antriebstechnik e. V. [1] with a rated capacity of P_{nom} = 2.75 MW. The maximum applicable torque load of this specific set-up amounts to $M_{max} \approx 1.5$ MN m at a minimum and a maximum rotational speed of $n_{min} = 6.5$ min^{-1} and $n_{max} = 17.5$ min^{-1} respectively.

Torque transfer standard

To calibrate the torque measurement in an NTB, it is to be compared to the torque value measured by a well-known torque transducer, which is also called TTS. A TTS transfers the precision of a torque calibration laboratory into another facility, here an NTB, and, therefore, traces the torque measurement to the national torque standard.

The TTS deployed here (Fig. 2) is a hollow shaft, multi-component transducer based on the strain gauge principle to measure forces and moments in all six degrees of freedom. As it is utilised to calibrate torque measurement, the main measuring bridge is the torque bridge measuring torque *M* around the main axis of the NTB's drive train (around the x-axis).

For an application under rotation, the TTS is equipped with a self-sufficient Data Acquisition (DAQ) system including batteries and a precise amplifier (MX238B, 225 Hz carrier frequency) to digitise the measuring signals and assign them with time stamps directly at the TTS.

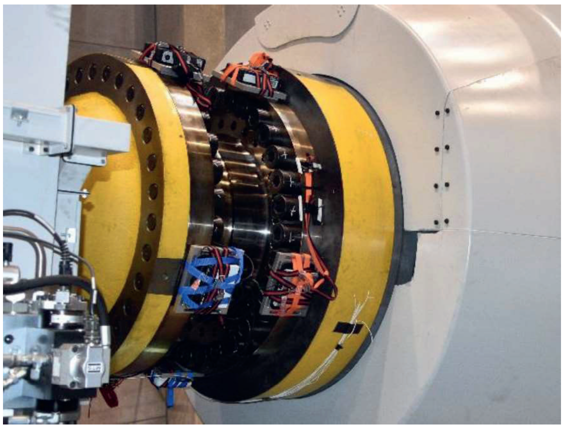

Fig. 2: TTS including DAQ and telemetry system mounted at the rotor hub flange of the nacelle under test on the NTB of CWD Aachen.

Afterwards, the signals are transmitted via WLAN through two access points to a computer. To avoid force and torque shunt and any imbalances caused by the additional platforms to mount the DAQ on the TTS, all components are disseminated symmetrically around the TTS's flanges. For an adequate resolution of 1° per revolution, the sampling frequency was set to f_{sample} = 150 Hz and the Bessel filter to f_{filter} = 50 Hz.

The 5 MN m torque transducer became a TTS by calibrating it up to 1100 kN m statically and without rotation acc. to DIN 51309 [4]. Defined within this calibration process, the coherence between the exactly applied torque steps M_p and the output signals S_p amounts to

$$M_p = 3851.1 \text{ kN m} \cdot (\text{mV/V})^{-1} \cdot S_p. \qquad (1)$$

Because of the very small non-linearities and reversibility of the TTS, a linear regression curve combined for increasing and decreasing torque load was calculated. Above 1100 kN m up to the demanded 1500 kN m, the calibration results were extrapolated using a simple extrapolation method based on the calibration data gathered [10] to estimate the measurement uncertainty of the TTS (Tab. 1).

Tab. 1: Relative measurement uncertainty (k = 1) of the TTS for the relevant torque load steps.

Torque load in kN m	**Rel. Uncert. $u_{cal}(M_L)$ (k = 1) in %**
375	0.055
750	0.045
1125	0.044
1500	0.049

As mechanical torque is to be measured to determine the power transmission of a nacelle, it must be measured directly at the nacelle's drive train input, which is the rotor hub flange.

Calibration procedure

The calibration procedure including the load cycle and the zero signal determination is based on common torque calibration standards, such as DIN 51309 [4] and EURAMET cg-14 [6]. However, these standards provide only methods for calibrations in a static manner without rotation. For that reason, a new procedure for torque calibration under various rotational speeds was developed [13].

Zero signal determination

The zero signal S_{zero} is the first signal taken before each load cycle without any load applied, as in common calibration standards, but under rotation. Its correctness and quality have an effect upon all measurement signals of the following load cycle as it is used to eliminate the offset of these signals.

Here, the zero signal was recorded with no load applied (M = 0 kN m), at the minimum possible rotational speed n_{min} = 6.5 min^{-1} and averaged over six full rotations (l = 6). To this end, full access to the nacelle control system was required. If this is not feasible, a static zero signal determination via relatively rotated positions could be performed (cf. [13]).

Load cycle

The sequences for the torque calibration are supplemented by varying rotational speed steps in order to analyse the coherence between both input parameters torque M and rotational speed n. Every DUT has device-specific operating points. As many operating points of DUTs tested on the NTB to be calibrated as possible must be mapped during the calibration process. However, the range of the so-called characterisation maps is confined by the boundary conditions of the DUT installed during the calibration measurements.

The characterisation maps are comparable to characterisation maps for electrical motors. In a characterisation map, several segments of the torque-rotational-speed-plane are passed through during the calibration procedure in order to issue a grid of reference-operating points, which are calibrated. This grid is stipulated by the minimum (n_{min}, M_{min}) and maximum (n_{max}, M_{max}) applicable torque M and rotational speed n. Ideally, the measurement points are equally spread (Δn and ΔM = const.) but hitting points of resonance must be prevented.

Moreover, to investigate the influence of rotational speed on the torque measurement and the mechanical hysteresis of the transducer to be calibrated, rotational speed and torque are combined in multiplex ways. As an example, the measurement values of one kind *cm2a* of a characterisation map are plotted in Fig. 3.

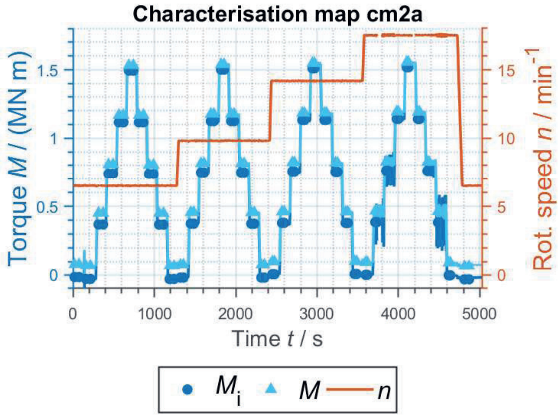

Fig. 3: Tared measurement signals of one sequence (cm2a) of the calibration procedure with varying torque (left ordinate, blue curves with symbols) and varying rotational speed (right ordinate, straight line orange curve).

The performance of the characterisation maps in the present experimental set-up was only possible due to full access to the DUT to control the torque applied. The rotational speed in turn was controlled by the NTB's prime mover.

Signal evaluation

To ensure a monitoring of all events occurring during the measurements, the data was recorded permanently. As the NTB is still calibrated per operating point (step), these points were denoted and a mean value per step over l = 6 revolutions of the drive train was build. Before doing so, a suitable dwell time per step t_{step} was satisfied, which endured for approximately 70 s per step here. As the signals were only averaged for a stationary state of the set-up, which means both M and n were constant in the aftermath of an alteration in M and/or n, t_{step} consists of different components:

$$t_{step} = t_{ramp} + t_{settling} + t_{meas}(n_{min}, l), \tag{2}$$

the time to ramp up to the predefined step t_{ramp}, the time to let the system settle down to reach a stationary state $t_{settling}$, and the actual measuring time t_{meas} depending on the minimum rotational speed n_{min} and the revolutions to average over l. The ramping up can be done fully or partially and in different ways; either in a unit step, a ramp or a sine and the ramping time varies accordingly. Moreover, the settling time varies vastly contingent on the NTB control system, which was here rather quick.

All signals per load step $\overline{S}_{meas}$ were average over an integer number l of revolutions (based on [3]), which was here $l = 6$, a compromise between the required measurement time and a sufficient number of revolutions, once a stationary state was reached.

$$\overline{S}_{\text{meas}} = m^{-1} \cdot \sum_{i=1}^{m} S_{\text{meas},i} \quad (3)$$

$$\text{with } m = \frac{60\ \text{s}}{n_{\text{NTB}} \cdot 1\ \text{min}}, \quad (4)$$

$l \in \mathbb{Z}_{>0}$, here $l = 6$.

The arithmetic mean is required to minimise influences due to the horizontal installation position and due to parasitic and purposefully applied loads. In a horizontal installation position, the dead weight of the transducers themselves causes permanent load in form of bending moments on the transducer. Furthermore, misalignments along the drive train, such as eccentricities, non-parallelism of flanges, and the inclination of the entire drive train, evoke parasitic loads. These parasitic loads in combination with the loads pointedly generated by the NTL to actively control the set-up to minimise unwanted vibrations and thereby protect the drive train affect all measurements and alter for each relative rotational position.
As mentioned above, each signal $S_{\text{NTB/TTS}}$ of both transducers is tared by the zero signal of the respective load cycle:

$$S_{\text{NTB/TTS}} = \overline{S}_{\text{meas, NTB/TTS}} - S_{\text{zero, NTB/TTS}}. \quad (5)$$

Before gathering any measurement data, all electrical components were pre-heated to avoid creep due to thermal alterations in the signal amplifiers.

Calibration results

The evaluation of the calibration results is based on ISO 7500-1 [5], which standardises the calibration of force measuring systems in uniaxial material testing machines by reference force transducers. This standard was assimilated to the set-up at hand: a uniaxial torque calibration with parasitic loads. The main difference between the cases of application besides the measurement parameter calibrated, force vs. torque, is the measurement under static conditions vs. stationary rotation respectively. The content of the following section is based on ISO 7500-1.
The calibration result of torque calibration in NTBs consists of:

- the relative indication deviation $\overline{q}(M_{\text{L}})$ per load step M_{L},
- the expanded measurement uncertainty $U(M_{\text{L}})$ for the indication deviation, and
- the relative reversibility.

Here, the calibration result is presented in form of a look-up table that can be consulted to correct the measurement result in a post-processing.

Measurement conditions

In general, this measurement set-up is very complex due to the additional mechanical loads exerted on the drive train as stated in [7], therefore, the measurement conditions to be considered are wide. To avert signal creep due to thermal effects, all electrical components were pre-heated prior to the measurements. However, general ambient conditions needed to be taken into account. Humidity influences can be neglected as the strain gauges are encapsulated inside the transducers, so can the air pressure for strain-gauge-based measurement tools. Common calibration standards stipulate a temperature stability of ± 1 K and within 18 to 28 °C during the measurements. Because of the manifold heat sources in an NTB such as gearbox, generator, prime mover, and NTL, the temperature around the NTB can fluctuate. These fluctuations were permanently monitored to detected that the temperature was stable to $\Delta T_{\text{loadcycle}} = \pm 1$ K during the measuring process. Compared to the conditions under which the TTS was calibrated, the temperature in the NTB was + 5 K higher. However, the TTS signal was not corrected for this temperature difference, but the temperature dependence of the TTS's sensitivity was considered in the measurement uncertainty.
Another condition to be considered are emergency brakes, which can result in a torque inversion of up to 80 % of the maximum torque applied beforehand. To minimise the hysteresis effect evoked thereby, the NTB was operated at maximum torque load for about 5 min after an emergency brake before carrying on with the measurements.
Moreover, parasitic and additional loads, as mentioned before, can have a crosstalk effect on the torque signal. Crosstalk means, the applied loads do not only have an influence on the intended measuring bridges, but also on other bridges [9].

Relative indication deviation

The relative indication deviation $q_j(M_{\text{L}})$ is the deviation of the torque value M_{i} measured directly in the NTB from the torque M indicated by the TTS relative to the TTS torque:

$$q_j(M_{\text{L}}) = \frac{M_{\text{i},j}(M_{\text{L}}) - M_j(M_{\text{L}})}{M_j(M_{\text{L}})} \cdot 100\ \%. \quad (6)$$

here $j = 1{,}2$

The indication deviation is calculated separately for each load step M_{L} and for each of the two repetitions $j = 1{,}2$.

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For the result of the torque calibration, the relative indication deviation $\bar{q}(M_\mathrm{L})$, the indication deviation is averaged over the two repetitions j:

$$\bar{q}(M_\mathrm{L}) = n^{-1} \sum_{j=1}^{n} q_j(M_\mathrm{L}), \qquad (7)$$

here for *cm2a* $n = 2$.

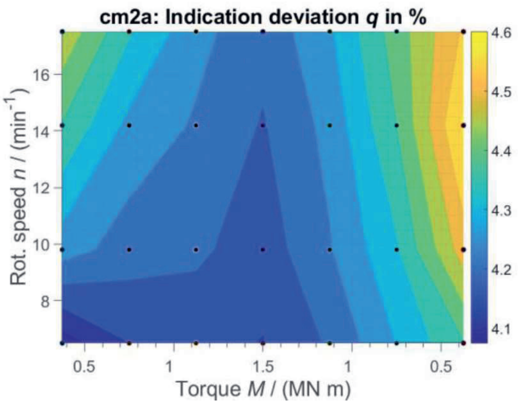

Fig. 4: Calibration result in form of a relative indication deviation $\bar{q}(M_\mathrm{L})$ between the torque transducer in the NTB and the TTS.

Fig. 4 and Tab. 2 reveal a dependence of the relative indication deviation not only on the torque applied, but also on the rotational speed prevailing. For the higher torque load steps, the relative indication deviation varies less with the rotational speed due to the better resolution and the advantages accompanied by that. However, extreme caution

Tab. 2: Relative indication deviation $\bar{q}(M_\mathrm{L})$ in % between the torque value measured by the transducer in the NTB and the torque value measured by the TTS.

Rel. indication deviation $\bar{q}(M_\mathrm{L})$ in %				
M_L↓ n→	**6.5**	**9.8**	**14.2**	**17.5**
375_up	4.075	4.275	4.395	4.488
750_up	4.150	4.224	4.287	4.355
1125_up	4.167	4.210	4.244	4.266
1500	4.148	4.173	4.196	4.216
1125_down	4.207	4.246	4.266	4.293
750_down	4.302	4.344	4.399	4.424
375_down	4.396	4.526	4.608	4.556

Relative reversibility

When increasing M_i and decreasing M'_i torque are observed separately, the relative reversibility v for decreasing load can be calculated. Necessary to that end, the TTS must be calibrated for increasing and decreasing load, which was the case here. For the reversibility measurement, one decreasing load cycle is functionally adequate. However, the reversibility highly depends on the maximum torque applied during the load cycle. Because of a non-linear scaling of the reversibility, it cannot be extended to arbitrary load cycles.

The relative reversibility is calculated based on the divergence between the increasing and decreasing load steps (cf. Tab. 3), which were interpolated to matchable full load steps for a comparability.

$$v(M_\mathrm{L}) = \frac{M'_\mathrm{i,interpol}(M_\mathrm{L}) - M_\mathrm{i,interpol}(M_\mathrm{L})}{M_\mathrm{interpol}(M_\mathrm{L})} \cdot 100\ \%. \qquad (8)$$

The relative reversibility can be vaguely divined by the colours in Fig. 4. Tab. 3 shows that the relative reversibility is more significant for a rotational speed of n = 6.5 min^{-1}. Moreover, the absolute reversibility decreases distinctly for increasing rotational speed.

Tab. 3: Relative reversibility $v(M_\mathrm{L})$ in % between increasing and decreasing torque load based on interpolated load steps.

Relative reversibility $v(M_\mathrm{L})$ in %				
M_L↓ n→	**6.5**	**9.8**	**14.2**	**17.5**
1125_down	0.040	0.000	0.000	0.000
750_down	0.151	0.001	0.001	0.001
375_down	0.321	0.003	0.002	0.001

Measurement uncertainty

The measurement uncertainty $u_\mathrm{c}(M_\mathrm{L})$ consists of three uncertainty contributions:

- the uncertainty contribution of the resolution $u_\mathrm{res}(M_\mathrm{L})$,
- the uncertainty contribution of the repeatability $u_\mathrm{rep}(M_\mathrm{L})$, and
- the uncertainty contribution of the transfer standard including additional uncertainty contributions $u_\mathrm{std}(M_\mathrm{L})$.

The uncertainty contribution of the relative resolution per load step $u_\mathrm{res}(M_\mathrm{L})$ is the square root of the sum of the squares of the NTB transducer's relative resolution per load step $a_\mathrm{M}(M_\mathrm{L})$ and its relative resolution after load release $a_\mathrm{Z}(M_\mathrm{L})$. The relative resolution after load release is to be considered, as every torque value per load step is tared using the zero signal. For both contributors, a rectangular distribution ($2\sqrt{3}$) is assumed.

$$u_\mathrm{res}(M_\mathrm{L}) = \sqrt{\left(\frac{a_\mathrm{M}(M_\mathrm{L})}{2\sqrt{3}}\right)^2 + \left(\frac{a_\mathrm{Z}}{2\sqrt{3}}\right)^2}. \qquad (9)$$

The relative resolution is the indication fluctuation of the NTB transducer divided by the respective load step. Hereby, the indication fluctuation is the difference between the minimum and maximum mean per revolution for the averaging sequence of six revolutions.

As a second uncertainty contributor, the relative repeatability is calculated in form of the standard deviation of the best expected value q_j and the relative mean indication deviation $\bar{q}$, where n (here n = 2) is the number of repetitions per load step:

$$u_{rep}(M_L) = \sqrt{(n(n-1))^{-1} \sum_{j=1}^{n} (q_j(M_L) - \bar{q}(M_L))}. \quad (10)$$

As a last component, the uncertainty contribution of the TTS $u_{cal}(M_L)$, which is assigned in the calibration certificate, is to be considered in the total measurement budget:

$$u_{std}(M_L) = \sqrt{(u_{cal}(M_L))^2 + A^2 + B^2 + C^2}. \quad (11)$$

Moreover, other uncertainty contributors were allowed for at this point: the composition of the measuring chain in form of the measurement uncertainty of the amplifier deployed as contributor A, the relative drift of the TTS over time as contributor B, and the temperature deviation between the temperature in the NTB and the temperature in the laboratory per 5 K, where the TTS was calibrated, as contributor C. These contributors are listed in Tab. 4.

Tab. 4: Additional uncertainty contributors considered in the total measurement uncertainty (cf. [14]).

Uncertainty contributions		Value in %
A	Amplifier calibration	1.20×10^{-5}
B	Drift	8.85×10^{-3}
C	Temperature influence	1.52×10^{-2}

The expanded absolute measurement uncertainty $U(M_L)$ for the relative indication deviation is the product of the coverage factor k (here k = 2, p = 95.45 %, normal distribution) and the combined absolute uncertainty $u_c(M_L)$:

$$U(M_L) = k \cdot u_c(M_L), \quad (12)$$

$$U(M_L) = k \cdot \sqrt{(u_{res}(M_L))^2 + (u_{rep}(M_L))^2 + (u_{std}(M_L))^2}.$$

Tab. 5: Absolute expanded measurement uncertainty U (k = 2) for the relative indication deviation $\bar{q}(M_L)$ in %.

Exp. rel. uncert. $U(M_L)$ (k = 2) in %				
$M_L\downarrow$ $n\rightarrow$	**6.5**	**9.8**	**14.2**	**17.5**
375_{up}	0.199	0.235	0.249	0.260
750_{up}	0.180	0.191	0.206	0.223
1125_{up}	0.178	0.185	0.178	0.201
1500	0.182	0.183	0.182	0.188
1125_{down}	0.182	0.186	0.183	0.183
750_{down}	0.196	0.189	0.203	0.188
375_{down}	0.231	0.241	0.255	0.241

As expected, the expanded measurement uncertainty (Tab. 5) decreases for increasing torque load up to 1100 kN m due to a better signal-noise-ratio, and a poor resolution and a worse repeatability in the lower measurement ranges. Above 1100 kN m, the measurement uncertainty increases because of the soared measurement uncertainty of the TTS evoked by the extrapolation of the calibration results.

Influence of rotational speed and misalignments

The influence of the rotational speed can be seen not only in the torque signals, but also in the additional loads on the TTS. In general, the signals of the additional loads are periodically recurrent.

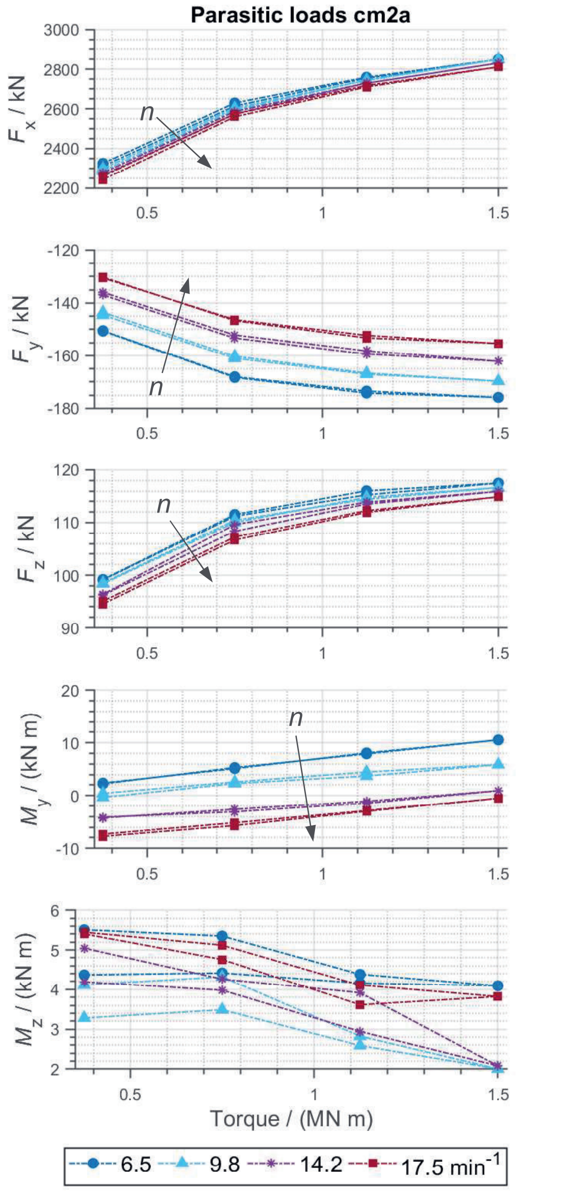

Fig. 5: Averaged parasitic loads on the TTS during the calibration measurements separately plotted for the different rotational speeds applied.

To analyse the influence of the torque alterations, which allows for investigations of misalignments, and of the rotational speed, the additional loads are averaged over the same sequence of six revolutions as the torque signals. These non-tared mean signals depending on the torque load step in combination with the rotational speed step are depicted in Fig. 5. Due to the fact, that no other measuring bridges than the torque bridge of the TTS are calibrated, only qualitative evaluations can be performed. For example, the thrust (axial force F_x) increases with increasing torque load and decreases slightly with increasing rotational speed. Moreover, the significant thrust offset of F_x = 2757.87 kN is a pointer to lateral bracing in the drive train. However, caution must be taken when analysing these signals any further, as the signals are very small measured by bridges conceptualised for much broader measuring ranges of several thousand kN and kN m. Therefore, further investigations with specific additional loads are to be performed in the future.

Unbalances in the drive train, that might affect the torque signals, were analysed by an FFT. Fig. 6 shows the power spectral density of both torque signals, M taken by the TTS and M_i recorded by the NTB transducer. The FFT is performed on the averaging sequence of the torque signal at the decreasing torque load step of M_L = 375 kN m at a rotational speed of n = 17.5 min^{-1}, where vibrations can already be seen in Fig. 3. These vibrations appear in form of a peak at 22.75 Hz in the power density spectrum in Fig. 6. In all other signals sequences per load steps, no peaks were revealed, which implies that there are no unbalances relevant at the prevailing rotational speeds.

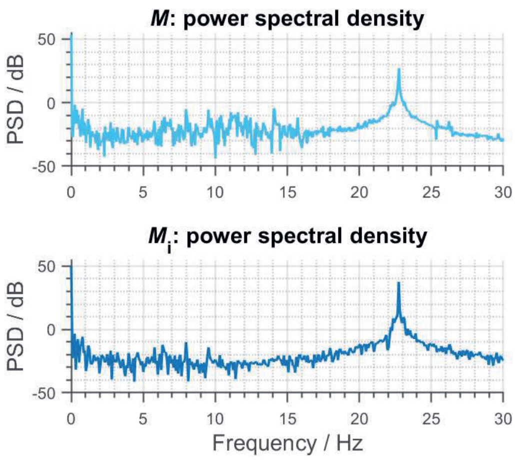

Fig. 6: Power spectral density of the two torque signals measured by the TTS (M) and by the NTB (M_i) at 375 kN m decreasing and 17.5 min^{-1}.

Conclusion and outlook

This paper presents the first attempt of calibrating the torque measurement in an NTB using one type of a characterisation map. It was found that the position of the reference transducer, the TTS, is important: it must be placed directly at the input of the nacelle, which is the nacelle rotor hub flange. Moreover, the measurement procedure for the calibration and its evaluation including the calculations of the expanded measurement uncertainty are introduced.

The calibration result is the relative indication deviation $\bar{q}(M_L)$ between the torque value measured by the NTB transducer and the torque indicated by the TTS, which is the reference torque, relative to this reference torque value. This work has revealed that the torque value and, therefore, the relative indication deviation, depend on the rotational speed, which is why the torque is to be calibrated in combination with rotational speed. The averaged relative indication deviation amounts to $\bar{q}(M_L)$ = 4.3 % and an associated expanded measurement uncertainty of $U(M_L)$ (k = 2) ≤ 0.26 % for this set-up. The results are available in form of a look-up table. In the future, it could also be possible to calculate multiple regression curves that can be used to correct the measurements in-situ after a calibration. Additionally, further future work will consider a representative amount of repetitions for each load step.

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