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Original
THE NEW 5 MN HEXAPOD-SHAPED MULTICOMPONENT BUILD-UP SYSTEM FOR FORCE MEASUREMENTS / Germak, ALESSANDRO FRANCO LIDIA; Palumbo, S.; Barbato, G.. - (2017), pp. 465-471. (XXV Congresso nazionale di Misure Meccaniche e Termiche Modena 14-16 settembre 2017).

Availability:
This version is available at: 11696/56265 since: 2017-10-04T11:24:56Z

Publisher:
Unità GMEE dell'Università degli Studi di Modena e Reggio Emilia

Published
DOI:

UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

Atti del

I Forum Nazionale delle Misure

XXXIV Congresso Nazionale di Misure Elettriche ed Elettroniche
XXV Congresso Nazionale di Misure Meccaniche e Termiche

14-16 Settembre 2017
Dipartimento di Ingegneria "E. Ferrari",
Università di Modena e Reggio Emilia
Modena

associazione italiana gmee gruppo misure elettriche ed elettroniche

MMT

Questo volume è stato composto in LaTeX tramite l'applicazione software sviluppata dall'Unità dell'Università di Genova e successivamente adattata e migliorata dall'Unità del Politecnico di Bari, dalle Università di Trento e Benevento e, in ultimo, dell'Università di Modena e Reggio Emilia.

ISBN 978-88-903149-9-5

Pubblicato a cura di Luigi Rovati e Stefano Cattini
Modena

Finito di stampare nel mese di Settembre 2017

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Pubblicazione a cura dell'Unità GMEE dell'Università
degli Studi di Modena e Reggio Emilia

THE NEW 5 MN HEXAPOD-SHAPED MULTICOMPONENT BUILD-UP SYSTEM FOR FORCE MEASUREMENTS

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ABSTRACT
In the framework of the EMRP Joint Research Project SIB63 "Force" with the title "Force traceability within the meganewton range", WP2, aiming to extend the traceability of the force measurements to the higher part of the scale, a new and innovative type of Build-Up System (BUS) force transducer, with a capacity of 5MN, has been designed and realized by INRIM.
It is composed by six Uniaxial Force Transducers (UFTs) and it has a hexapod-shape. It can be used to extend the scale from 1 MN to 5 MN with internal traceability for the vertical (axial) force and, thanks to his scheme, additionally provides measurements of transversal forces, bending and torsion moments.
In the paper, the description of the design, of the calibration procedure and of the data analysis is provided.

1. INTRODUCTION
The new 5 MN HSM-BUS, as any other type of Build-Up System (BUS) [1], has been designed to be used as reference transducer for measuring the force generated by the primary high force machine with a maximum capacity of 10 MN. It can be calibrated before the assembling process, and this leads to enhance the internal traceability of INRiM force laboratory. It can lead not only to measure forces 5 times higher than the nominal value of a the single uniaxial force transducers, but gives also information about the other components of the force vector and of the moment vector. These particular behaviors denote the HSM-BUS as the perfect reference for force calibrations under an hydraulic press. In fact, the HSM-BUS can be entirely calibrated inside the laboratory, and can be also used to align the force transducer under calibration with the vertical force and not only with the geometric center of the Force Standard Machine (FSM) as usually done. Another important characteristic of the HSM-BUS can be found in its calibration, since it is sufficient to calibrate the single Uniaxial Force Transducers (UFTs) and the system geometry [2].

2. DESIGN
The HSM-BUS uses six UFTs in order to multiply five times the capacity of the system (considering the mounting angles). This structure has also the advantage to be a multi-component force transducer (MFT), i.e. it can measure not only the principal axial force (Fz), but also all force vectors and moment ones [3]. The additional information on spurious component can be used to get a better accuracy on the Fz measurements. The 5 MN hexapod-shaped MFT is designed to work with a nominal force value of 5 MN, using 6 UFTs with maximum load of 1 MN, in order to be calibrated using the 1MN Deadweight Standard Force Machine at INRiM.

UFT: In a MFT with hexapod geometry are used six UFTs (Fig. 1), disposed two by two, to recreate an hexapod structure, realizing a pseudo-isostatic structure.
Another peculiarity of the hexapod-shape MFT, is that its UFTs work in traction, and not in compression as in a generic BUS. A further difference, is the inclination of the UFTs respect the horizontal, that leads to the necessity to continually re-orient the single UFT in order to avoid spurious components and flex-traction effects. This re-orientation movement can be obtained using a couple of elastic hinges at both ends of every UFTs. But, due to dimensional limitations, the using of elastic hinges is not possible, and it was used spherical joints (Fig. 2).

Fig. 1 *Structure of the uniaxial force transducer (UFT)*

Fig. 2 *Spherical joint*

System geometry: An hexapod-shaped structure is considered a structure having six foots; the ideal structure consists in three pair of each, each one of them create a triangle. The system geometry of the new 5 MN MFT can be briefly outlined with the views of the XY-plane and of XZ-plane. In the first view (left of Figure 3) we can see the distribution of the UFTs (numbered from 1 to 6) on the plates, the radius r and the angle γ (remembering that angle δ is complementary to it). In the second view (right part of Figure 3), it is clear the inclination of every UFTs with the horizontal, and are shown the two functional angles α and β.
As it can be seen in Figure 3, due to dimensional limits, it was not possible to connect two UFTs into the same point; so, instead of a triangle, each pair of UFTs create a trapezoid.

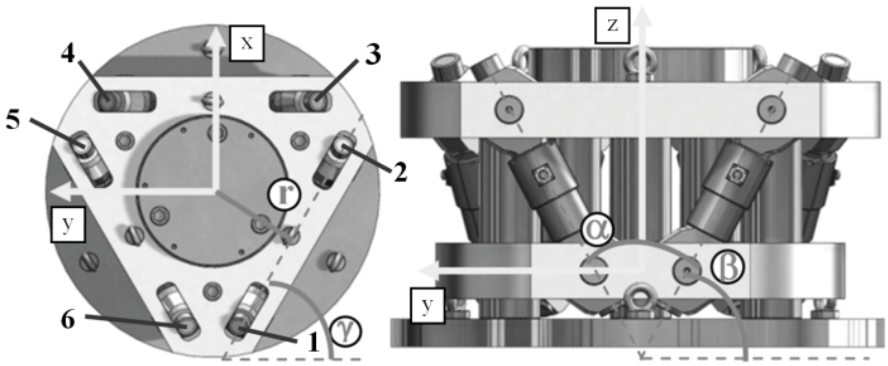

Fig. 3 *The geometry of MFT of the 5 MN HSM-BU*

HSM-BUS desing: The 5 MN hexapod-shaped MFT (Fig. 4) is designed to work with a nominal force value of 5 MN, using 6 UFTs with maximum load of 1 MN, in order to be calibrated using the 1MN Deadweight Standard Force Machine at INRiM.
Since the UFTs must work in traction, and not in compression as the MFT, it was necessary to create an inversion frame, in order to put in traction the UFTs. Such a structure enables measuring three force components (transversal, F_x and F_y, and axial, F_z), and three moment components, (tilting, M_x and M_y, and torsion, M_z), only combining the signal outputs of the UFTs.

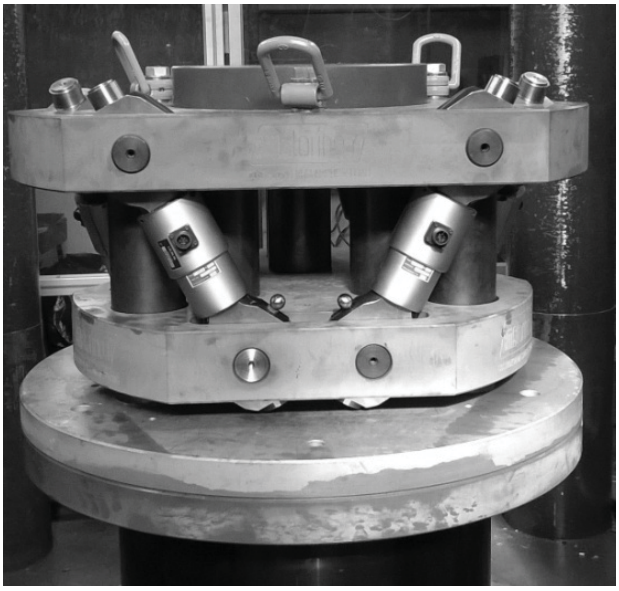

Fig. 4 *The 5 MN HSM-BUS*

3. CALIBRATION PROCEDURE

UFT calibration: The calibration of the single UFTs is an important contribution to the uncertainty budget of the MFT. The calibration procedure is conform to the UNI EN ISO 376 [4] and can be summarized as:

- Two loading phases at initial position (indicated as 0°), only with incremental force values
- Two other loading phases with relative rotation of the position (approximately 120° and 240°) with incremented and decremented force values

The values obtained are then evaluated fitting the calibration data with a linear regression with equation (1):

$$y = a + b \times x + c \times x^2 + d \times x^3 \quad (1)$$

Every single UFTs has its respective fitting equation that is used to convert the signal output into a force signal, and are resumed in Table 1.

Tab.1 *UFT fitting equations*

UFT	a	b	c	d
1	0.0108	499.6504	-0.9076	-0.1541
2	0.0003	499.2770	-1.1627	-0.0269
3	-0.0087	500.8994	-1.2907	0.0101
4	-0.0098	500.6190	-1.2488	-0.0090
5	-0.0104	500.5718	-1.3007	0.0172
6	-0.0234	500.1856	-1.0986	-0.0547

Geometry calibration: The calibration of the system geometry must be focused on the evaluation, with the lower possible uncertainty, of the two functional angle, α and β. Since it would be not so easy to evaluate directly the magnitude of these angles, it is possible to evaluate the two functional angles starting from the analysis of the system geometry of the HSM-BUS, below represented:
As can be seen, each pair of UFTs realize an ideal trapezoid, characterized by these geometrical elements *s*, *t* and *d*, as indicated in the Figure 5 and Table 2.

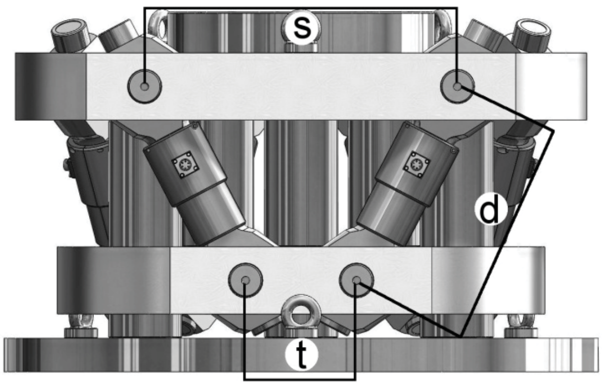

Fig. 5 *System geometry of the HSM-BUS*

Tab.1 *Geometrical elements of the ideal trapezoid of Figure 5*

Side	Symbol	Value /mm
upper base	*s*	467,06
lower base	*t*	166,00
diagonal	*d*	326,00

The respective values of the geometrical elements are taken from the technical drawings. Using this type of geometry, it is possible to define the two functional angles as:

$$\alpha = 2 \cdot \sin^{-1}\left(\frac{s-t}{2 \cdot d}\right)$$
$$\beta = \cos^{-1}\left(\frac{s-t}{2 \cdot d}\right) \quad (2)$$

The results are summarized in Table 3.

***Tab.2** nominal values of the functional angles*

Angles	Radiant	Degrees
α	$9{,}60\text{x}10^{-1}$	55,0°
β	$1{,}09\text{x}10^{0}$	62,5°

4. DATA COMPARISON

At the end of the work, the new 5 MN HSM-BUS was compared with the 5 MN national reference UFT under the hydraulic press following the UNI EN ISO-376 [4] procedure. The mean relative difference is equal to -4.4 x 10^{-3}. Since the results does not fit the level of uncertainty desired, it is necessary to study the re-orientation of the cell under load. During the preliminary study of HSM-BUS design [1], it was evaluated the variations of the system geometry with a FEM simulation. It was obtained that the functional angle α should became:

$$\alpha_{sim} = \alpha_{theor} - \Delta\alpha = \alpha_{theor} - (\mathrm{a} + \mathrm{b} \cdot \mathrm{F_{nom}}) \tag{3}$$

Following, data of the HSM-BUS have been corrected by the simulated variation of the functional angle and compared with the 5 MN national reference UFT. Results of corrected and uncorrected data are represented in Figure 6.

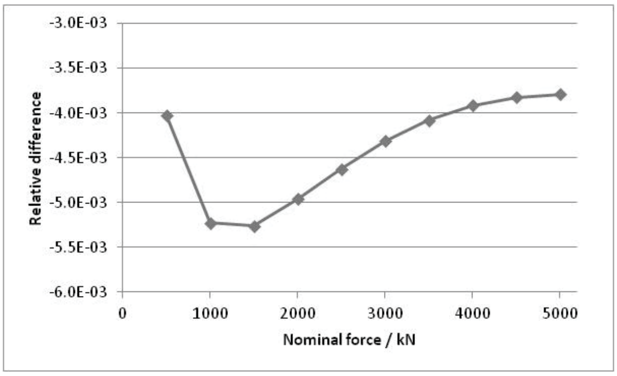

***Fig. 6** Relative difference between the new 5 MN HSM-BUS and the 5 MN national reference UFT*

The mean relative difference is equal to -4.4E-03. Since the results does not fit the level of uncertainty desired, it is necessary to study the re-orientation of the cell under load.
During the preliminary study of HSM-BUS design [2], it was evaluated the variations of the system geometry with a FEM simulation. It was obtained that the functional angle α should became:

$$\alpha_{sim} = \alpha_{theor} - \Delta\alpha = \alpha_{theor} - (\mathrm{a} + \mathrm{b} \cdot \mathrm{F_{nom}}) \tag{4}$$

Where the factor $\Delta\alpha$ is described by Table 4.

***Tab.3** Factor $\Delta\alpha$ parameters*

Parameter	Value /°
a	9.4534×10^{-3}
b	1.201×10^{-5}

The data of the HSM-BUS corrected by the simulated variation of the functional angle compared with the 5 MN national reference UFT are represented in Figure 7.

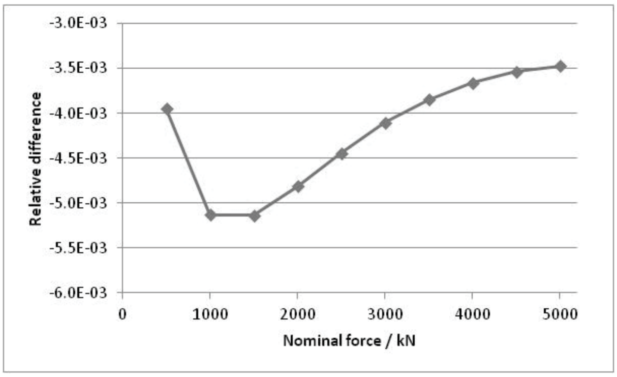

Fig. 1 *Relative difference between the HSM-BUS with correction and the 5 MN national reference UFT*

The mean relative difference is equal to -4.2 x 10^{-3}. This result shows that the variation of the system geometry under load may affect the force values and cannot be neglected. On the other hands, the simulation is not sufficient to fit the desired level of uncertainty, and these variations have to be measured.

Additionally, a standard calibration of the HSM-BUS have been carried out according to the UNI EN ISO-376 standards [4] and the relative errors on repeatability, *b*, and reproducibility, *b*', as weel the relative expanded uncertainty (confidence level of 95%), W_{nf}, have been evaluated as reported in Table 5.

The HSM-BUS, seen as a force transducer, does not exceed the limit of the class 0.5, the same of the actual national standards.

Tab. 5 *Data comparison with correction*

F / kN	b / %	b' / %	W_{nf} / %
500	0.100	0.048	0.104
1000	0.045	0.031	0.071
1500	0.083	0.032	0.086
2000	0.087	0.026	0.085
2500	0.073	0.029	0.080
3000	0.067	0.030	0.078
3500	0.055	0.026	0.070
4000	0.051	0.024	0.068
4500	0.041	0.023	0.064
5000	0.035	0.025	0.063

5. CONCLUSIONS

The results coming from a first comparison between the new 5 MN HSM-BUS and the 5 MN national reference UFT shows that it is important to concentrate on the variation of the system geometry under load, with particular attention to the functional angle α due to the reorientation of the UFT's under the load. For this reason, it has been realized a new UFT with a MEMS [5] integrated, in order to study the angle with the horizontal of this UFT under load, as shown in Figure 8.

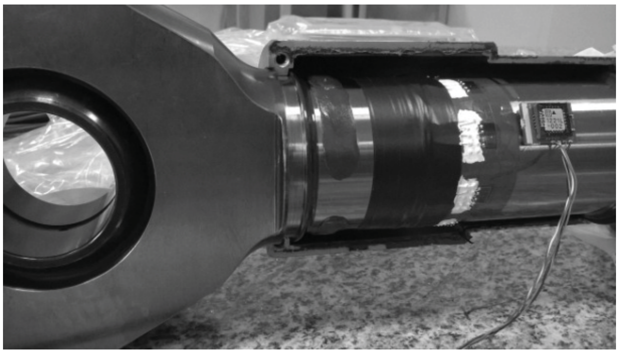

***Fig. 8 T**he UFT with integrated MEMS*

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 [6].

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

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