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TRANSDUCER RESPONSE UNDER NON-STANDARDISED TORQUE LOAD PROFILES

R. S. Oliveira[1], P. Weidinger[2], Z. Song[3], L. Vavrečka[4], J. Fidelus[5], T. Kananen[6], S. Kilponen[7]

Instituto Nacional de Metrologia, Qualidade e Tecnologia, RJ, Brazil, [1] rsoliveira@inmetro.gov.br
Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
[2] paula.weidinger@ptb.de, [3] zihang.song@ptb.de
Cesjy Metrologicky Institut (CMI), Praha, Czech Republic, [4] lvavrecka@cmi.cz
Główny Urząd Miar (GUM), Warsaw, Poland, [5] janusz.fidelus@gum.gov.pl
Teknologian tutkimuskeskus VTT Oy (VTT), Kajaani, Finland
[6] timo.kananen@vtt.fi, [7] sauli.kilponen@vtt.fi

Abstract:
In nacelle system test benches, different wind profiles are simulated by applying different torque loads and rotational speeds amongst other things. Unlike load sequences during calibration measurements, these profiles are neither constant nor increasing and decreasing through controlled steps. This article proposes a sequence of partial range and shuffled torque load tests that combine torque rates and filter settings to evaluate parameters affecting the measurement results, such as output sensitivity, linearity, and hysteresis.

Keywords: torque calibration; DIN 51309; DKD-R 3-9; transient torque load; randomly shuffled loading

1. INTRODUCTION

For the efficiency determination of wind turbines and to analyse their drive train, the measurement of mechanical torque is the most crucial parameter. Both wind speed and Hardware-in-the-Loop (HiL) tests on nacelle system test benches (NTB) are neither constant nor increasing and decreasing under controlled sequential steps. It is rather a random sequence of different wind speeds and, therefore, of different rotational speed and torque loads.

Moreover, wind gusts can cause enormous torque changes over a short time period (Figure 1). These changes can happen very fast [1].

In NTBs, HiL tests that simulate different wind profiles are conducted leading to alternating and transient torque loads. The same applies to gearbox tests and to measurements for an efficiency determination of motors and generators [2], [3].

In case the torque measurement in an NTB is traced to national standards, the load cycles for both torque and rotational speed are increasing and decreasing stepwise [4]. These load cycles do not meet the requirement of a calibration to be as close as possible to the later application.

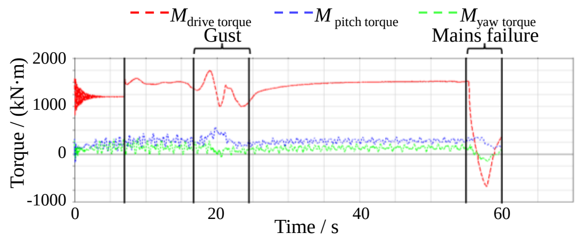

Figure 1: Torque loads at the rotor hub of a nacelle on a nacelle system test bench caused by simulated wind fields including gust and mains failure (adapted from [1])

To analyse the response of the transducer to non-traditional calibration loads, this paper proposes the application of two different load configurations.

The first test method, to be called as “Fast-loading profiles” applies torque under diverse steps and torque rates and carries out the transducer’s output reading in a time period much smaller than that practiced by the calibration standards, such as the 30 s minimum interval for stabilisation and dwell in the DIN 51309, for example. In this weak stabilisation condition, a parallel analysis of the digital filtering influence is also interesting.

The second test method, to be called “Randomly shuffled loading profiles”, takes the same torque points to be measured in the transducer’s range and shuffles them in a randomised order. In this method, the stabilisation interval for each torque point is the same as that used according to [5].

It is important to highlight that these test methods are still static ones, with the torque rates being null in the moment of the reading.

2. STANDARDISED TORQUE CALIBRATION

For tracing transducers to national standard units, standard calibration procedures are used whereas the transducer's performance and its deviation from the national standard is evaluated. This is mostly done in a static and step-by-step manner.

The DIN standard, DIN 51309, determines that the sensor calibration range should consist of equally spaced torque measurement points. For the best possible classification of the transducer to be calibrated, a minimum number of eight torque steps should be used, appropriately distributed over the measuring range including its lower limit. The series of measurements is formed by the sequence of increasing incremental static loads and followed by the decreasing sequence of these same loads (Figure 2). This series of measurements is repeated with the transducer mounted in different positions 120° apart in the national torque standard machine in order to minimise the effects of misalignment and gravity. To examine the reproducibility, an additional incremental load series in one of the three mounting positions is performed.

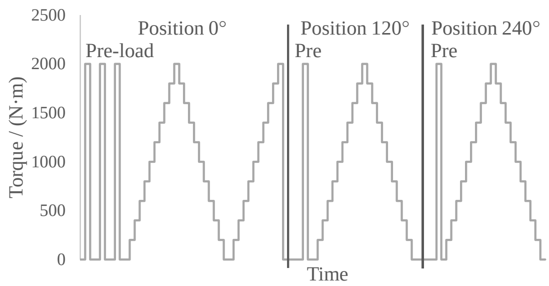

Figure 2: Pre-loading and loading sequences in different mounting positions acc. to DIN 51309 (adapted from [5])

The time span between two consecutive torque levels should be as equal as possible and the indicator reading should be taken after the indication has stabilised.

3. FAST-LOADING PROFILES

The fast-loading profiles are based on the Appendices A.3.1 and A.3.2 of the guide DKD-R 3-9 [6]. Originally, this DKD guide is intended to be used for the characterisation of force transducers under continuous load profiles. The measurements acc. to these appendices are applied to characterise and classify if a certain transducer can work as a reference to the continuous calibration method. Nevertheless, the main idea and methodologies can also be applied to torque transducers to analyse the influence of the fast loadings on sensitivity and hysteresis.

The equipment used consists of a special HBK transducer with a nominal range of 2 kN·m, a DMP 40 readout unit, and a deadweight machine with a range of 1 kN·m.

First, the transducer had to be calibrated, up to 1 kN·m according to the DIN 51309 standard, in order to have the standardised parameters.

3.1. Influence On The Sensitivity

Thus, the first fast-loading test based on Appendix A.3.1 of [6] applies torque from zero up to a torque point in the range, measure the transducer signal right after the transient period is over in a time much smaller than the stabilisation period in the DIN 51309 calibration step, and then return to zero. This is repeated for 20 % steps up to the nominal value. For this case, the measured values are 200 N·m, 400 N·m, 600 N·m, 800 N·m and 1000 N·m. This is done using the dead weight torque standard machine but with the data being gathered continuously. In order to have a brief analysis also for the influence of the digital filtering in the results, a Bessel filter with two different cut-off frequencies is applied: the first frequency, 0.01 Hz, represents the DIN 51309 calibration configuration, and the second one, 2 Hz, emulates a real configuration for torque measurement in the NTB. As an example of results and to better visualise these fast-loading profiles, in Figure 3 the curves for the first two torque values (200 N·m and 400 N·m) and the different filters can be seen.

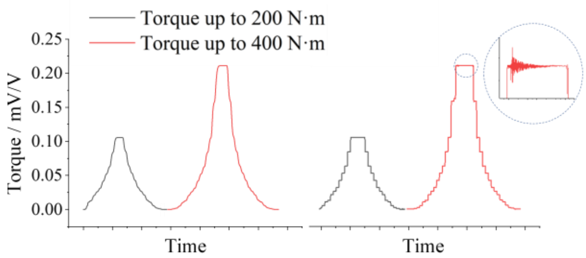

Figure 3: Sensitivity fast-loading tests using Bessel filters with cut-off frequencies 0.1 Hz (left) and 2 Hz (right)

On the left side, the two load curves are seen in a very smooth tracing while on the right side, a more realistic shape of these curves can be seen, with the small steps occurring due to the sequential deposition of the masses in a deadweight machine. The zoom window shows all transient effects caused by the release of the scale pan and the application of the reference deadweight value.

According to the DKD-R 3-9 guide, the measured sensitivity values i.e., the output signal per torque applied, for each torque value, must be compared to the corresponding sensitivities achieved in the DIN 51309 calibration, resulting in a relative difference ΔS_{rel}. These differences can be seen in Figure 4 for the five torque values.

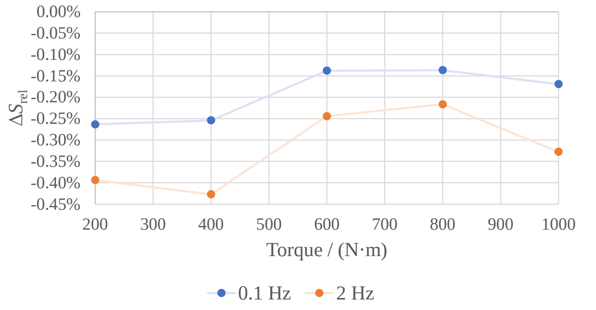

Figure 4: Relative difference (ΔS_{rel}) between the fast-loading and DIN 51309 calculated output sensitivities for different torque values and filter cut-off frequencies

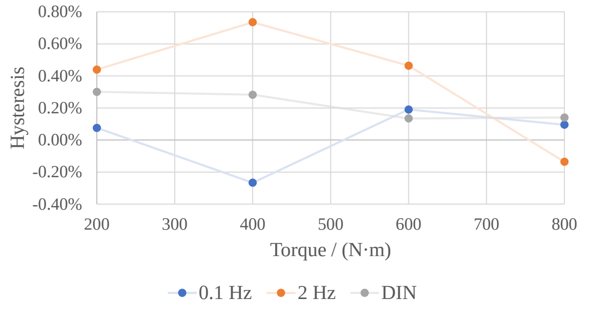

Figure 6: Hysteresis calculated for the DIN 51309 and for the fast-loading jumps, with different cut-off frequencies for the filter

3.2. Influence On The Hysteresis

The second fast-loading test is based on Appendix A.3.2 of [1] and evaluates the hysteresis by applying increasing torque from zero up to a torque point in the range, measuring the transducer signal after the transient period is over, returning to applying increasing torque till the nominal value, applying decreasing load till reaching the measuring point again, measuring the transducer signal after the transient period is over, and then returning to zero torque. This can be seen as a partial load sequence, which is repeated for other points in the range. The measured points for this study are 200 N·m, 400 N·m, 600 N·m, and 800 N·m, again with different digital filter cut-off frequencies, 0.01 Hz and 2 Hz, and data being gathered continuously. As an example of results and to better visualise these load sequences, in Figure 5, the curves for the first two torque values (200 N·m and 400 N·m) and the different filters can be seen.

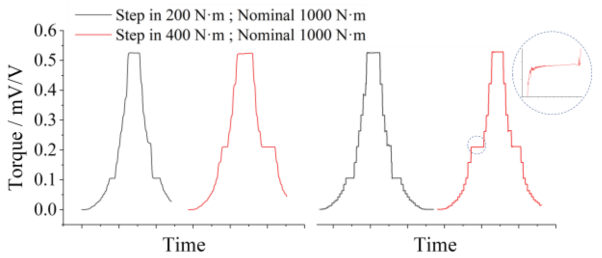

Figure 5: Hysteresis fast-loading tests using Bessel filters with cut-off frequencies 0.1 Hz (left) and 2 Hz (right)

Again, the zoom window shows all transient effects caused by the release of the scale pan and the application of the reference deadweight.

The hysteresis is calculated through the difference between increasing and decreasing step values. So, the hysteresis for fast-loadings can be compared to the ones resulted from the DIN 51309 through the difference Δu. For the five torque values, these differences in the hysteresis can be seen in Figure 6.

A summary of the results of the fast-loading profiles is given in Table 1. There is also an average torque rate for each torque value calculated during incremental loading in the output sensitivity test.

Table 1: Summary of the results calculated from the fast-loading tests

Reference Torque / N·m	**Torque Rate / N·m/s**	**ΔS_{rel} / %**		**Δu / %**	
		0.1 Hz	**2 Hz**	**0.1 Hz**	**2 Hz**
200	3.57	-0.26	-0.39	-0.22	0.14
400	4.55	-0.25	-0.43	-0.55	0.45
600	6.19	-0.14	-0.24	0.06	0.33
800	8.25	-0.14	-0.22	-0.04	-0.28
1 000	9.80	-0.17	-0.33	---	---

3.3. Summary Of Fast-Loading Profiles

From these fast-loading tests, a brief conclusion can be drawn: both the torque rate under load until the measuring point is reached and the cut-off frequency have a considerable influence on the evaluated parameters of output sensitivity and hysteresis.

It is important to highlight that the working principle of this deadweight machine, even if it works properly to the standardised calibration of torque transducers, affects this kind of analysis proposed, and mainly for the hysteresis, since the loosening of the scale pan has some different transient and oscillation responses to the incremental and decremental torque plateaus.

4. RANDOMLY SHUFFLED LOADING PROFILES

In order to analyse the influence of changes in the calibration load cycle impacting the use of a previous DIN 51309 metrological characterisation, a randomised load cycle (Figure 7) was generated. Those are the same points measured in the standard method but with their order of application shuffled in the cycle.

To ensure a sole analysis of the randomised effect, the same shuffled load cycle is used for all three mounting positions (3 × 120°).

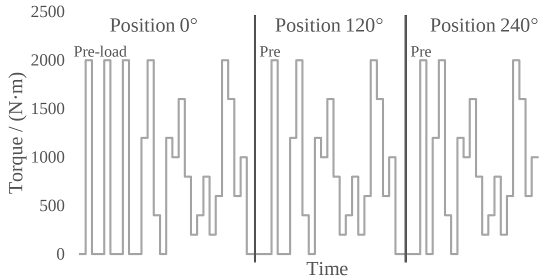

Figure 7: Shuffled points within a cycle and repeated in the different mounting positions

The measurement set-up is the same as for DIN 51309 calibrations with the same adapters, alignment requirements, amplifier filter settings, requirements on ambient conditions and stabilisation period to record the measured value.

The equipment used consists of a Raute Precision torque transducer, model TT1, with a nominal range of 2 kN·m, a DMP 40 readout unit, and a deadweight machine with a range of 2 kN·m.

For the test sequence, first a complete calibration according to DIN 51309 is carried out with the transducer and the results, here called 'Normal' data, to serve as reference to compare with the randomised loads.

For evaluating the measurement data gathered in the randomised proposal, the shuffled single values were sorted into a linearly increasing and decreasing loading sequence, creating the here called 'S-Random' data. As an approach, the values were sorted based on their previous value: In case the previous value is lower than the actual value, it is designated as increasing point; and in case the previous value is higher than the actual value, it is denoted as a decreasing point. The original unsorted values are kept in the vector 'U-Random'.

Table 2 shows the deviations between the average measurements of 'Normal' and 'S-Random', respectively ΔY and ΔY_{h}, to use the same nomenclature of DIN 51309.

Another approach for this evaluation is the calculation of the transducer output sensitivity per torque step. Figure 8 shows the average output sensitivities for each torque point in the data storage method. It is clear how the 'S-Random' diverges from the 'Normal' and also from the 'U-Random' data, while these last two are better homogeneously distributed in the middle of the graph.

Here it is important to highlight that the output sensitivities for 'Normal' and 'S-Random' are calculated using the same reference torque vector, it means, the increasing and decreasing sequence. For the 'U-Random', the output sensitivities are calculated using the transducer output intervals and the reference torque intervals occurring at the time of the reading.

Table 2: Deviations between 'Normal' and 'S-Random' for the average measurements of Y and Y_{h}

Reference Torque / N·m	**Deviations**	
	ΔY / %	**ΔY_{h} / %**
200	0.024 7	0.010 2
400	0.006 5	-0.005 1
600	-0.001 6	-0.009 5
800	-0.002 9	-0.008 9
1 000	-0.002 9	-0.009 1
1 200	0.003 2	-0.003 8
1 600	0.004 1	-0.001 4
2 000	0.001 1	0.001 1

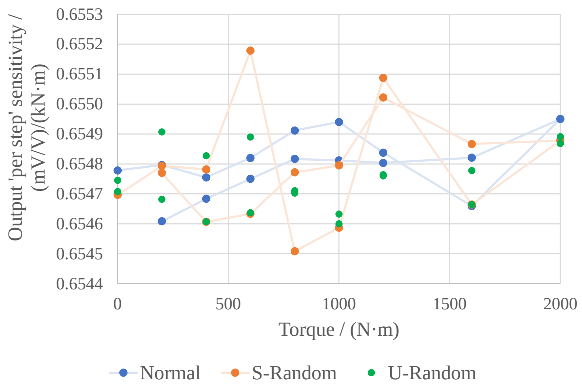

Figure 8: Output sensitivity per torque step

In Figure 9, a comparison between the linearity deviation curves for both 'Normal' and 'S-Random' is given. It can be seen that the 'S-Random' has difficulties to follow the 'Normal' linearity path, even if maintaining the deviation limits.

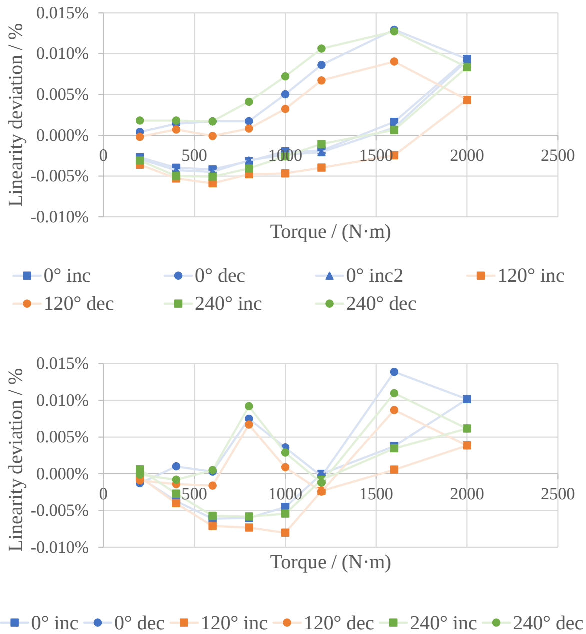

Figure 9: Linearity analysis for 'Normal' (top) and 'S-Random' (bottom) load profiles

If calculating the measurement uncertainty according to DIN 51309, the behaviour as shown in Figure 10 can be found. For the cubic interpolation method, the uncertainty is limited only by the uncertainty of the reference torque values. Instead, the linear curve regression method shows much higher values, and it can be seen that, for the 'Normal' data (in grey), there is the trend of decreasing measurement uncertainty as the torque increases, but for the 'S-Random' data (in yellow), this tendency is not so clear, mainly in the beginning and in the middle of the torque range.

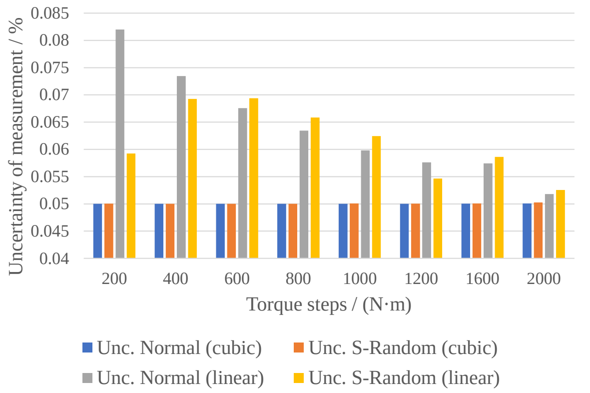

Figure 10: Expanded measurement uncertainties ($k = 2$) for 'Normal' and 'S-Random' data

This can also be observed for the relative contributions of each source parameter in the uncertainty budget (Figure 11). Here, it is clear that in 'S-Random' the linear regression relative contribution does not decline as observed for the 'Normal' analysis.

5. SUMMARY

Torque values measured under these non-traditional or non-standard conditions demonstrated the susceptibility of transducers to conditions and load profiles prior to the desired measurement plateau.

Contrary to what common sense might suggest, both the influence of the previous load and the creep and hysteresis phenomena play a role, although the measurement plateaus are stable over time in the shuffled profiles.

The fast-loading tests have characteristics that differ from those traditionally used in calibration procedures; however, there are still the measurement plateaus, which are in the static regime. The results obtained point to the need to analyse the responses of torque transducers under non-static regimes, addressing continuous and dynamic load regimes with non-stable plateaus and higher torque variation rates, as are the applicable load profiles on NTBs for example.

The presented results confirmed that the method and the parameters adopted during signal processing have an enormous contribution to the correct interpretation of the measured phenomenon. For future studies, it is interesting to approach this evaluation under a more specific methodology, especially in relation to non-static conditions, such as transient and oscillatory conditions in such regimens.

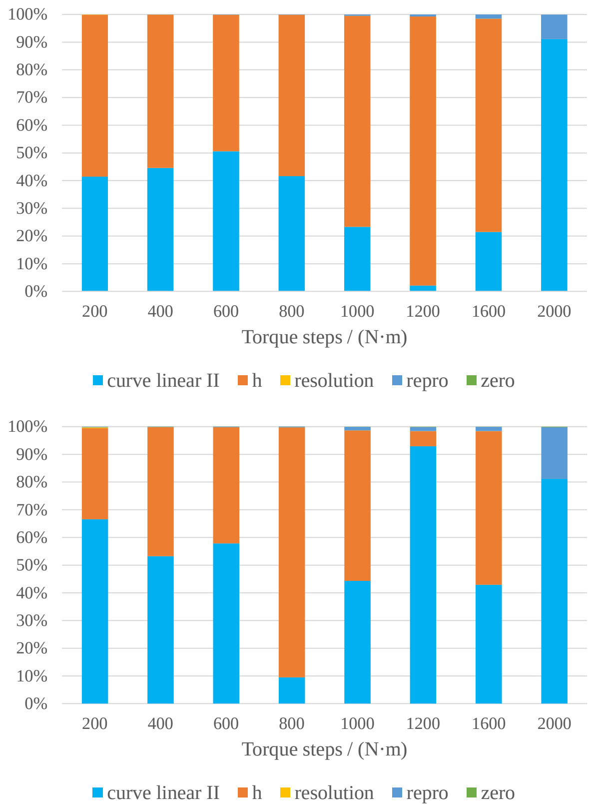

Figure 11: Measurement uncertainty budget relative contributions from each source parameter for 'Normal' (top) and 'S-Random' (bottom) using linear regression

6. ACKNOWLEDGEMENTS

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