XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September, 17 – 22, 2006, Rio de Janeiro, Brazil

INVESTIGATION OF PARASITIC COMPONENTS IN PTB's 2 MN DEADWEIGHT MACHINE BY USING THE INRIM SIX-COMPONENT DYNAMOMETER

C. Ferrero [1], *C. Marinari* [2], *R. Kumme* [3]

[1] INRIM, Torino, Italy, C.Ferrero@inrim.it
[2] INRIM, Torino, Italy, C.Marinari@inrim.it
[3] PTB, Braunschweig, Germany, Rolf.Kumme@ptb.de

Abstract:. The present paper describes the intercomparison realized in June 2004 in order to evaluate the main metrological characteristics of the PTB 2 MN standard deadweight machine by using the 500 kN INRIM six-component dynamometer. The main results (side components, bending and twisting moments) are reported**,** which indicate that they are of a very low level. Measurements of the dynamic components during weight changes and free suspension of the system are also presented.

Keywords: Force, force standard machine, multi-component dynamometer, intercomparison

1. INTRODUCTION

Ideally, force standard machines should apply uniaxial loads only. In practice, mis-alignments and deformations of the force standard machines result in finite values of the five parasitic components of the force/moment tensor. The effect of these components on the load cell output is one of the principal reasons why measured differences between deadweight force standard machines are sometimes an order of magnitude greater than the estimated uncertainties of the axial force values [1]. The main sources of the differences are parasitic effects caused by undesirable components (side forces and moments) generated by asymmetry in machine structure, non-symmetric deformations of the loaded machine, faulty load cell positioning on the machine and machine-load cell interaction

In order to improve primary force standards as well as to understand anomalies and optimise calibration methods, it is essential to measure the effect of different parameters on the parasitic components.

In June 2004, INRIM's six-component dynamometer were used to measure the parasitic components of PTB 2 MN deadweight machine (DWM). The results are reported here, together with measurements of the influence of different weight combinations and dynamic effects on these components.

2. THE PTB 2 MN DEADWEIGHT FORCE STANDARD MACHINE

The PTB DWM, has the following characteristics: maximal capacity, 2000 kN; lowest load 50 kN; loading frame: two columns. It has different types of weight pieces. The first step is 50 kN and realized by the loading frame. In the range from 50 kN up to 2000 kN forces can be realized in steps of 10 kN by using different deadweight combinations from the 5 stacks of deadweights shown in Fig. 1. The principle of the machine is described in detail in [2-4]. The relative uncertainty of the machine is ≤ $2 \cdot 10^{-5}$ ($k = 2$) over the whole range depending of the individual force step and deadweight combination.

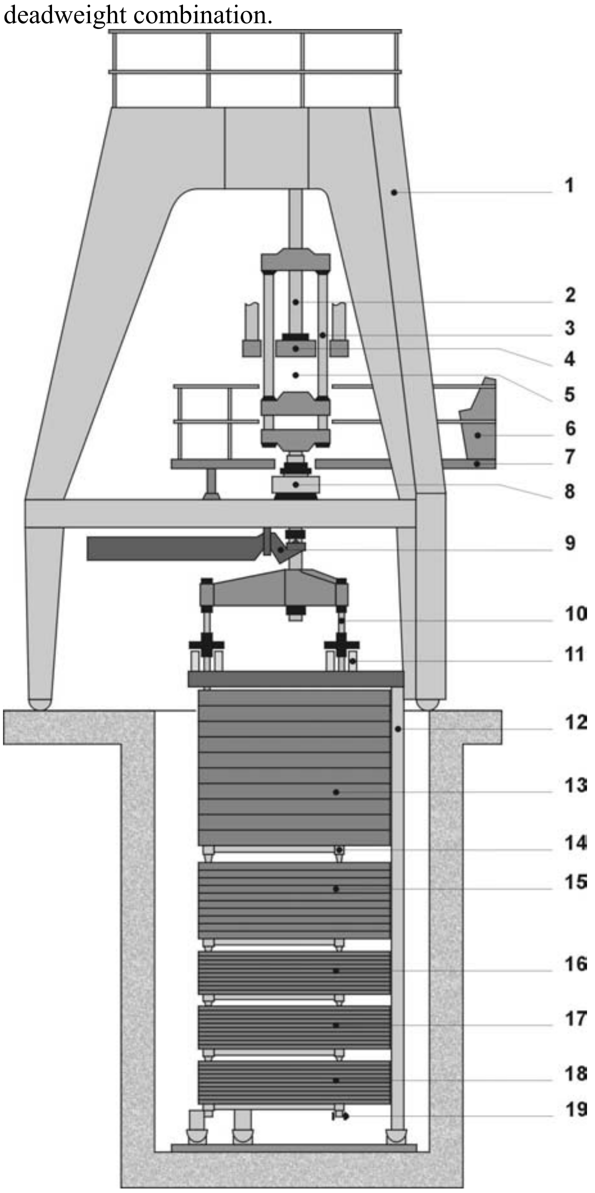


Fig. 1. Principle of 2 MN deadweight force standard machine: 1 tripod platform, 2 fitting room for compression devices, 3 frame 50 kN, 4 crosshead (adjustable), 5 fitting room for tension devices, 6 control console, 7 working platform, 8 frame support (old), 9

compensating lever, 10 three columns of the scale pan, 11 scale pan support / centering, 12 support rack for the deadweights (9 columns), 13 stack 5: 10 x 100 kN, 14 frame, 15 stack 4: 10 x 50 kN, 16 stack 3: 10 x 20 kN, 17 stack 2: 10 x 20 kN, 18 stack 1: 10 x 10 kN, 19 air bearing

3. THE INRIM SIX-COMPONENT DYNAMOMETERS

In the early 1980s, INRIM designed and constructed a 100 kN six-component dynamometer [5, 6] to measure parasitic components. Ten deadweight force standard machines around the world have since been evaluated with this dynamometer [7 to 13]. The ability to monitor all six components in real-time, during both load changes and free oscillation of the system, proved to be a valuable tool in the identification of loading anomalies. Following the success of this work, the European Union commissioned INRIM to design and construct a 500 kN six-component dynamometer [9]. Both dynamometers are composite load cells consisting of six uniaxial load cells arranged to measure the orthogonal forces, bending, and twisting moments. Decoupling between the load cells is provided by the use of elastic flexures.

The 500 kN capacity INRIM six-component dynamometer is 780 mm high and with a diameter of 420 mm, it is 550 kg heavy (fig 2). The dynamometer was described in detail in a previous paper [9].

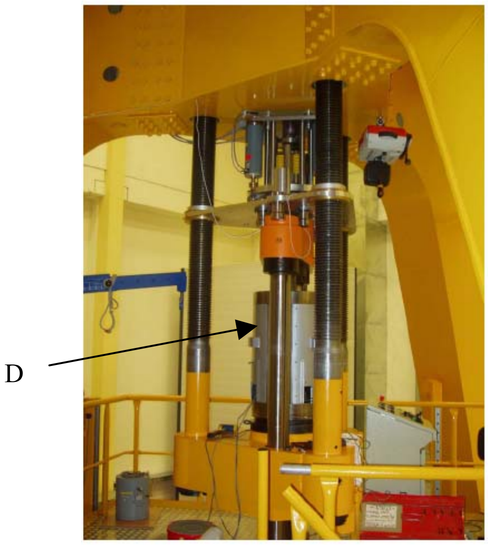


Fig. 2. INRIM 6-component dynamometer (D) on the PTB 2 MN DWM

The composite configuration chosen for the dynamometer design has several advantages with respect to other types of multi-component dynamometers:

a) high sensitivity to transverse components (detection of small inclination angles) and to twisting moment
b) low interaction between the axial component and the transverse components;
c) lower dependence on interface conditions and, consequently, on parasitic components during the load transmission phase; these components may cause permanent changes in other cell-machine systems;

The dynamometer is connected to an AC digital indicator (HBM DK38 S6 with 10 nV/V resolution). A Labview program controls and logs the sequential measurement of the outputs of the six load cells.

The orientation of the dynamometer in the machine defines two orthogonal horizontal axes (X, Y). The dynamometer measure the vertical force (F_Z), the two horizontal forces (F_X, F_Y), the two bending moments about the horizontal axes (M_X, M_Y), and the twisting moment about the vertical axis (M_Z).

For the determination of all force and moment components the signals of the three horizontal load cells (H_1, H_2, H_3) and the signals of the three vertical load cells (V_1, V_2, V_3) of the dynamometer are further evaluated with the knowledge of the dynamometer transfer-matrix, which was the result of the dynamometer calibration at INRIM.

The versatility characteristics of the dynamometer and the measurement method adopted make it possible to study dynamic phenomena of the machine/dynamometer system, which are understood both as load-application transients and as free oscillations of the system under constant load. Real-time diagrams of the evolution of the force tensor applied to the dynamometer are a very useful tool to detect anomalies that otherwise would be difficult to locate.

4. MEASUREMENT PROCEDURE

The tests were designed to measure three aspects of the performance of the 2 MN machine:

- the effect of axial load value on parasitic component values;
- the influence of different weight combinations on component values;
- the dynamic components generated by the machine during both weight changes and steady state operation.

4.1 Influence of different weight combinations

Changing the combination of weights used to generate a specific force will result in a change in centre of gravity and moment of inertia of the suspended mass. This may cause significant variations in the parasitic components.

4.2 Determination of dynamic components

Tests were carried out to measure the dynamic parasitic components generated during both weight changes and free oscillation of the system.

5 EXPERIMENTAL RESULTS AND ANALYSIS

Measurements were repeated with the dynamometers at four different angular positions relative to machine axes (0°, 180°, 90°, 270°), and were made at a temperature of (20.2 ± 0.2) °C.

At each orientation, preload cycles of rated load applied for two minutes followed by zero load for five minutes were performed.

Measurements were taken at incremental loads only, with readings taken two minutes after load application or removal.

5.1 Preliminary tests carried out before to start for measurements:

Influence of loading transient

The continuous recording of the signals from the three horizontal load cells (H_1, H_2, H_3) makes it possible to evaluate if any anomalous load levels arise during the load application transient, for increasing and decreasing load, from 0 up to 500 kN. In fig 3 an example of continuous recording signals.

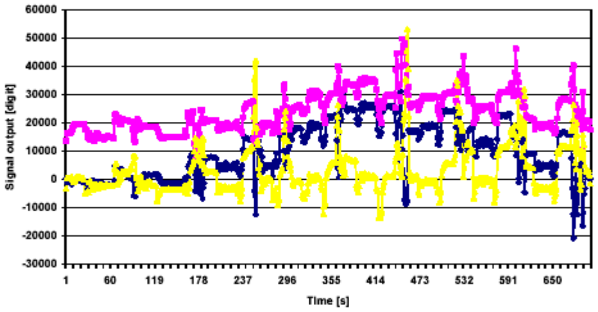


Fig. 3. Continuous recording of the three horizontal load cells output (in digit), during load application (from 0 up to 500 kN)

Influence of different weight-piece oscillations

The continuous recording of the signals from the three horizontal load cells (H_1, H_2, H_3) was analysed during the reading time (60 s) in order to check at any load level, the different amplitudes of weight piece oscillations. Fig. 3, as an example, clearly shows the peaks occurring in transients of weight-piece application on the carrier which give rise to dynamic components in the machine-dynamometer interface.

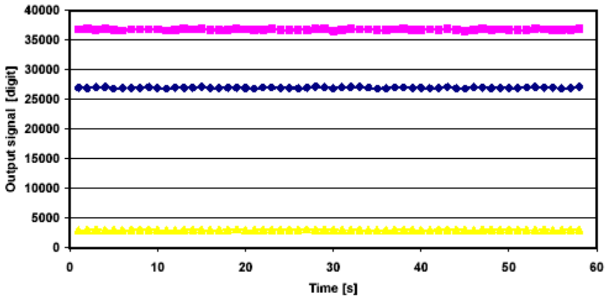


Fig. 4. Recording of the three horizontal load cells output (in digit) during data reading (500 kN load level)

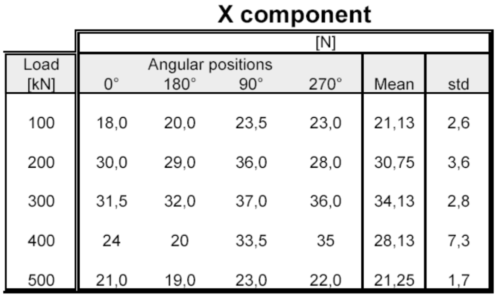
Between two successive peaks there can be seen the free oscillations of weight pieces. The values (in digit) appearing in the figures do not reveal significant differences for side components F_x and F_y. This means that the weight pieces oscillate freely, so that no particular effects were observed in the machine-dynamometer coupling, when changing load.

5.2 Parasitic component

a) Side components (F_x, F_y)

With load ranging from 100 kN up to 500 kN and the dynamometer positioned at 0°, component F_x increased from 18 N to 31.5 N and down to 21 N; in this load interval the mean values covering all the dynamometer positions indicated in Table 1 range from 21 N to 34 N.. Component F_y varies from 8.0 N to 63 N at 0°, and the mean values range varies from 10.25 N to 66.5 N (Fig. 5). The maximum deviation from the mean value, Δ, is 2.2 N with F_z = 300 kN and 0.5 N with F_z = 500 kN, for the four angular positions.

Table 1. Side component F_x measurement by INRIM 500 kN six component dynamometer.



X component

Load [kN]	[N] Angular positions 0°	 180°	 90°	 270°	 Mean	 std
100	18,0	20,0	23,5	23,0	21,13	2,6
200	30,0	29,0	36,0	28,0	30,75	3,6
300	31,5	32,0	37,0	36,0	34,13	2,8
400	24	20	33,5	35	28,13	7,3
500	21,0	19,0	23,0	22,0	21,25	1,7

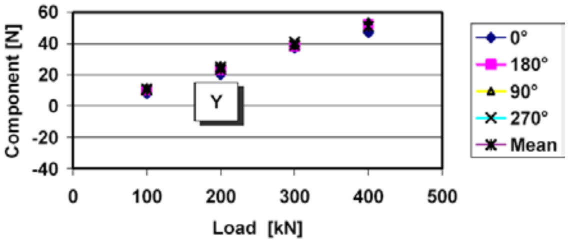


Fig. 5. Side component F_y measurement by INRIM 500 kN six component dynamometer

The above results indicate that the PTB 2 MN deadweight machine produces only small side forces (F_x, F_y) and that these components vary linearly if the case of F_y with axial load F_z. The F_x/F_z ratio is about 4 10^{-5}; the F_y/F_z ratio is about 8.5 10^{-5}. (Fig.6)

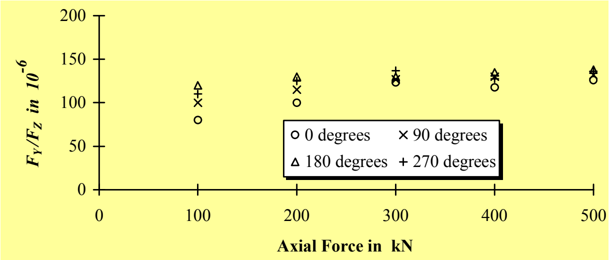


Figure 6. PTB Relative values of side force F_y/F_z

Side-component linearity vs. axial load indicates that with the PTB machine components mainly depend on the initial geometrical condition (inclination) of the main machine and that the machine does not undergo noticeable distortions when load is varied.

b) Twisting moment M_z

The values of twisting moment M_z resulted to be lower than 10 N·m so that this moment can not influence the value of the vertical load (Fig.7).
The twisting moment was not affected by different weight-piece oscillation amplitudes. Variation M_z remained, as a rule, within ± 3 N·m (Table 2).

Table 2. Twisting moment M_z measurement by INRIM 500 kN six component dynamometer.

N component

Load [kN]	[Nm] Angular positions 0°	180°	90°	270°	Mean
100	-2,2	-3,0	-2,5	-3,3	-2,8
200	-0,6	-0,8	-1,0	-1,2	-0,9
300	-0,3	-1,0	-0,7	-0,9	-0,7
400	2,7	4,0	5,0	4,5	4,1
500	5,0	7,0	10,0	8,5	7,6

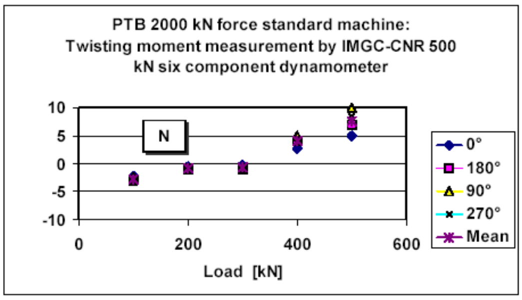


Figure 7. PTB Relative values of twisting moment, *Mz*

c) Bending moments M_x, M_y

As a rule, bending moment M_y resulted smaller than 45 N·m, with F_z = 500 kN; bending moment M_x was about 73 N·m at the same load level. This means that the reproducibility of the load application point was better than $\Delta y = M_y/F_z \le \pm 0.1$ mm and than $\Delta x = M_x/F_z \le \pm 0.15$ mm at rated load, with the dynamometer at different angular positions.

5.3 Influence of different weight piece combinations

The observed differences ($\Delta F_x \le 1$ N; $\Delta F_y \le 1$ N at 500 kN) were very small and did not affect the machine behaviour. Also the axial load ($\Sigma Vi = V1 + V2 + V3$) was not affected by the different weight-piece combinations. The relative deviation between the two values obtained at 500 kN with and without the mass of 50 kN was always less than $1 \cdot 10^{-5}$.

6. DISCUSSION

6.1 Determination of parasitic components

The side force was observed to be proportional to the axial load.

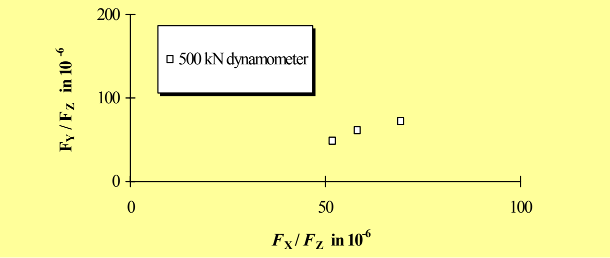


Figure 8. Mean side force component values measured by 500 kN dynamometer.

These results indicate that the magnitude of the side force generated by the 2 MN machine is less than 0.01 % of the vertical force. This component depends mainly on the initial level of the lower plate. The lack of any second order dependence on load indicates that the plate angle does not vary under load.
The inclination correction corresponding to the measured side force component:

$$\frac{\Delta F_Z}{F_Z} = \frac{F_X^2 + F_Y^2}{2F_Z^2} \quad (1)$$

is insignificant ($< 1 \cdot 10^{-7}$) in comparison to the uncertainty of the vertical force value [10].

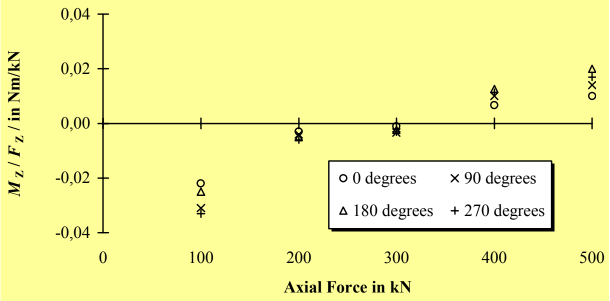


Figure 9. PTB Relative values of twisting moment, M_Z

All measurements of the twisting moment, M_Z, gave values of less than 0.03 Nm per kilonewton of axial force (Fig. 9). These values were not significantly affected by the amplitude of oscillation of the suspended weights.

The insignificant values of M_X and M_Y probably result from the method used to centre devices in the PTB machine.

6.2 Influence of different weight combinations

The insignificant effect on the parasitic components of different weight combinations is not unexpected as each weight's centre of gravity was adjusted to within 1 mm of its geometric centre.

6.3 Dynamic components

Peak values occurring during weight transitions are clearly visible, as are the subsequent free oscillations of the weights.

The traces recorded of the parasitic components of the suspended mass show sinusoidal behaviour with little damping. This indicates that there is no contact with main frame, leaving the system free to oscillate.

CONCLUSION

The tests carried out on the PTB 2 MN machine, as regards the measurement of parasitic components and the influence of several parameters on the values of such components, allow the following main results:

a) Side forces (F_x, F_y) are repeatable for the standard deadweight machine and correspond to a maximal inclination of the main frame of the order of 10^{-4} rad ($F_x \leq 35$ N; $F_y \leq 70$ N).
b) High repeatability of the values of side components F_x and F_y vs. axial load, for each angular position, is an indication that the standard deadweight machine is highly stable and repeatable (Fig. 6).
c) Linearity of side components (F_x, F_y) vs axial load indicates that those components mainly depend on how the machine has initially been settled (initial inclination β) and that, consequently there occur no distortions or rotations of the loading or main frames with variations of the applied load: in fact sizable quadratic effects would otherwise be introduced.
d) High reproducibility of side components F_x, F_y values vs axial load for different angular positions of the dynamometer in respect of the machine axis Z.
This implies:
    d.1) good reproducibility of the vectorial forces (axial force and side components) generated by the PTB standard deadweight machine;
    d.2) a very low effect of machine-dynamometer interactions (rotation effects).

Bending moments values M_x, M_y checked up to rated load confirm that the eccentricity is lower than 0.2 mm of the load application line to the axis of the dynamometer.
Twisting moment M_Z is usually lower than 0.03 Nm per kilonewton at all load levels indicating that there is no contact between the suspended weights and the machine frame.

The parasitic components are independent of weight combination, indicating good vertical alignment of the weights.

The dynamic assessment of the machine shows that the parasitic components generated during weight changes are of similar magnitudes to those measured statically, and that the suspended mass is free to oscillate.
The parasitic components of the PTB-2 MN deadweight force standard machine have been successfully measured. The results indicate that their effect on the calibration of compression load cells and other compression force transfer devices is likely to be insignificant.

REFERENCES

[1] Peters M: Reasons for and consequences of the rotation and overlapping effect. Proc. of the 10th Conf. of IMEKO TC3, Kobe, Japan, 1984.
[2] 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.
[3] Adolf, K.; Peschel, D.: Normalmesseinrichtung zur Darstellung von Kräften bis 2 MN (KNME 2 MN). Metrologische Abhandlungen 3 (1983) 2, pp. 119-131, ISSN 0232-3915
[4] Dietrich, M.; Hasche, K.; Peschel, D.: About the uncertainty of the higher capacity primary standard and the dissemination of force in ASMW. Proceedings of the 11th IMEKO Conference, Amsterdam 1986, pp. 217-226.
[5] C. Ferrero C 1988 Evaluation of force standard machines with two multicomponent dynamometers. BCR-Applied Metrology. Commission of the European Community, Luxembourg
[6] C. Ferrero, C. Marinari, E. Martino, A six-component dynamometer to measure parasitic load components on deadweight force standard machines, Proceedings of the 10th IMEKO TC3 Conference, Kobe, 1984, p. 127-134.
[7] C. Ferrero, Q. Z. Li, International comparison of axial load in deadweight force standard machines, Proceedings of the 12th IMEKO World Congress, Beijing, 1991, p. 172-177.
[8] C. Ferrero, The measurement of parasitic components in national force standard machines, Measurement, 8 (2) (1990) 66-76.
[9] C. Ferrero, C. Marinari, E. Martino, The new 0,5 MN IMGC six-component dynamometer, Proceedings of the 13th IMEKO World Congress, Torino, 1994, p
[10] C. Ferrero, "Multicomponent calibration systems to check force sensors", Proc. 1st ISMCR -IMEKO TC-I7 Meeting, Houston, USA, pp. 5.1.1-1.16, 1990
[11] C. Ferrero, C. Marinari, Li Qing Zhong, : "The measurements of parasitic components and the influence of load transfer systems on a force standard machine", ICEM, Beijing, 1985.
[12] C. Ferrero, C. Marinari, E. Martino, "Evaluation of parasitic components on National deadweight force standard machines", 11th IMEKO Conf., Amsterdam, 1986.
[13] C. Ferrero, C. Marinari, "Metrological characterization of load cells by means of different multicomponent calibration systems", Jurema 32, Zagreeb, 1987.