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Theoretical Analysis of Measurement Flexures at the 5 MN·m Torque Standard Machine at PTB

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Summary:
A hinge flexure for measuring purposes is presented. Its usage in the 5 MN·m torque standard machine at PTB is described. Essential measurement uncertainty influences such as interferometer, retroreflector position and deflection line deviation are discussed.

Keywords: force measurement, torque measurement, multicomponent measurement, stiffness measurement, flexure hinge, compliant mechanism, beam theory

Introduction

At the PTB a new 5 MN·m torque standard machine (TSM) is built to calibrate torque transducers [1]. The machine's measurement system has a lever where the torque transducer under test is flange-mounted to. The lever itself is jointed on six hinge flexures (also called measurement flexures (MF) hereafter) to receive the lever forces axially and measure them with attached transducers. The MF support force transducers measuring either lever forces of torque moment (TM) or bending moment (BM). In this context, it is enough to focus only on the bending moment MF (BMMF, see Figure 1). Not only do these hinge flexures reduce bending moments and torsion onto the force transducer but their deflection helps measuring them. The transversal force and the torsion they receive account to a small amount of the overall calibration moment that needs to be measured and can't be neglected for accuracy reasons. The deflection caused by transversal force and torsion at MF is measured by an interferometer because strain gauge measurement lacks the needed precision due to high crosstalk. The stiffness is calibrated in a MF calibration set-up (CSU), the required force and torsion is measurable [2]. To provide a traceable calibration moment the MF force and torsion measurement must be characterized by a measurement uncertainty analysis.

Measurement Uncertainty Analysis

An uncertainty measurement analysis for the reaction force and torsion for is performed. Table 1 depicts all quantities which contribute to the uncertainty budget. The following sections discuss the most essential uncertainty quantities.

Measurement flexure calibration

There are two different calibration cases: Bending moment and torsion. Both calibration moments are always combined with a transversal force. This force is measured indirectly by the deflection. Thus, it is important that the deflection line in calibration setup and TSM operation match. The crucial question to the effectiveness of this approach is how reliantly the mass-lever system "imitates" the load within TSM operation and result in the same deflection line.

In the CSU a simple mass-lever system is used. The force is introduced on the height of the middle of the MF. This causes a linear decrease of

Table 1 List of measurement uncertainty influences

MF Calibration	Calibration uncertainty	
	Deflection line deviation	Different Load
		Additional TSM Load
	Assembly	
	Alignment	
	Fixation	
Interferometer	Calibration uncertainty	
	Environment	
	Retroreflector (RR)	
	Resolution	
	User	
RR Position	CSU Lever	Force
		Torsion
	TSM Lever	Deformation RR
		Deformation MF
		Lever Rotation angle

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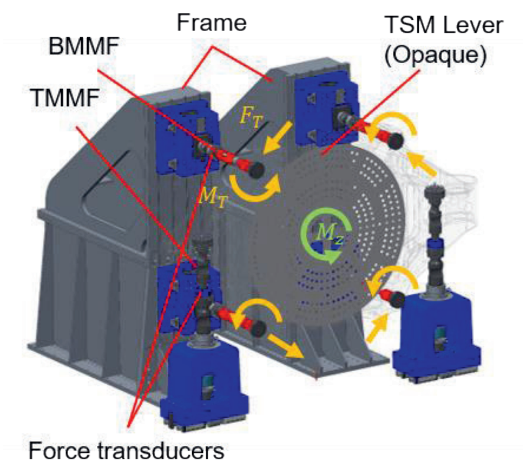

Figure 1 Parasitic MF Loads during TSM operation

bending moment with zero moment in the middle of the MF (see Figure 2). In TSM operation, it is rather a forced displacement at the MF's end producing the same force and moment reaction as in CSU. To comprehend why both load scenario match, an analytical model is created. Flexure hinges are widely investigated in the field of precision positioning. There exist various theories to describe the deflection of beams. The resulting deflection line and the preceding presumptions differ, and a literature research is performed to find the most appropriate theory [2],[4].

The analytical model is used to validate the FE-models made in ANSYS. The FE-models are used to analyze if additional axial force, orthogonal bending moment or torsion have an influence on the deflection line in TSM operation. Furthermore, the FE model quantifies the linearity.

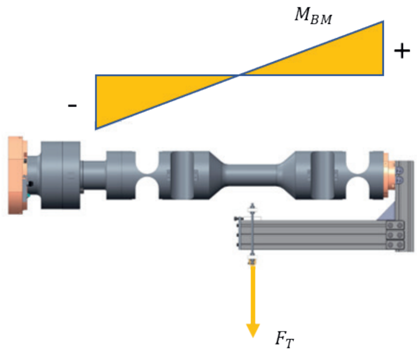

Figure 2 Measurement flexure calibration set-up

Interferometer

For displacement measurements a SIOS interferometer MI5000 is used. It is equipped with two retroreflectors and was calibrated at PTB. The calibration incorporates uncertainty influences the environment quantities and the retroreflector as well. The uncertainty of the interferometer depends on the distance between the laser and the reflector. The uncertainty of the interferometer influences the MF's overall uncertainty at two stages: When the MF is calibrated and when then MF displacement is measured during TSM operation. All three displacement measurements need to be analyzed.

Retroreflector position

Not only the retroreflector's distance to the laser but also the positions where the measurement takes place adds up to the uncertainty. Because the points of interest can't be measured directly the measurements are taken at a place that have a linear correlation to the points of interest. During MF calibration, the reflector is placed close to the cantilever depending on the calibration desired. The FE analysis reveals the relative displacement difference between set point and measured point and its impact on the measurement uncertainty.

During TSM operation the reflector can't be placed at the MF because it is covered by a mounting plate. Thus, the MF displacement correlates with the lever rotation angle α. The angle measurement α is approximated by two simple distance measurements which must be addressed in the measurement uncertainty analysis. The movement of the lever and the additional deformation of the lever under load lead to a deviation from idle rotation which must be added in the uncertainty budget. All the deviations from idle rotation are extracted from a FE analysis.

Summary

The usage of an interferometer to measure reaction force and moment of measurement flexures were discussed. The key components of the measurement uncertainty budget were presented. The influence of the retroreflector positions was discussed. The method how to estimate the deflection line deviation by an analytical and a FE-model were described, and the deflection measurement deviation quantified.

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