Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Multicomponent force transducer calibration procedure using tilted plates

To cite this article: Stefano Palumbo *et al* 2018 *J. Phys.: Conf. Ser.* **1065** 042015

IOP Conf. Series: Journal of Physics: Conf. Series **1065** (2018) 042015 doi:10.1088/1742-6596/1065/4/042015

Multicomponent force transducer calibration procedure using tilted plates

Stefano Palumbo[123], Andrea Prato[1], Fabrizio Mazzoleni[1] and Alessandro Germak[1]

[1] INRiM, Istituto Nazionale di Ricerca Metrologica, 10135 Torino, Italy
[2] Politecnico di Torino, DET, 10129 Torino, Italy
[3] IIT, Istituto Italiano di Tecnologia, Graphene Labs, 16163 Genova, Italy

E-mail: a.germak@inrim.it

Abstract. The calibration of a multicomponent force transducers (MFTs) represents a challenge in the meganewton range. In fact, the generation of transversal forces and moments is complex since a force standard machine (FSM) is only able to apply an uniaxial force. Furthermore since MFTs are composed of multi-transducers, each one dedicated to a particular component, correlations between force and moment components are possible. Therefore, a calibration system that could simultaneously generate all force/moment components and could be suitable in every FSM is needed. For this purpose, a couple of tilted plates was designed. Calibration measurements were performed on a 2 MN MFT at INRiM, LNE and PTB. Exploitation matrixes and performance indicators showed good results, unless small but not negligible correlations between MFT outputs. In particular some spurious values due to the uncertainty in the vertical force application point influenced the moment components.

1. Introduction

Calibration of MFTs strictly depends on the range of the applied transversal forces. From 0 N to an upper limit of 1 kN, it is possible to use two graduate rotating tables combined with a mass able to generate an accurate vertical force [1]. To increase this range to the meganewton range, side loads are usually generated with systems based on pulleys, while moments are obtained with torque measurement structures [2]. At the Physikalisch-Technische Bundesanstalt (PTB), a FSM able to apply and read all force and moment components was developed [3]. In particular a different system for the application of side loads and torque moment was realised, each one with its advantages and disadvantages. Most of MFTs are composed of multiple force/moment outputs, each one dedicated to a single component. Nevertheless every output generally does not only depend on the relevant measured component. Therefore, a MFT calibration system should combine force and moment components in order to verify the exact correlation between them and, at the same time, should fit every type of FSM. In this work, a calibration method using tilted plates, which guarantees the simultaneous generation of force and moment components, is presented. Measurements performed at INRiM, PTB and LNE are compared in order to evaluate the correlation between the MFT outputs.

2. Calibration system

Before designing the calibration system, all the MFTs and FSMs located at INRiM, LNE and PTB were surveyed and screened. At the end of this work, a 2 MN MFT (with diameter of 170 mm and height of 300 mm) developed at INRiM [4] and able to simultaneously measure force and moment components (F_x, F_y, F_z, M_x, M_y and M_z), was chosen and a system of tilted plates was designed. This system does not require any change on the structure of the FSM, unlike [2], is able to combine the desired force and moment vector components, unlike [1], and can be performed in any calibration laboratory, unlike [3]. The MFT has 6 independent output channels (U_j), each dedicated to a single force and moment component. In our analysis, the torque moment M_z was excluded. Each channel has one or more strain gauges disposed anticlockwise along the MFT body. The MFT's reference system inside the tilted plates is represented in figure 1.

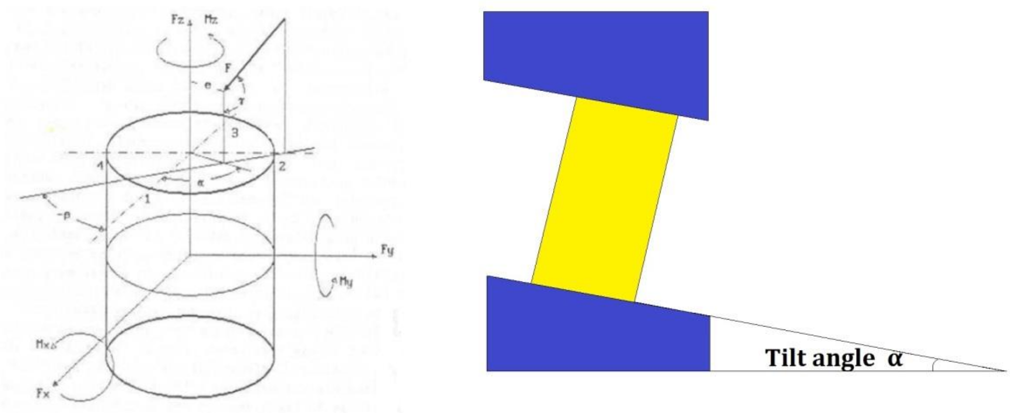

Figure 1. Reference system of the MFT inside a couple of tilted plates.

Measurements were performed on the deadweight FSM with loads of 500 kN and 1000 kN at INRiM, on a deadweight FSM with a load of 500 kN at LNE, and on a hydraulic amplification FSM with loads of 500 kN, 1000 kN and 2000 kN at PTB. The main elements of the entire calibration system were the tilted plates. For this project three pairs of tilted plates were realised, with a tilt angle α of 0°, 1° and 2°. The system allowed to tilt the MFT inside the FSMs and provided an orthogonal surface to apply the axial force. Furthermore, by rotating the MFT by an angle ω inside the tilted plates, the vertical axial force F of the FSM was decomposed in the three components according to equation (1). The application of a moment was given by the eccentricity ε_x and ε_y, along x and y axis respectively, with respect to the central axis of the FSM, as shown in equation (1).

$$\begin{cases} F_x = F \cdot \sin\alpha \cdot \sin\omega \\ F_y = F \cdot \sin\alpha \cdot \cos\omega \\ F_z = F \cdot \cos\alpha \\ M_x = F\cos\alpha \cdot \left(\varepsilon_x \cdot \sin\omega + \varepsilon_y \cdot \cos\omega\right) \\ M_y = F\cos\alpha \cdot \left(\varepsilon_x \cdot \cos\omega + \varepsilon_y \cdot \sin\omega\right) \end{cases} \quad (1)$$

3. Calibration procedure

The calibration procedure of the MFT can be summarized as follows: the MFT was aligned and centred with the single vertical force load (reference point 0); the MFT was then positioned with an eccentricity of 3 mm along the y-axis (point A); the MFT was displaced with a further eccentricity of 3 mm still along the y-axis (point B); the MFT was displaced with a further eccentricity of 3 mm along the x-axis (point C); the eccentricity of the MFT along the y-axis was reduced of 3 mm (point D). For each step of the above procedure, the MFT was rotated by an angle ω of 45° in order to complete a full turn. These steps were repeated for each pair of planes. From equations (1-2) it is possible to obtain all the desired force and moment components, by combining the tilt angle α, the angle of rotation ω and the eccentricity ε. Every combination of these three parameters leads to the creation of a different set of forces and moments, and this set of values can be represented in the experimental planes. The experimental planes are fundamental because they immediately show if the chosen points are sufficient to cover a large number of measurement conditions between two different components or if redundant points that can be avoided are present. Two examples for transverse forces F_x and F_y, which are eccentricity-independent, and for moment components M_x and M_y are depicted in figure 2.

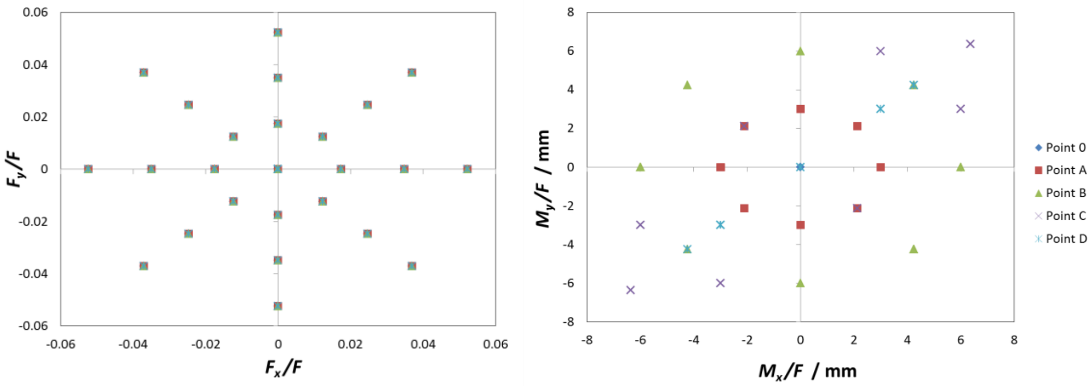

Figure 2. Experimental planes of F_x vs F_y (left) and M_x vs M_y (right).

4. Data analysis

In the ideal MFT, every output is only dependent on the relevant force or moment component. This condition can be easily analysed with the coefficient matrix. In fact, each force and moment component (F_j) can be seen as a linear combination of the MFT outputs, as shown in equation (2):

$$\mathrm{F_j} = \mathrm{a_{1j}U_1} + \mathrm{a_{2j}U_2} + \cdots \mathrm{a_{5j}U_5} = \sum_{\mathrm{i}=1}^{5} \mathrm{a_{ij}U_i} \quad (2)$$

Coefficients a_{ij} are necessary to calculate the force/moment components F_j, and these coefficients can be obtained with n linearly independent sets of values, i.e. the set of measurements coming from the experimental planes. Therefore, equation (2) can be solved as:

$$\begin{gathered} \mathrm{F} = \mathrm{U} \cdot \mathrm{A} \\ \mathrm{U^T F} = \mathrm{U^T U} \cdot \mathrm{A} \\ [\mathrm{U^T U}]^{-1} \mathrm{U^T F} = \mathrm{A} \end{gathered} \quad (3)$$

Matrix **A** is also called exploitation matrix. For an ideal MFT, the exploitation matrix is a diagonal matrix, which means no correlation between force and moment components. The exploitation matrixes obtained from the measurements performed at INRiM, LNE and PTB are shown in table 1.

Table 1. The exploitation matrixes from the measurements performed at INRiM, LNE and PTB

	INRiM					*LNE*					*PTB*				
	F_x	F_y	F_z	M_x	M_y	F_x	F_y	F_z	M_x	M_y	F_x	F_y	F_z	M_x	M_y
F_x	497.1	-10.9	-6.4	63.0	-8.7	307.2	55.4	20.7	35.1	10.1	275.2	-137.6	-10.2	18.1	3.7
F_y	2.5	491.0	3.5	-13.2	55.0	54.5	474.5	-3.2	-2.5	54.9	115.9	406.1	-16.6	-27.4	38.8
F_z	5.6	-8.0	1246.2	1.0	-1.3	2.9	-7.0	1245.6	0.6	-1.0	1.4	-9.7	1247.9	1.0	-0.8
M_x	1.4	3.4	0.3	8.0	-1.5	2.5	3.1	-0.3	4.6	0.2	-2.6	8.5	-7.3	6.5	-4.5
M_y	-6.7	8.8	0.7	-5.2	11.7	10.3	3.3	-1.8	-1.4	6.0	2.4	17.6	0.7	-4.6	13.9

It is evident that the largest terms are located on the diagonals, however out-of-diagonal terms are not equal to zero. In order to evaluate the effects and the consistency of the force/moment components interaction, performance indicators are introduced. The first parameter I_1 is an indicator of the "average deviation" from the ideal condition, which is given by equation (4):

$$I_1 = \frac{\left(\Sigma_{ij}\frac{|a_{ij}|^*}{n}\right)}{\left(1+\Sigma_{ij}\frac{|a_{ij}|^*}{n}\right)} \quad \text{with } i \neq j \tag{4}$$

Where n is the normalised exploitation matrix order and $|a_{ij}|^*=|a_{ij}/a_{ii}|$ is the absolute value of the ij-th coefficient of the normalised exploitation matrix **A***. Nevertheless the only parameter I_1 is not enough since it is not able to discriminate whether the total variation is due to a single value or if it is due to a general variation of the coefficients. For this reason, it is necessary to analyze the parameter I_2 which represents the "maximum deviation" of the out-of-diagonal coefficients of the matrix **A***:

$$I_2 = \max_{i\neq j}|a_{ij}|^* \tag{5}$$

A MFT has a low sensitivity to force/moment components interaction if such indicators are nearby equal to zero. Obtained experimental performance indicators are reported in table 2.

Table 2. Performance indicators in the different laboratories

Institute	I_1	I_2
INRiM	0.37	0.75
LNE	0.49	1.73
PTB	0.56	1.30

5. Conclusions

A MFT calibration procedure using tilted plates was tested on a 2 MN MFT at INRiM, LNE and PTB. Experimental planes chosen for the calibration procedure covered all possible combinations of force and moment components. Exploitation matrixes showed a good diagonalization for the force components, whereas moment components showed some spurious values, due to the uncertainty on the application point of the vertical force, that significantly influence the moment components. Differences between laboratories are due to the different FSMs used.

6. Acknowledgments

The activity of these research has been carried out in the framework of the EMRP Joint Research Project SIB63 "Force" with the title "Force traceability within the meganewton range", WP2 [5].

7. References

[1] Barbato G, Bray A, Desogus S, Franceschini F and Germak A 1992 Field calibration method for multicomponent robotic force/moment transducers *II International Symposium on Measurement and Control in Robotics (Tsukuba Science City, Japan, 15-19 November)* pp 233-238
[2] Bray A, Barbato G and Levi R 1990 *Theory and practice of force measurement* (London: Academic Press)
[3] Röske D 2003 Metrological characterization of a hexapod for a multi-component calibration device *XVII IMEKO World Congress (Dubrovnik, Croatia, Jun. 2003)*
[4] Barbato G, Bray A and Germak A 1986 Calibration and verification of multicomponent dynanometers in the meganewton range *XI International Conference on measurement of force and mass (Amsterdam Amsterdam, The Netherlands, 12 - 16 May 1986)* pp. 257-266
[5] Kumme R, Tegtmeier FT, Röske D, Barthel A, Germak A and Averlant P 2014 Force traceability within the meganewton range *XXII IMEKO World Congress (Cape Town, Republic of South Africa, 3-5 February 2014)*