Development of a traceability chain for multicomponent forces and moments

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The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Final Workshop of ComTraForce project, 24/02/2023

Introduction

- Task 3.6: Development of a traceability chain for multicomponent forces and moments

- The aim of this task is to extend the previous tasks into the development of a traceability chain for static and continuous multicomponent force and moment measurements at an uncertainty level suitable with classifications given in standardization

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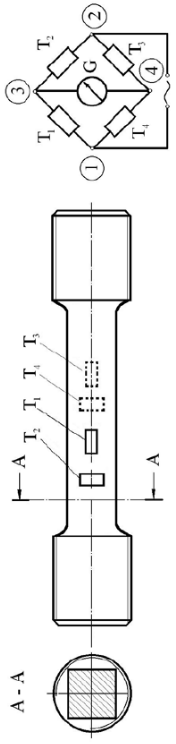
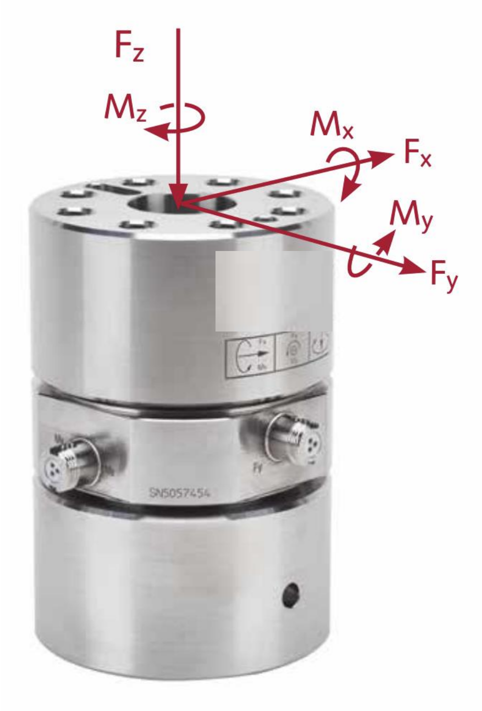
Types of multicomponent transducers

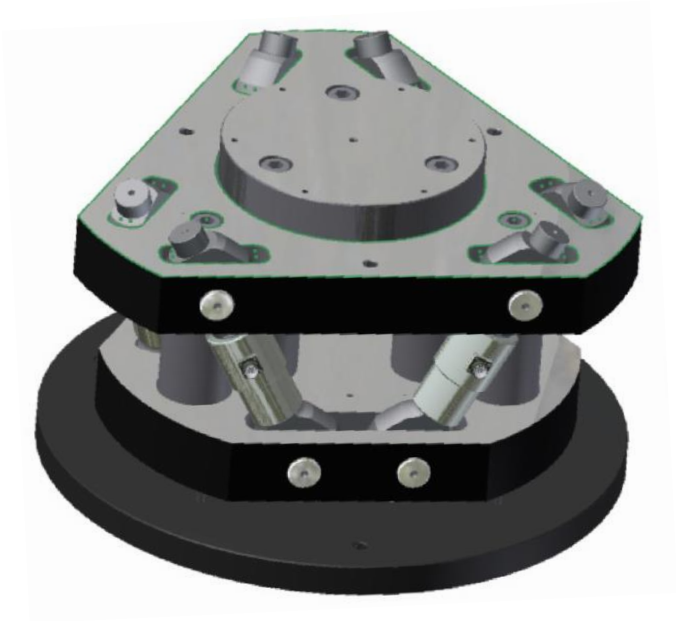
Strain-gauged



Piezoelectric

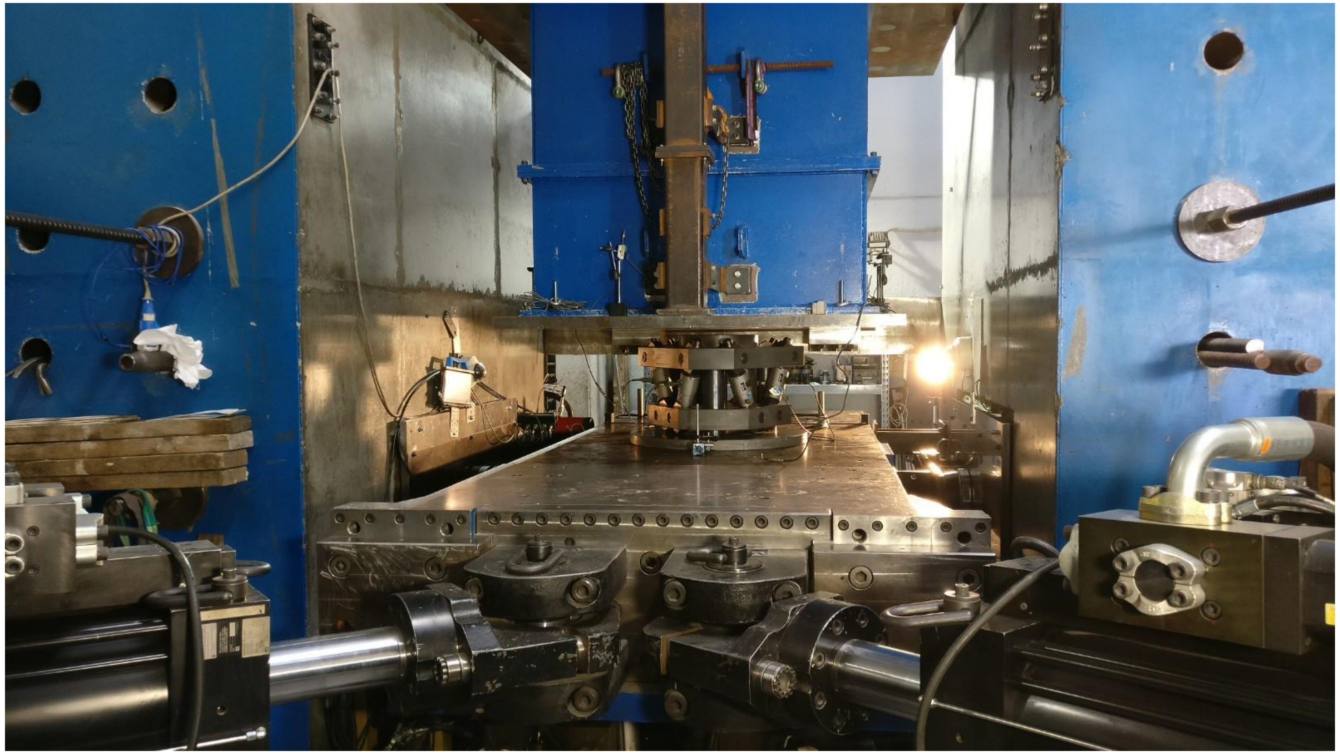


Build-up systems



Multicomponent testing machines

Tenaris Dalmine S.p.A.



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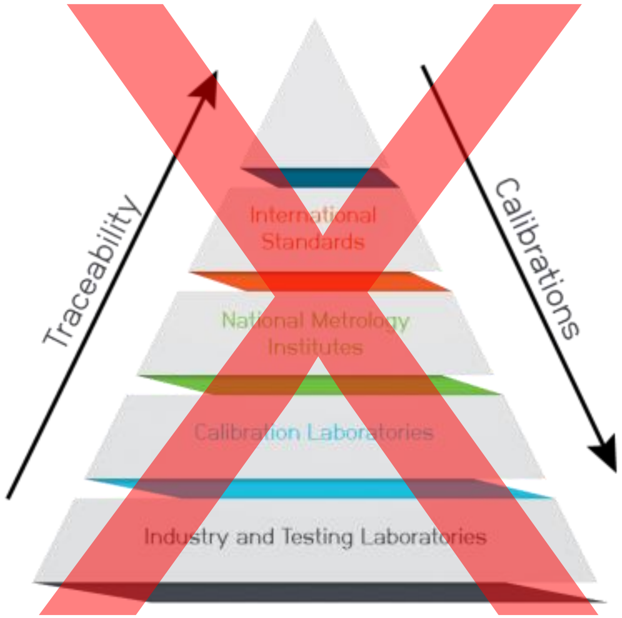
Need

A specific traceability chain for multicomponent transducers, at international level, is still missing together with standardized calibration methods for such transducers and testing machines



Multicomponent calibration systems

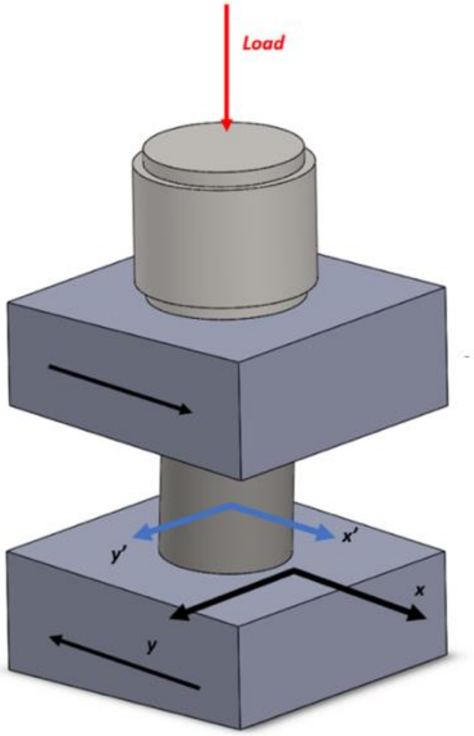
PTB Hexapod-structured 6-axis

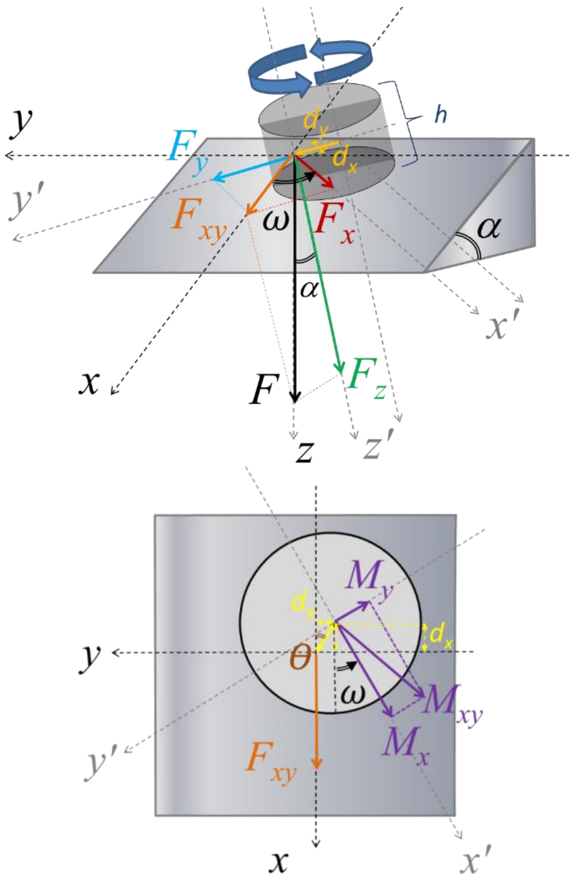
INRIM dead-weight 6-axis calibration system

3-axis calibration system at Kistler

Multicomponent calibration systems

Primary standards integrated with tilted plates (F_z in compression only)





1 MN deadweight FSM at INRiM

Forces and moments generation using tilted plates

A multicomponent force and moment transducer (MCFMT) during calibration

$$\begin{cases} F_x = F \cdot sin\,\alpha \cdot cos\,\omega \\ F_y = F \cdot sin\,\alpha \cdot sin\,\omega \\ F_z = F \cdot cos\,\alpha \\ M_x = F \cdot cos\,\alpha \cdot \sqrt{{d_x}^2 + {d_y}^2} \cdot sin(\omega + \theta) + \dfrac{F \cdot sin\,\alpha \cdot sin\,\omega \cdot h}{2} \\ M_y = -iF \cdot cos\,\alpha \cdot \sqrt{{d_x}^2 + {d_y}^2} \cdot cos(\omega + \theta) - \dfrac{F \cdot sin\,\alpha \cdot cos\,\omega \cdot h}{2} \\ M_z = F \cdot sin\,\alpha \cdot d_y \end{cases}$$

- *F* = applied force
- *α* = a tilt angle of the plates
- *h* = MCFMT of height,
- *ω* = anticlockwise (from the top) rotation angle
- d_x and d_y = misalignments along *x*- and *y*-axis
- $\theta = \left| tan^{-1}\left(\frac{d_y}{d_x}\right) \right|$

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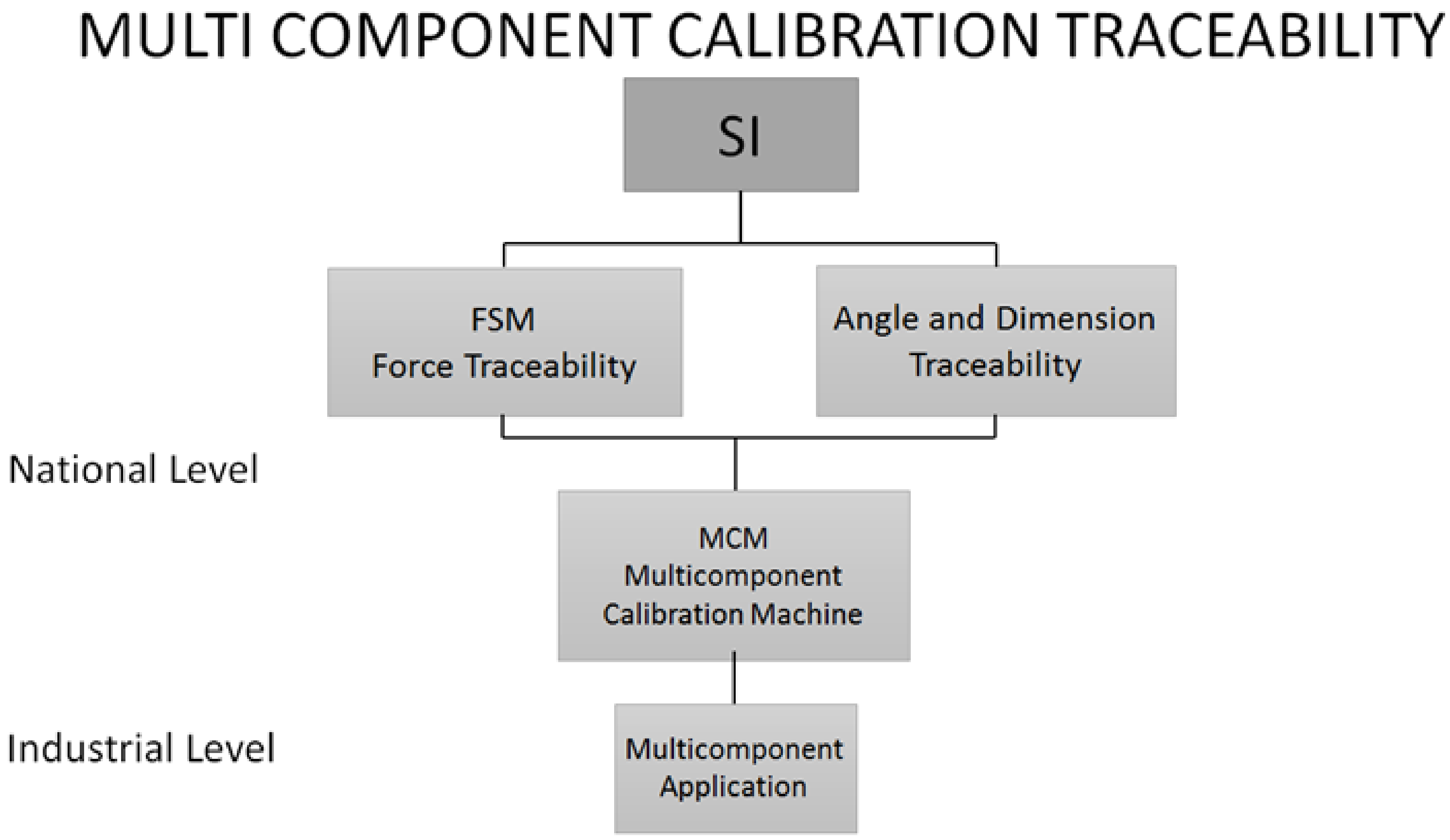
Forces and moments generation using tilted plates

A multicomponent force and moment transducer (MCFMT) during calibration

Component	*Rel. exp. unc.*
F_x	3.8×10^{-2}
F_y	3.8×10^{-2}
F_z	2.0×10^{-5}
M_x	4.8×10^{-2}
M_y	4.8×10^{-2}
M_z	8.2×10^{-2}

Variable x_k		$u^2(x_k)$	c_k	$u_k^2(M_y)$	Rank
Symbol	Value				
F	100 kN	1.0E+00	2.4E-02	5.8E-04	6
α	3°	3.3E-03	4.5E+01	6.9E+00	4
ω	135°	1.3E+00	2.5E+00	8.2E+00	3
d_x	0.016 m	3.3E-07	7.1E+04	1.7E+03	1
d_y	0.016 m	3.3E-07	7.1E+04	1.7E+03	2
h	0.100 m	3.3E-07	3.7E+03	4.6E+00	5
M_y	2402.1 N·m	Std. uncert. $u(M_x)$		57.8 N·m	
		Exp. uncert. $U(M_x)$		115.7 N·m	

Traceability chain



Calibration of multicomponent transducers

Each component F_k (k=1, n) can be expressed, in first analysis, as a linear combination of the transducer outputs d_i (i=1, n), considering the second-order interactions negligible

Analytical form

$$\begin{cases} F_x = d_1A_{11} + d_2A_{21} + d_3A_{31} + d_4A_{41} + d_5A_{51} + d_6A_{61} \\ F_y = d_1A_{12} + d_2A_{22} + d_3A_{32} + d_4A_{42} + d_5A_{52} + d_6A_{62} \\ F_z = d_1A_{13} + d_2A_{23} + d_3A_{33} + d_4A_{43} + d_5A_{53} + d_6A_{63} \\ M_x = d_1A_{14} + d_2A_{24} + d_3A_{34} + d_4A_{44} + d_5A_{54} + d_6A_{64} \\ M_y = d_1A_{15} + d_2A_{25} + d_3A_{35} + d_4A_{45} + d_5A_{55} + d_6A_{65} \\ M_z = d_1A_{16} + d_2A_{26} + d_3A_{36} + d_4A_{46} + d_5A_{56} + d_6A_{66} \end{cases}$$

Matrix form

$$\boldsymbol{F} = \boldsymbol{d}\,\boldsymbol{A}$$

A is the $n \times$ n coefficients matrix, also called exploitation matrix:

- Diagonal terms = main sensitivities
- Out-of-diagonal terms = transverse sensitivities or cross-talk terms

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Calibration of multicomponent transducers

- Exploitation matrix ***A*** and its $A_{i,j}$ coefficients can be evaluated through a linear regression

$$\boldsymbol{A} = [\boldsymbol{d}^T \boldsymbol{d}]^{-1} \boldsymbol{d}^T \boldsymbol{F}$$

- Sensitivity matrix ***S*** is obtained by inverting matrix ***A***:

$$\boldsymbol{S} = \boldsymbol{A}^{-1} = [\boldsymbol{F}^T \boldsymbol{F}]^{-1} \boldsymbol{F}^T \boldsymbol{d}$$

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Calibration of multicomponent transducers

Uncertainty of exploitation matrix ***A***, in terms of combined variance, is given by

$$\mathbf{u}^2(\boldsymbol{A}) = \begin{bmatrix} u^2(A_{11}) & \cdots & u^2(A_{1k}) \\ \vdots & \ddots & \vdots \\ u^2(A_{i1}) & \cdots & u^2(A_{ik}) \end{bmatrix} = \begin{bmatrix} u^2(A_{11})' & \cdots & u^2(A_{1k})' \\ \vdots & \ddots & \vdots \\ u^2(A_{i1})' & \cdots & u^2(A_{ik})' \end{bmatrix} + \begin{bmatrix} u^2(S_{11})\frac{{A_{11}}^2}{{S_{11}}^2} & \cdots & u^2(S_{1i})\frac{{A_{i1}}^2}{{S_{1i}}^2} \\ \vdots & \ddots & \vdots \\ u^2(S_{k1})\frac{{A_{1k}}^2}{{S_{k1}}^2} & \cdots & u^2(S_{ki})\frac{{A_{ik}}^2}{{S_{ki}}^2} \end{bmatrix}^T$$

where

$$\begin{bmatrix} u^2(A_{11})' & \cdots & u^2(A_{1k})' \\ \vdots & \ddots & \vdots \\ u^2(A_{i1})' & \cdots & u^2(A_{ik})' \end{bmatrix} = \boldsymbol{c}\,\boldsymbol{u}^2(\boldsymbol{F})$$

c, which is the matrix of the squared terms of ***[d^T^d]^-1^d^T*** matrix

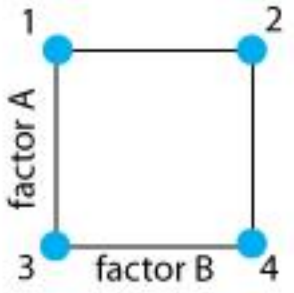
$$\begin{bmatrix} u^2(S_{11}) & \cdots & u^2(S_{1i}) \\ \vdots & \ddots & \vdots \\ u^2(S_{k1}) & \cdots & u^2(S_{ki}) \end{bmatrix} = \boldsymbol{h}\,\boldsymbol{u}^2(\boldsymbol{d})$$

h, which is the matrix of the squared terms of ***[F^T^F]^-1^F^T*** matrix

Calibration of multicomponent transducers

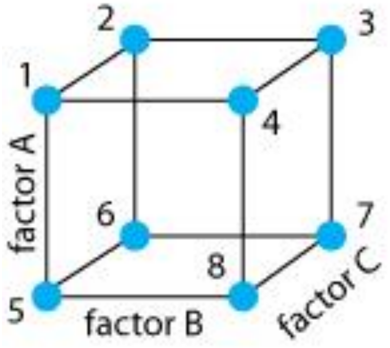
- Calibration is performed with different combinations of components which represents the **experimental plan**

- The experimental plan has a huge influence on the calibration sensitivities and associated uncertainties (Ronald Fisher, 1926)



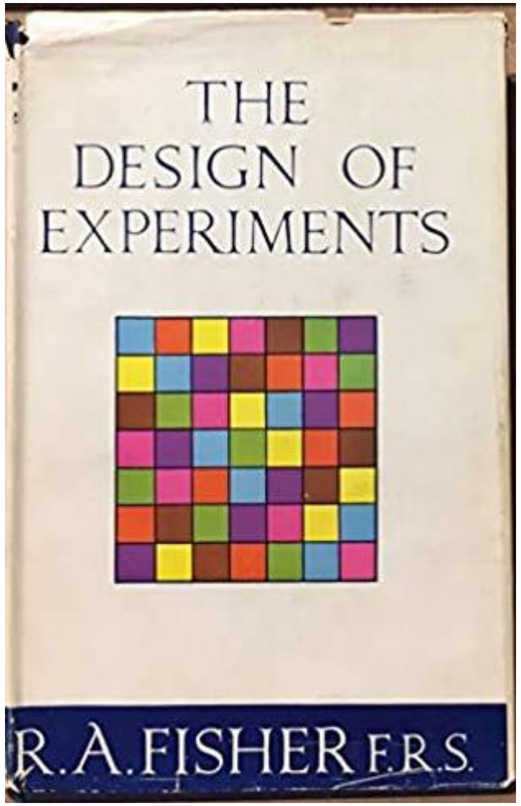
factor levels

trial	A	B
1	+	–
2	+	+
3	–	–
4	–	+



factor levels

trial	A	B	C
1	+	–	–
2	+	–	+
3	+	+	+
4	+	+	–
5	–	–	–
6	–	–	+
7	–	+	+
8	–	+	–



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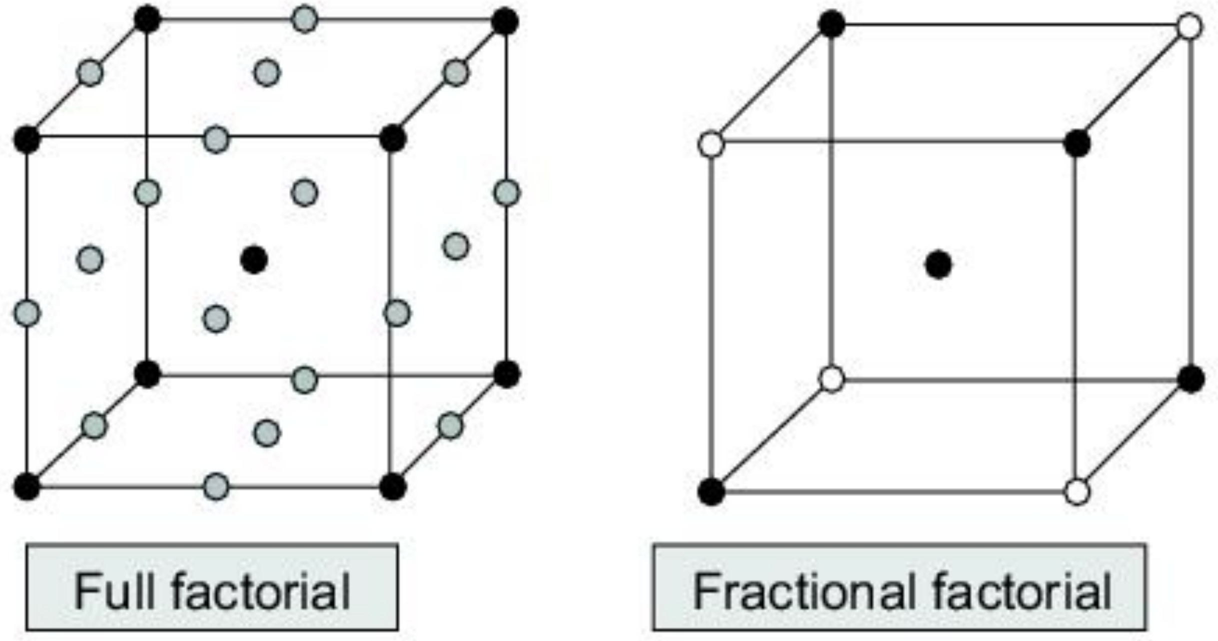
Calibration of multicomponent transducers

- If the lowest level of uncertainty is requested, a **full factorial experimental plan**, with a large number of applied loads combinations

- If higher uncertainties are tolerated, a lower number of measurements can be performed



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Calibration of multicomponent transducers

Prato, A., Borgiattino, D., Mazzoleni, F., Facello, A., Germak, A., *Calibration of multicomponent force and moment transducers using force standard machines integrated with tilted plates*, 2022, Meas. Sci. Technol. 33 095023.

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Example

Strain-guaged tranasducer HBM MCS10-**100**-6C

Capacity	F_x [N]	F_y [N]	F_z [N]	M_x [Nm]	M_y [Nm]	M_z [Nm]
	20000	20000	100000	2000	2000	1500

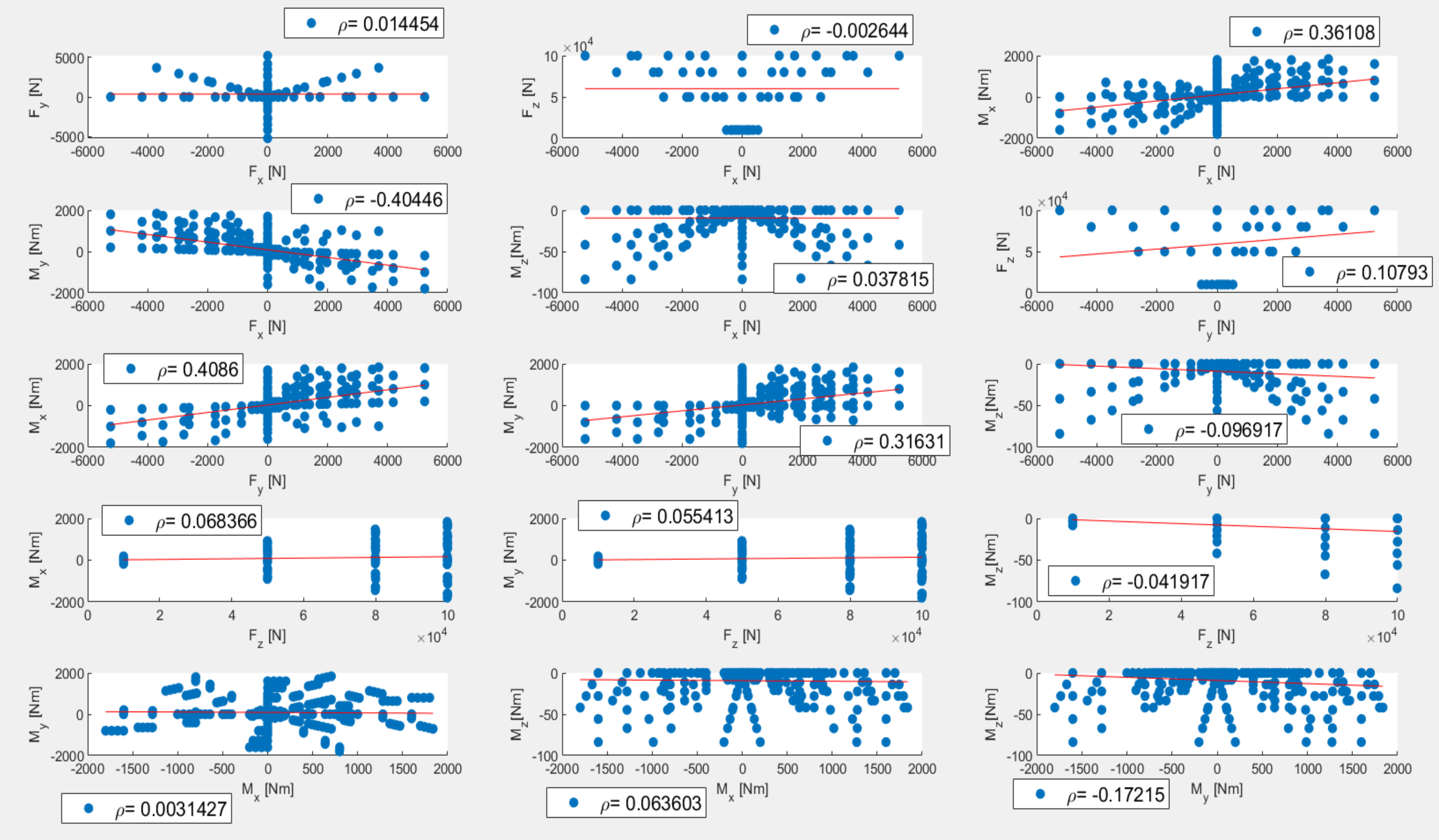
Experimental plan

- 480 measurement conditions
- Correlation between each couple of components is close to 0

Quantity	*Parameter*	*Values*
Tilt angle	α	0°, 1°, 2°, 3°
Rotation	ω	0°, 45°, 90°, 135°, 180°, 270°, 360°
Displacement x-axis	x	0 mm, 8 mm, 16 mm
Displacement y-axis	y	0 mm, 8 mm, 16 mm
Applied load in compression	F	(10 - 50 – 80 - 100) kN

Experimental plan

- 480 measurement conditions
- Correlation between each couple of components is close to 0



Calibration results

Exploitation Matrix ***A* /** kN/(mV/V) and kN·m/(mV/V)]

A=

15.018	-0.18659	0.1169	0.10013	-0.60078	0.00051422
0.1388	14.973	-0.26827	0.39462	0.1947	0.0013087
0.0033828	0.10145	80.513	0.019584	0.03569	-0.012612
-0.020414	-0.026723	0.16856	1.0927	-0.0082712	-0.0018298
0.032942	0.052589	-0.25198	-0.012029	1.0417	0.0012569
0.06965	0.061789	0.38534	-0.17952	-0.015401	1.311

Relative expanded uncertainty / %

$$U(A)^{100kN}_{compl}\% = \begin{bmatrix} \mathbf{0.75} & 96.79 & 568.2 & 100.7 & 26.9 & 786.2 \\ 81.63 & \mathbf{1.15} & 21.66 & 26.78 & 143.1 & 521.5 \\ 694.3 & 19.26 & \mathbf{0.01} & 71.13 & 40.42 & 9.95 \\ 93.07 & 107.60 & 7.59 & \mathbf{1.67} & 267.2 & 98.71 \\ 55.27 & 60.09 & 5.94 & 147.5 & \mathbf{2.13} & 133.2 \\ 1189 & 2440 & 10.87 & 342.2 & 2373 & \mathbf{5.45} \end{bmatrix}$$

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Calibration of multicomponent force and moment testing machines

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Tested machines

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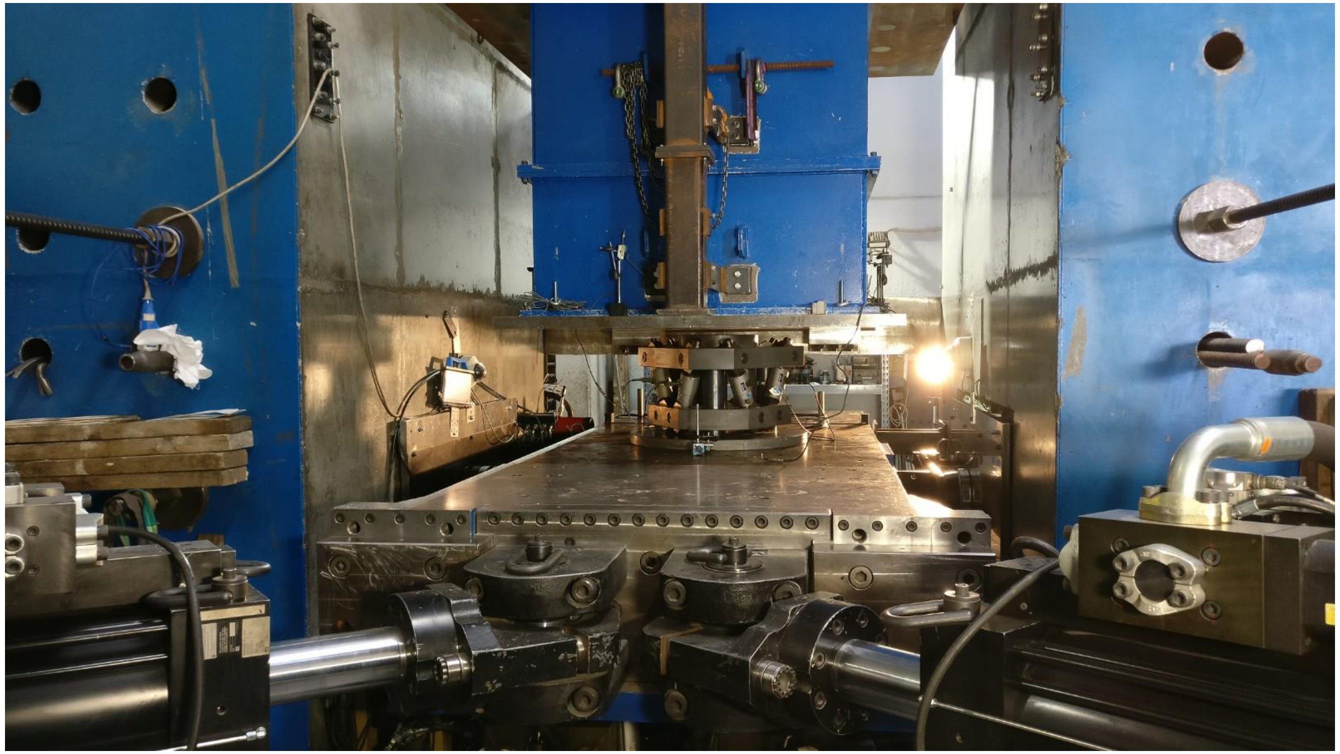

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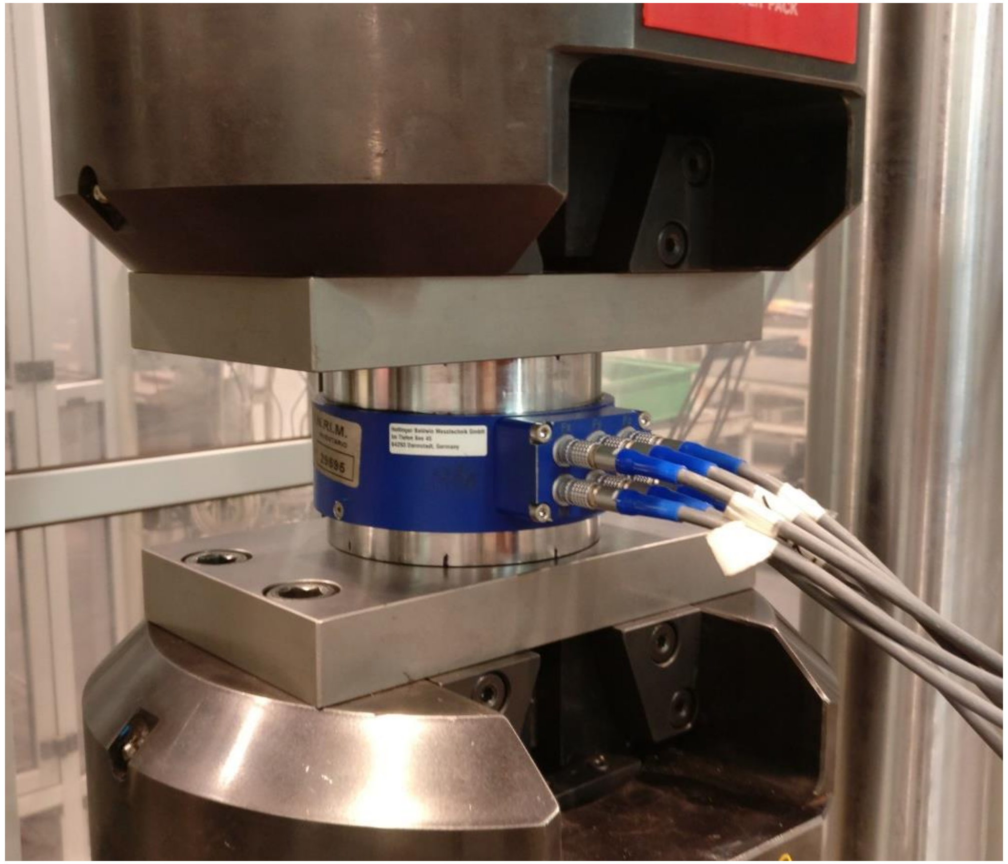
Multicomponent force and moment transfer standard in the testing machine



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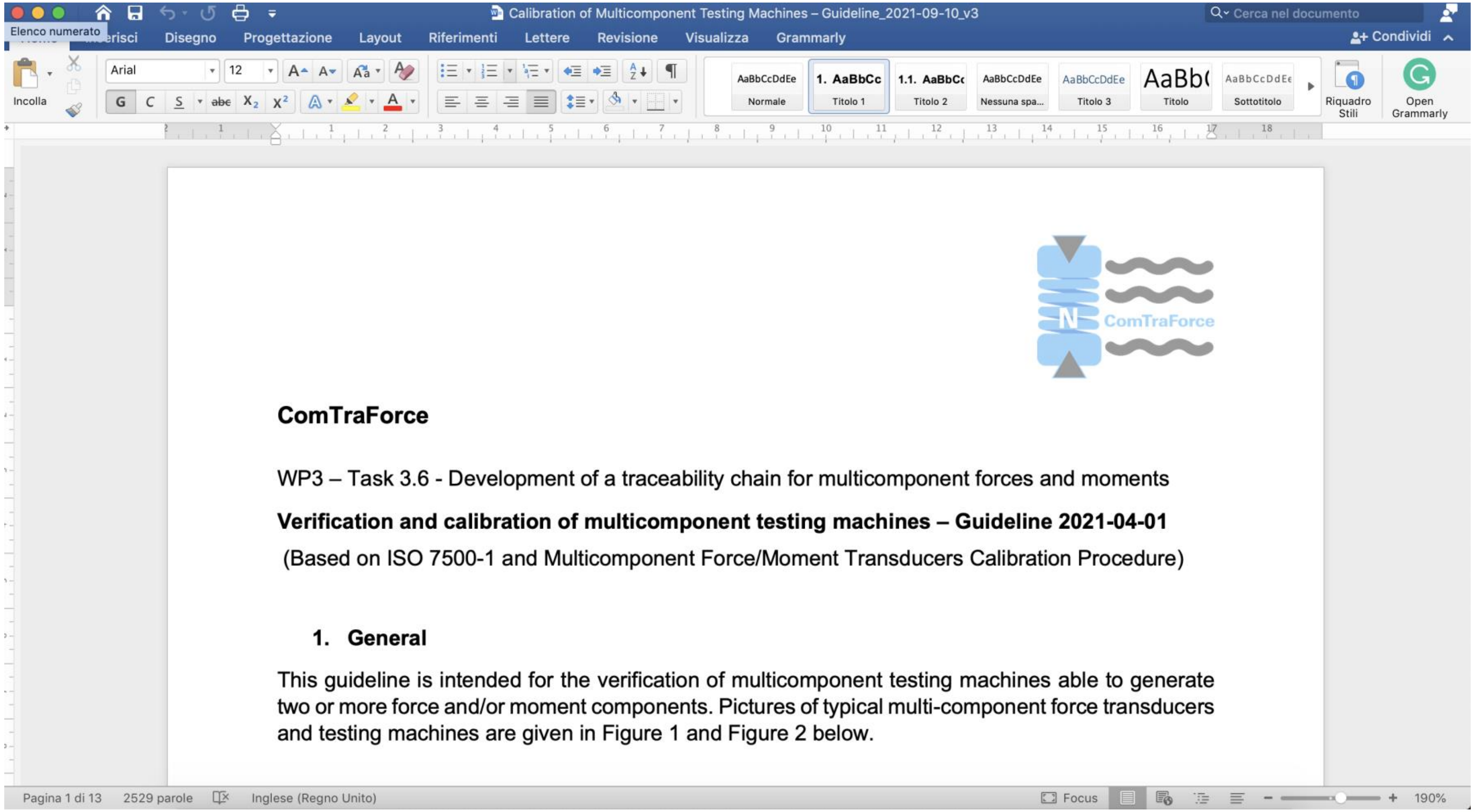
Calibration guideline



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WP3 – Task 3.6 - Development of a traceability chain for multicomponent forces and moments

Verification and calibration of multicomponent testing machines – Guideline 2021-04-01

(Based on ISO 7500-1 and Multicomponent Force/Moment Transducers Calibration Procedure)

1. General

This guideline is intended for the verification of multicomponent testing machines able to generate two or more force and/or moment components. Pictures of typical multi-component force transducers and testing machines are given in Figure 1 and Figure 2 below.

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Experimental plan

Measurements shall be taken in order that at least n=4 levels (possibly at -100 %, -20 %, 20 % and 100 % of the maximum capacity of the machine) for each k^{th} (k=1…m) force/moment component of the machine should be generated in all possible combinations.

The number of force/moment components combinations to be generated is given by:

$$N = n^m$$

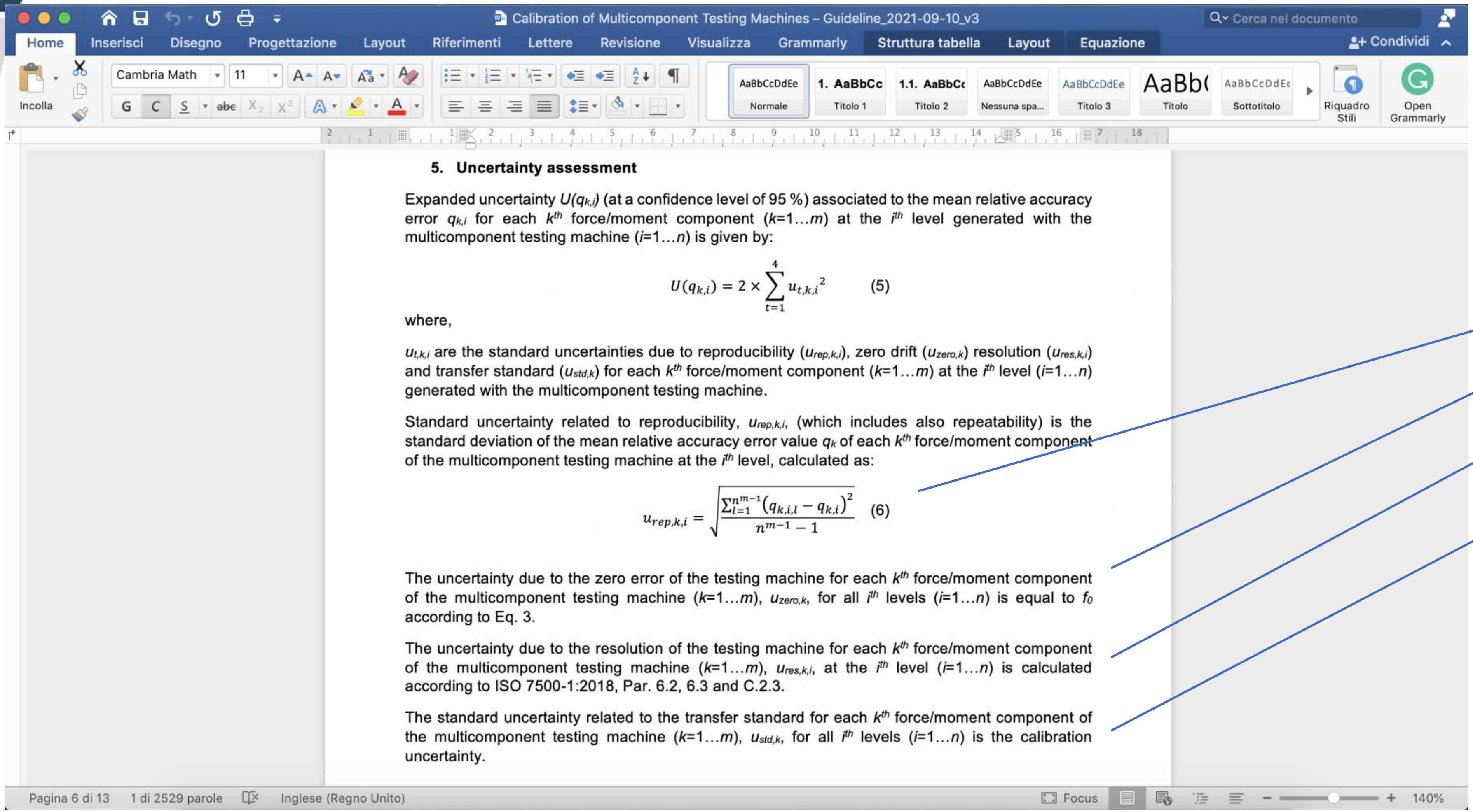
where *n* is the number of levels and *m* is the number of force and moment components of the machine

Accuracy error

For each k^{th} force or moment component (k=1…m) at each i^{th} level (i=1…n), calculate the **mean relative accuracy error** from the n^{m-1} measurements as follows (similarly to ISO 7500-1):

$$q_{k,i} = \frac{\sum_{l=1}^{n^{m-1}} q_{k,i,l}}{n^{m-1}} = \frac{\sum_{l=1}^{n^{m-1}} \frac{\left(F_{k,machine,i,l} - F_{k,std,i,l}\right)}{F_{k,std,i,l}}}{n^{m-1}}$$

Uncertainty budget



5. Uncertainty assessment

Expanded uncertainty $U(q_{k,i})$ (at a confidence level of 95 %) associated to the mean relative accuracy error $q_{k,i}$ for each k^{th} force/moment component (k=1…m) at the i^{th} level generated with the multicomponent testing machine (i=1…n) is given by:

$$U(q_{k,i}) = 2 \times \sum_{t=1}^{4} u_{t,k,i}{}^2 \qquad (5)$$

where,

$u_{t,k,i}$ are the standard uncertainties due to reproducibility ($u_{rep,k,i}$), zero drift ($u_{zero,k}$) resolution ($u_{res,k,i}$) and transfer standard ($u_{std,k}$) for each k^{th} force/moment component (k=1…m) at the i^{th} level (i=1…n) generated with the multicomponent testing machine.

Standard uncertainty related to reproducibility, $u_{rep,k,i}$, (which includes also repeatability) is the standard deviation of the mean relative accuracy error value q_k of each k^{th} force/moment component of the multicomponent testing machine at the i^{th} level, calculated as:

$$u_{rep,k,i} = \sqrt{\frac{\sum_{l=1}^{n^{m-1}} \left(q_{k,i,l} - q_{k,i}\right)^2}{n^{m-1} - 1}} \qquad (6)$$

The uncertainty due to the zero error of the testing machine for each k^{th} force/moment component of the multicomponent testing machine (k=1…m), $u_{zero,k}$, for all i^{th} levels (i=1…n) is equal to f_0 according to Eq. 3.

The uncertainty due to the resolution of the testing machine for each k^{th} force/moment component of the multicomponent testing machine (k=1…m), $u_{res,k,i}$, at the i^{th} level (i=1…n) is calculated according to ISO 7500-1:2018, Par. 6.2, 6.3 and C.2.3.

The standard uncertainty related to the transfer standard for each k^{th} force/moment component of the multicomponent testing machine (k=1…m), $u_{std,k}$, for all i^{th} levels (i=1…n) is the calibration uncertainty.

- Reproducibility
- Zero error
- Resolution
- Transfer standard

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Experimental plan

Level *i*	***F_z* / kN**
Level 1 (-100 %)	*-80*
Level 2 (-20 %)	*-16*
Level 3 (+20 %)	*+16*
Level 4 (+100 %)	*+80*

- negative F_z = tension
- negative M_z = clockwise (from the top)

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Experimental plan

Measurement condition, j	F_z / kN	M_z / N m
1	-80	-600
2	-80	-120
3	-80	+120
4	-80	+600
5	-16	-600
6	-16	-120
7	-16	+120
8	-16	+600
9	+16	-600
10	+16	-120
11	+16	+120
12	+16	+600
13	+80	-600
14	+80	-120
15	+80	+120
16	+80	+600

The number of force/moment components combinations to be generated is given by:

$$N = 4^2 = 16$$

- 2 components (F_z and M_z)
- 4 levels

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Results

$F_{z,machine}$ / kN	q	u_{rep}	u_{zero}	u_{ris}	u_{std}	$U(q)$
-80	**2.6%**	1.6%	0.1%	0.0%	0.6%	**3.4%**
-16	**2.4%**	7.7%	0.1%	0.0%	0.6%	**15.4%**
16	**0.4%**	7.2%	0.1%	0.0%	0.6%	**14.4%**
80	**-0.5%**	1.5%	0.1%	0.0%	0.6%	**3.2%**
$M_{z,machine}$ / N m	q	u_{rep}	u_{zero}	u_{ris}	u_{std}	$U(q)$
-600	**11.4%**	1.7%	0.6%	0.0%	5.5%	**11.6%**
-120	**6.6%**	6.8%	0.6%	0.0%	5.5%	**17.6%**
120	**19.5%**	6.4%	0.6%	0.0%	5.5%	**17.0%**
600	**13.8%**	1.7%	0.6%	0.0%	5.5%	**11.6%**

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Uncertainty of multicomponent forces and moments in industrial applications

$$U(F_k) = 2\sqrt{\left(\frac{U_{cal}(F_k)}{2}\right)^2 + u_{drift}^2(F_k) + u_{rev}^2(F_k) + u_{TC_0}^2(F_k) + u_{TC_S}^2(F_k) + u_{dyn}^2(F_k) + u_{res}^2(F_k) \ldots}$$

- Contribution due to reversibility
- Drift in sensitivity since calibration
- Effect of being used at a different temperature
- Effect of being used with different end-loading conditions
- Effect of being used with a different time-loading profile
- Effect of being used in dynamic conditions
- If applicable, effect of replacement indicator

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THANK YOU FOR THE KIND ATTENTION

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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