A finite element analysis of effects on force lever systems under nacelle test bench conditions

G Foyer and H Kahmann

Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany

E-mail: gisa.foyer@ptb.de

Abstract. Multi-MN·m torque measurements are needed in testing for the wind industry. As no national or international torque standard exists in that range, a force lever system has been designed to achieve traceability through force and length measurements. The system has been analysed numerically and the influences of nacelle test benches, such as rotation and additional mechanical loads, have been investigated.

1. Introduction

Wind turbines have been growing and are still increasing in size to fulfil today’s ambitious political and social aims. Several nacelle test benches (NTBs) have been constructed in the last few years to further technical development in the wind industry. These facilities provide testing opportunities for new wind turbines that cannot be achieved with field tests. As the measurement of torque is an important component in the investigation of wind turbines and their efficiency, the precision of above-mentioned measurement has become much more important.

Torque loads in NTBs are in the multi-MN·m range but the currently largest torque standard machine is only capable of exerting loads up to 1.1 MN·m. To fill this gap, the European research project Torque measurement in the MN·m range was started in 2015 in the framework of the European Metrology Programme for Innovation and Research (EMPIR). It aims at developing a calibration procedure for NTBs but also at investigating improved transfer standards for the multi-MN·m range. One approach to the second aim is to use a force lever system (FLS). Such a system consists of several force transducers and a lever construction that can be mounted on an NTB. As NTBs also exert additional mechanical loads, work under rotation and not under standard metrology laboratory conditions, along with a myriad of influences on the measurement procedures and the design must be considered. Within the European research project, several FLSs have been designed (see e.g. [1]–[3]). In the following, one of the designs is presented together with a finite element analysis and a discussion of several influences which occur in NTBs and their effect on the measurement uncertainty.

2. Force lever system and finite element study description

The FLS presented in this paper consists of three force transducers of the hollow shaft type, two lever plates and three connection rods (see figure 1). The latter are supposed to transmit additional mechanical loads apart from the torque load without influencing the main force measurement much. The force transducers are connected via a pre-stressed bolt that is fixed with a calotte-nut construction on both sides. The connection rods are linked to the lever plate with a roller bearing. The system is designed for
a torque load of 5 MN-m which leads to a force transducer measurement range of up to 2.5 MN. A detailed description of the design process can be found in [3].

The theoretical principle of the mode of operation of such an FLS is shown in figure 2. It depicts a view of a profile through the middle of the force transducers and the connection rods without cutting the lever plates. Furthermore, the reaction moments and forces in the plane of the profile are shown. A definition of the composition of the overall torque $M$ is given in equations (1) - (2). The lever lengths are defined as the distance between the torque load axis and the axis of the force transducer or connecting rod. It can be noted that all initial lever lengths should be corrected for their change due to deformation under load to obtain the full torque introduced.

$$M = \sum_{i=1}^{n}(F_{tr,i} \cdot l_{tr,i} + M_{tr,i}) + \sum_{j=1}^{m}(M_{con,j} + F_{con,j} \cdot l_{con,j})$$

(1)

$$l = l_{init} - \Delta l_{def}$$

(2)

To analyse the FLS and to determine the load distribution, a finite element (FE) study using the software ANSYS was performed. Two different aims were followed during the setup of the numerical model: determining a model to investigate the structural behaviour of the FLS, and finding a model to analyse further influences on the FLS. Different options in mesh design and contact definitions were used. The contacts between the transducer and the adaptation, and between the lever plates and the spherical shaped calottes were always defined as fixed contacts. The contact between the pre-stressed bolt and the calottes as well as the contact between the connection rods and the lever plates were varied between those with fixed contacts and those subject to friction. Furthermore, three different mesh variations were chosen: a very coarse mesh (element size < 50 mm), a mesh with refinements (element
size < 15 mm) at the main contact areas and a mesh which is additionally refined at the transducers (element size < 5 mm).

The defined reaction moments and forces have been analysed for all alternatives and the effect of the mesh variations on the contact reactions and the deformation was found to be very small. The effect of the contact definitions is, however, rather large as expected. In Table 1, all contributions to the calculated torque load \( M \) are summarised for the three contact definition alternatives. The distribution of the torque load to the different elements of the FLS differs greatly. Especially the alternative where all contacts are assumed to be fixed shows much larger forces at the connection rods but less at the force transducer. These deviations lead to a wide range of results within the single contributions. The relative range, which is calculated by dividing the span between the maximum and minimum value by the mean value, reaches up to 280\%. However, the calculated torque \( M \) and the torque taken from ANSYS as a reaction torque of the FLS \( M_{\text{FEM}} \) are not affected by this issue. For all three cases, it can be stated that to achieve a measurement uncertainty of < 0.1\%, it is necessary to record not only the main force measurement \( F_{\text{tr}} \) but also the bending moment at the force transducers \( M_{\text{con}} \) and the lateral force at the connection rods \( F_{\text{con}} \), otherwise a very large systematic error would occur.

| Contact definitions       | \( F_{\text{tr}} \cdot l_{\text{tr}} \) kN m | \( M_{\text{tr}} \) kN m | \( F_{\text{con}} \cdot l_{\text{con}} \) kN m | \( M_{\text{con}} \) kN m | \( M \) kN m | \( M_{\text{FEM}} \) kN m |
|---------------------------|-----------------------------------------------|--------------------------|-----------------------------------------------|--------------------------|----------------|--------------------------|
| Friction                  | 4943.60                                       | 30.97                    | 21.72                                         | 2.17                     | 4998.47       | 4999.97       |
| Fixed transducer          | 4940.28                                       | 48.16                    | 8.69                                          | 1.88                     | 4999.01       | 4999.86       |
| Fixed connections         | 4387.75                                       | 42.58                    | 566.09                                        | 2.07                     | 4998.49       | 4999.09       |
| Rel. range \[\frac{\text{max-\text{min}}}{\text{mean}}\] in % | 11.68                                         | 42.36                    | 280.33                                        | 14.30%                   | 0.01          | 0.02          |

3. Influences on the force lever system in a nacelle test bench

The general influences on measurements in NTBs have already been presented and discussed in [4]. A specific overview for the FLS presented in this paper is given in figure 3. The measurement with an FLS is influenced mainly by the calibration of the lengths and the force transducer, the deformation, climate conditions, additional mechanical loads and misalignments during installation.

![Figure 3. Influences on torque measurement with the FLS described in an NTB.](image)

To analyse the effects on the designed system, ANSYS was used again and parametrical studies were performed on the influences on the lever length (temperature and deformation under load, torque and other mechanical loads) and on the effect of additional loads and rotation on the force measurement. Misalignments have been neglected until now and only a setup with fixed contacts was used to simplify the analysis. Figure 4 shows an example of the change in the overall torque value due to a change of the
rotational speed to 12 \((\pm 1)\) turns per minute and a rise of temperature from 20 °C to 27 \((\pm 2)\) °C. In both cases, the torque was calculated using equations (1) - (2) and compared to the torque load achieved in a simulation with only 5 MN·m torque load.

**Figure 4.** Change of the calculated torque load due to rotation (left) and temperature change (right).

The effect of the rotation is comparatively small. In the case of a 5 MN·m torque load, a relative change of the torque of \(2\times10^{-5}\) is expected. The analysis shows smaller additional axial forces on the transducer than found in [1]. This deviation is mostly caused by the different lever lengths. The analysis of the change in temperature shows a much larger influence which only considers the effect due to thermal expansion and not the effect on the force transducer sensitivity. For a 5 MN·m torque load, a relative change of \(3.5\times10^{-3}\) is calculated. Therefore, it is advisable to use a temperature correction for the calculation to achieve the aspired measurement uncertainty.

4. Discussion and conclusion

It was shown how a torque load progresses through an FLS, and how torque measurement with an FLS is affected by special conditions in NTBs. As the results are only based on FE analyses which were shown to be rather sensitive to the change in boundary conditions, the findings have to be handled with care. Furthermore, the effect of a change in temperature, as it occurs in NTBs, was found to have a non-negligible effect on the measurement. It can be assumed that similar results will be found for the effect of additional mechanical loads.

Based on these observations, it can be concluded that it is very important to define a very detailed calibration procedure for an FLS as a measurement uncertainty of \(<1\%\) is envisioned. Corrections of influencing factors are needed. Furthermore, it is important to measure not only the forces but also the bending moments at the force transducers as well as the torque load on the connection rods to minimise systematic errors.

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