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PTB AND INRIM HIGH FORCE INTERCOMPARISON UP TO 9 MN

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Abstract:. The present paper describes the long term stability of the main metrological characteristics of the two reference transducers of 3 MN and 9 MN together with the relevant uncertainties evaluated from the measurements carried out by INRIM and PTB by bilateral comparisons. In June 2004, the new INRIM – 3 MN build-up system (BU), the 9 MN and 5 MN transducers were also intercompared, by using the PTB 2 MN DWM and the 16.5 MN Hydraulic Multiplication Machines (HMM). The main results are reported. Furthermore long term investigations carried out over 20 years and the work obtained within a EUROMET project are described.

Keywords: force standard machine, long term stability, intercomparison.

1. INTRODUCTION

The measurement of a physical quantity needs the establishment of a metrological chain, the starting point of which is the primary standard of the quantity. This standard must be transferable to secondary standards and to working standards having the required metrological characteristics.

In Italy, the force standards are maintained at the INRIM (former IMGC of the National Research Council and IEN). From 10 N to 1 MN, the primary standards are deadweight machines (DWM) having $2{\cdot}10^{-5}$ relative uncertainty.

From 1 MN to 9 MN, a force comparator machine is used, based on reference force transducers of 3 MN, 5 MN and 9 MN capacity with relative uncertainty of $5{\cdot}10^{-4}$. In the force comparator machine the forces are generated by a four columns hydraulic system and measured by several reference force standards with traceability to Physikalisch-Technische Bundesanstalt (PTB-Germany).

In Germany, the force standards are maintained at the PTB. From 1 N to 2 MN, the standards are deadweight machines (DWM) having $2{\cdot}10^{-5}$ relative uncertainty. Up to 16.5 MN the force standard is a hydraulic amplification force standard machine with a relative uncertainty of $1{\cdot}10^{-4}$.

The present paper describes the long term stability of the main metrological characteristics (calibration factor, repeatability, rotation effect, hysteresis, etc.) of the two reference transducers of 3 MN and 9 MN together with the relevant uncertainties evaluated on the measurements carried out at PTB in a period of 20 years, under a PTB-INRIM bilateral comparison and a EUROMET project.

In 2003 a 3 MN build-up system was designed and realised at INRIM and a new 5 MN transducer was acquired to improve the measurement capabilities in the range of large forces.

Otherwise the use of force comparator machines as standard machines needs great care, because the main errors could be originated by the reference transducers. A merely theoretical evaluation of the comparator machine may be not sufficient. For this reasons in June 2004 the new INRIM – 3 MN build-up system (BU) the 9 MN and 5 MN transducers were also intercompared by using the PTB 2 MN DWM and the 16.5 MN Hydraulic Multiplication Machines (HM).

2.GENERAL EVALUATION OF THE BUILD-UP METHOD

The term " build-up method" strictly speaking refers to two different configurations:

a) The true build-up method consists in placing the transducer to be calibrated in series with the build-up system, which consists of three reference transducers arranged in parallel to each other. The reference transducers in the build-up system are of equal capacity, at least one third that of the transducer to be calibrated, and are located in one plane at three equidistant points around a circumference.

The load on the transducer to be calibrated is thus provided as the sum of the loads applied to the single reference transducers. This was realised at INRIM with the 3 MN Build-Up System.

b) With the 3 MN Build-Up system other reference transducers can be calibrated up to 3 MN. The reference force transducer method, which consists in placing the transducer to be calibrated in series with a reference transducer of equivalent capacity to it.

The two transducers are then loaded by a hydraulic machine, so that the load axis passes through the axis of the two transducers. For the reference force transducer, the calibration curve, obtained for example with a primary force standard machine, is known. This is obtained at INRIM with the 3 reference load cells of 3 MN, 5 MN and 9 MN.

3. EXPERIMENTAL RESULTS AND ANALYSIS

In June 2004, the new INRIM – 3 MN build-up system (BU), the 9 MN and 5 MN dynamometers were also intercompared, by using the PTB 2 MN DWM and the 16.5 MN Hydraulic Multiplication Machines (HMM).

The elastic element of the 3MN and 9MN load cells used at INRIM comprises a solid cylinder with a flat lower surface and an upper surface in the form of a spherical cap. The elastic element of the 5 MN load cell comprises a solid cylinder with a flat lower and upper surfaces. The 3MN cell has a diameter of 110mm and a height of 330mm, the 9MN cell has a diameter of 200mm and a height of 400mm, while the 5MN cell has a diameter of 168 mm and a height of 380 mm.

3.1. 3 MN and 9 MN load cells results

The results of the calibration made using the PTB dead-weight hydraulic amplification machine (capacity 16.5MN, declared uncertainty $1 \cdot 10^{-4}$) are compared. The calibrations were done in 1984, 1988, 1991, 1995 , 1997 and 2004 for the 9MN cell and in 1984, 1991 1997 and 1999 for the 3MN cell.

The following characteristics of each reference transducer were compared: calibration factor, repeatability with and without rotation, hysteresis, zero variations at zero load.

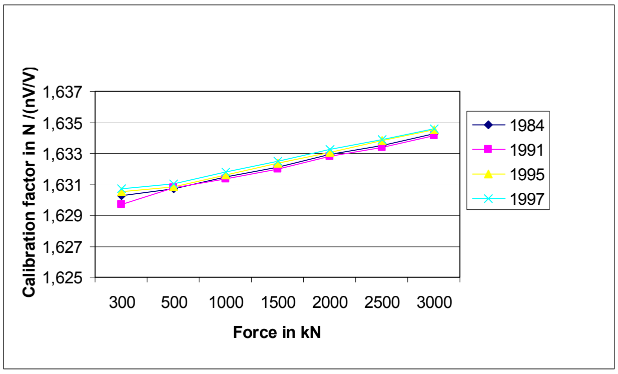

Figure 1. 3MN force transducer - Calibration factor

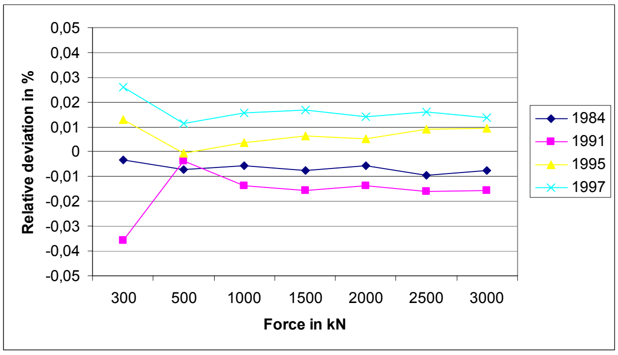

Figure 2. 3 MN force transducer – Relative deviation to the mean calibration factor obtained from Fig. 1.

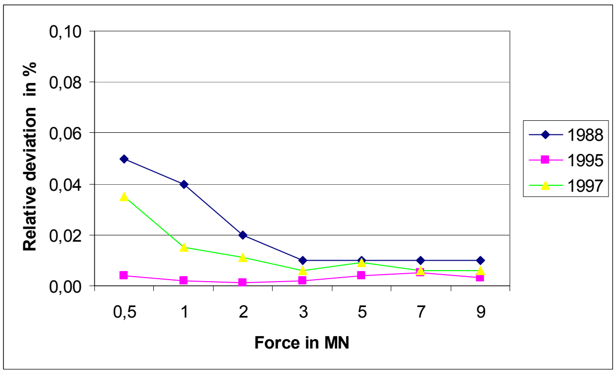

Figure 3. 9 MN force transducer - Repeatability

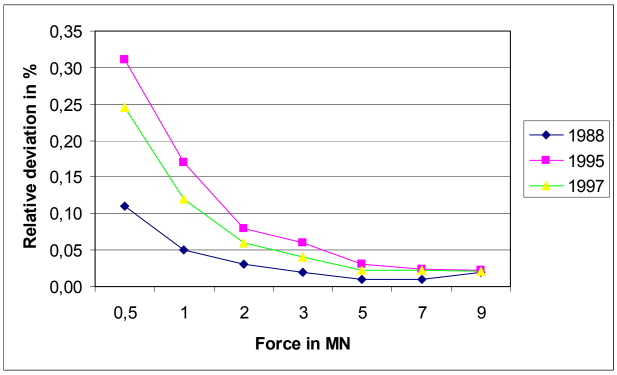

Figure 4. 9 MN force transducer - Rotation effect

It should be remembered that, given the long time interval considered, the standards applied by PTB to calibrate the force transducers have changed (DIN 51301 until 1988, which provided for three cycles at 0° with four angular positions: 0°, 90°, 180° and 270°; and EN 10002/3 after that, which entailed two cycles at 0° with three angular positions: 0°, 120° and 240°).

To determine the hysteresis, and in particular its value at 50% of the rated load, test cycles with increasing and decreasing loads were performed. For each test cycle, the zero load signal was determined.

The most important results are reported in the following Figures and Tables.

Figures 1 and 5 show the calibration factors of the two load cells during the 13 years since the first evaluation, while Figures 2 and 6 show the deviaton of the calibration factor from the average value obtained from the values of the different years.

Figures 3 and 4 report the repeatability values with and without rotation for the 9MN reference transducer, for different axial loads for the period 1984 to 1997

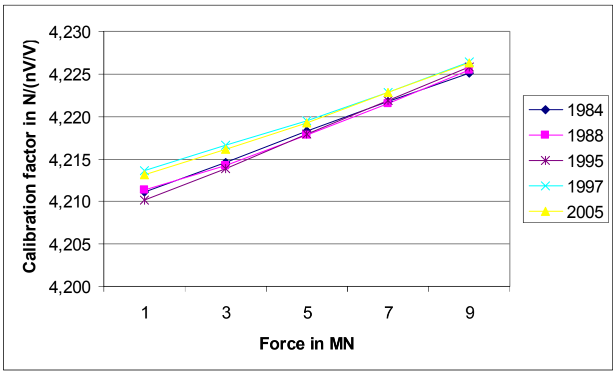

Figure 5. **9MN load cell - Calibration factor**

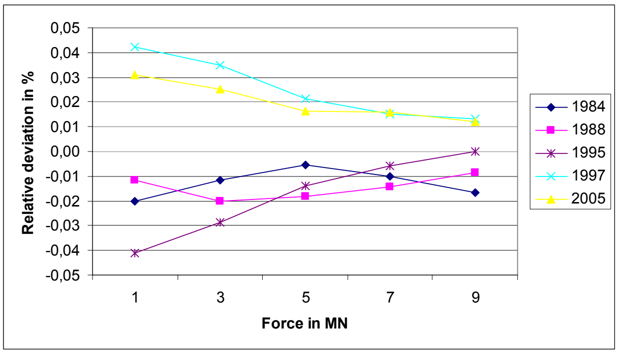

Figure 6. **9 MN force transducer – Relative deviation to mean calibration factor obtained from Fig. 5.**

The most important evaluations are as follows: Repeatability: the results show that it is better in case without rotation than in case with rotation. The rotation effect thus worsens repeatability, as occurs for most force transducers. For both load cells the dispersion of the calibration factor decreases as the load increases; for small loads, as has been shown in detail with multi-component measurements, the interface effects and the machine-dynamometer interaction are more significant.

The variations in the calibration factor were within +/- $3{\cdot}10^{-4}$ from 1984 to 1997 for the two 3MN and 9MN reference standards, within $1{\cdot}10^{-4}$ from '97 to 2004 for the 9 MN and within $0.5 \cdot 10^{-5}$ for the 3MN load cells. The zero signal variation referred to signal at the maximum load are in the same order for both load cells; the maximum value did not exceed $3{\cdot}10^{-4}$. These values appear to be fairly independent of time, after an initial period of ageing.

3.2. BUILD-UP System

3.2.1. Calibration of the Build-up System at INRIM

The Build-up system was calibrated on the INRIM DWM.

After performing the individual calibrations and validation tests, it was proceeded to the calibration of the Build-Up system, that is, the three force transducers of 1000 kN coupled in parallel.

The Build-up system was set up and calibrated (Fig. 7) simultaneously with the reference transducers in series up to the capacity of 900 kN, with the INRIM 1 MN DWM (expanded relative uncertainty of $2{\cdot}10^{-5}$).

Fig. 7. **Calibration of the INRIM – 3 MN Build-up system on the INRIM – 1 MN DWM**

The most relevant values obtained during the calibrations, such as repeatability with and without rotation errors, and the determination of the relative expanded uncertainty were determined.

The evaluation of the expanded relative uncertainty of measurements of the build-up system, reported in Table 1, has been made by using a traditional laboratory procedure [6].

TABLE 1. Expanded Uncertainty Evaluation

	Probability distribution	Standard uncertainty (k=1)
Individual calibration of the 1 MN force standard transducers • Reference force applied • Resolution • Repeatability without rotation • Repeatability with rotation • Reversibility • Zero error • Interpolation error	• Normal • Rectangular • Rectangular • U shaped • Rectangular • Rectangular • Triangular	$1 \cdot 10^{-5}$
• Total calibration uncertainty		$8 \cdot 10^{-5}$ F/3
Use of the Force Transducers • Creep (30 min.) • Long time drift • Temperature drift (2° C)	• Normal • Rectangular • arcsine	$0.3 \cdot 10^{-4}$ F/3 $0.8 \cdot 10^{-5}$ F/3 $0.15 \cdot 10^{-4}$ F/3
$u_c^2 = (8 \cdot 10^{-5}\ F/3)^2 + (0.3 \cdot 10^{-4}\ F/3)^2 + (0.8 \cdot 10^{-5}\ F/3)^2 + (0.15 \cdot 10^{-4}\ F/3)^2 = (8.4 \cdot 10^{-5}\ F/3)^2$		
BUILD-UP $3\ u_c^2 = 3(8.4 \cdot 10^{-5}\ F/3)^2 = 2.3 \cdot 10^{-9}\ F^2$		
Force generating system • internal coherence of the masses • intercomparison		$0.8 \cdot 10^{-4}$ F
Build-up system	$u_c^2 = 2.3 \cdot 10^{-9}\ F^2 + 6.4 \cdot 10^{-9}\ F^2 =$ $= 8.7\ 10^{-9}\ F^2$ $u_c = 0.93 \cdot 10^{-4}$ F $U = 2\ u_c = 1.87 \cdot 10^{-4}$ F $U_{bmc} = 2 \cdot 10^{-4}$ F	

3.2.2. Calibration of the Build-up System at PTB

In June 2004, the new INRIM – 3 MN build-up system (BU), was intercompared with the PTB 2 MN DWM and the PTB-16.5 MN HM Machines (Fig. 8). The main results are reported in tables 2 to 4.

The calibration on the PTB-HM machine was repeated with the BU in one angular position (PTBHM1) and in three angular positions (PTBHM2).

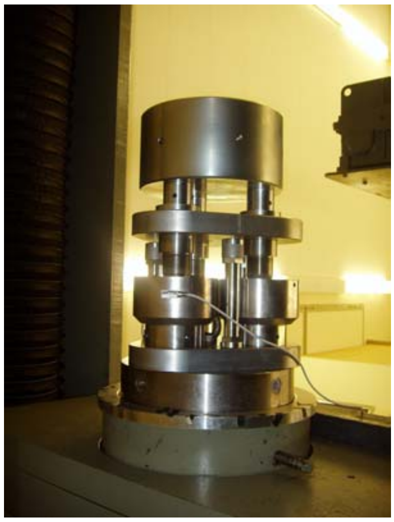

Fig. 8. Calibration of the INRIM – 3 MN Build-up system on the 16.5 MN PTB hydraulic multiplication machine

Table 2. Calibration of the INRIM 3MN – BU on the PTB and INRIM force standard machines. The Table shows the deflection in digits [div] for different force steps.

AXIAL LOAD	IMGC DWM	PTB 2 MN DWM	PTB HM1 1 position	PTB HM2 3 position
kN	[div]	[div]	[div]	[div]
300	198560	198586	198529	198500
600	396985	397048	396932	396901
900	595418	595494	595384	595343
1200		793980	793859	793812
1500		992526	992392	992341
1800		1191086	1191027	1190946
2000		1323460		
2100			1389569	1389512
2400			1588172	1588144
2700			1786832	1786780
3000			1985431	1985394
	1800kN-600kN	794038	794095	794045
		3MN - 600kN	1588499	1588493

Table 3. Relative deviation obtained on the PTB force standards determined from the deflection values in table 2.

AXIAL LOAD	2MN-HM1	HM1-HM2
kN	10 E-4	10 E-4
300	2,9	1,46
600	2,9	0,78
900	1,8	0,69
1200	1,5	0,59
1500	1,4	0,51
1800	0,5	0,68
2000		
2100		0,41
2400		0,18
2700		0,29
3000		0,19

Table 4. Relative deviation between INRIM-DWM and PTB machines with the 3 MN BU System.

AXIAL LOAD	IMGC-PTBHM	IMGC-PTB2MN
kN	10 E-4	10 E-4
300	1,6	-1,3
600	1,3	-1,6
900	0,6	-1,3

The 3 MN build-up system revealed a relative deviation less than $2{\cdot}10^{-4}$ in agreement with preliminary results up to 1000 kN on the INRIM DWM

3.3. 5 MN transducer results

The new INRIM - 5 MN reference transducer was intercompared, by using the PTB-16.5 MN Hydraulic Multiplication Machines (HM) and the INRIM 3 MN Build-Up System. In the intercomparison different procedures were also applied, namely:

With the PTB Hydraulic Machine

a) the DKD-PTB procedure which provided for three cycles at 0° (with increasing and decreasing loads equal to 0, 0.5 MN; 1 MN; 2 MN; 3 MN; 4 MN; 5 MN), and one cycle for the other 3 angular positions (90°, 180° and 270°) , with only increasing loads (0; 0.5 MN; 1 MN; 2 MN; 3 MN; 4 MN; 5 MN).

b) the ISO 376 Standard which entailed two cycles at 0° with three angular positions: 0°, 120° and 240°.

With the INRIM Build-Up System

c) the ASTM-INRIM procedure which provided for one cycle at the four angular positions: 0°, 90°, 180° and 270° for increasing and decreasing loads (0; 0.3 MN; 0.6 MN; 0.9 MN; 1.2 MN; 1.5 MN; 1.8 MN; 2.1 MN; 2.4 MN; 2.7 MN and 3 MN).

The 5 MN shows a reproducibility of $1{\cdot}10^{-4}$ during the measurements carried out in PTB with the 16.5 HMM, and in INRIM by using the Build-Up system.

4. CONCLUSIONS

The results of the calibrations performed at PTB over the last 20 years not only confirm the principal results of the force transducer characteristics expressed after the first decade of use of the INRIM reference standard, they also enable us to make the following evaluations:

The two reference force standards of 3 MN and 9 MN showed an average stability of the order of $2 \cdot 10^{-4}$ over four years, while the 5 MN shows a reproducibility of $1 \cdot 10^{-4}$ during the measurements carried out with the PTB, and INRIM force standard machines.

The 3 MN build-up system revealed a relative deviation less than $2 \cdot 10^{-4}$ in agreement with preliminary results up to 1000 kN on the INRIM DWM.

In agreement with these measurement results the different load cells could be used in the INRIM Comparator Machine with a declared relative expanded uncertainty of $5 \cdot 10^{-4}$

Otherwise the use of force comparator machines as standard machines requires great care, because the main errors could be originated by the reference transducers and by the characteristics of the systems to generate and transfer the loads. It is thus advisable to check the calibration characteristics of the load cells with a frequency depending on the conditions of their use, and on the number of calibrations performed.

REFERENCES

[1] A. Gizmajer, "Some improvements in the Build-up System", Round Table, IMEKO XII, Beijing, 1991

[2]. C. Ferrero, C. Marinari, E. Martino, "Force Metrology in Italy: the new 1 MN force standard",. XVI IMEKO TC3, Korea 1998, 127-135

[3] H. Wieringa., "Design of 1,65 and 4,95 MN Transfer Standard Based on the Build-Up Procedure", Proc. 10th Conference of IMEKO TC-3 on Measurement of Force and Mass, Kobe, Japan, September 1984, pp. 205-208.

[4] A. Gosset, "Workshop on statement of uncertainty force standard machines", EUROMET Project 310, 1994 pp. 205-210.

[5] C. Ferrero, C. Marinari, E. Martino" Development and metrological characterization of a build-up force standard up to 3 MN" XVII IMEKO World Congress June 22–27, 2003, Dubrovnik, Croatia

[6] EN 10002-3:1994 – "Metallic Materials - Tensile Testing - Calibration of Force Proving Instruments Used for the Verification of Uniaxial Testing Machines".

[7] EA 10/04 – "Uncertainty of Calibration Results in force Measurements", European co-operation for Accreditation.

[8]. W. Weiler, A. Sawla, "Force standard machines of the National Institute for Metrology". PTB – Bericht ME-62, 1984

[9] M. Peters, D. Peschel, R. Kumme, D. Mauersberger: „PTB's „new" 2 MN Deadweight Force Standard Machine, Proceedings of the 19th IMEKO TC3 Conference, 2005.

[10] M. Peters, "Development and Realization of a New Control Principle for the 16.5 MN Force Standard Machine at PTB", Proceedings of the 12th IMEKO World Congress, Sept. 5-10, 1991, Beijing, China.

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