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Static and dynamic evaluation of the CENAM (Mexico) 150 kN primary force standard machine by means of the INRiM (Italy) 100 kN six-component dynamometer

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Abstract

In order to improve the metrological characteristics of the primary force standard machines, as well as to understand the causes of anomalies and to optimise calibration methods, it is important to measure the value and the effect of the parasitic components which could influence the final value and uncertainty of the applied vertical loads.

The paper describes the measurements performed on the 150 kN CENAM (Mexico) primary force standard deadweight machine in order to evaluate the value and the direction of the parasitic components (two side forces F_X and F_Y; two bending moments F_L and F_M, and the twisting moment F_N) generated by the standard machine The influence of the parasitic components on the Force Standard Machine accuracy and the values of dynamic components during the load application transient are studied as well. This evaluation was carried out in the framework of a scientific agreement between the Istituto Nazionale di Ricerca Metrologica (INRiM, Italy) and the Centro Nacional de Metrologia (CENAM, Mexico).

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

1. Introduction

Any improvement in primary and transfer standards is an improvement in the whole hierarchical system of force measuring devices and is consequently converted into greater reliability in industrial production. Substantial progress in the field of force standards can be achieved through the measurement of parasitic components as functions of various parameters, in order to bring the sources of error under control, and take effective remedial steps.

The measurements carried out on several National Force Standard Machines in the world, by using the INRiM six-component dynamometers, showed that such instruments are an essential tool in order to verify and improve the metrological characteristics of force standard deadweight machines.

In May 2007, INRiM’s 100 kN six-component dynamometer was used to measure the parasitic components: transverse forces and moments, and the influence of different parameters (e.g., weight-piece combination, different positions of the loading crossbeam) on the values of parasitic components of the 150 kN CENAM force standard machine at Queretaro, Mexico.

A new data acquisition system allowed, for the first time, to measure the values of the dynamic parasitic component during load transfer transients from 20 to 80 kN.

The present paper deals with the main results of measurement, together with the evaluation of the influence of different parameters and dynamic effects on the parasitic components.

2. The 150 kN CENAM Force Standard Machine

The 150 kN CENAM primary force standard was constructed by C. Galdabini spa (Italy), with the following main characteristics:

- a supporting structure and a loading frame of the three-column type, to ensure high stiffness along the different directions
- weight pieces of austenitic stainless steel AISI 304
- binary weight-piece combination
- individual suspension and transfer of the weight pieces
- balancing of the weight of the loading-frame and of the load-transmission system by means of a lever system.

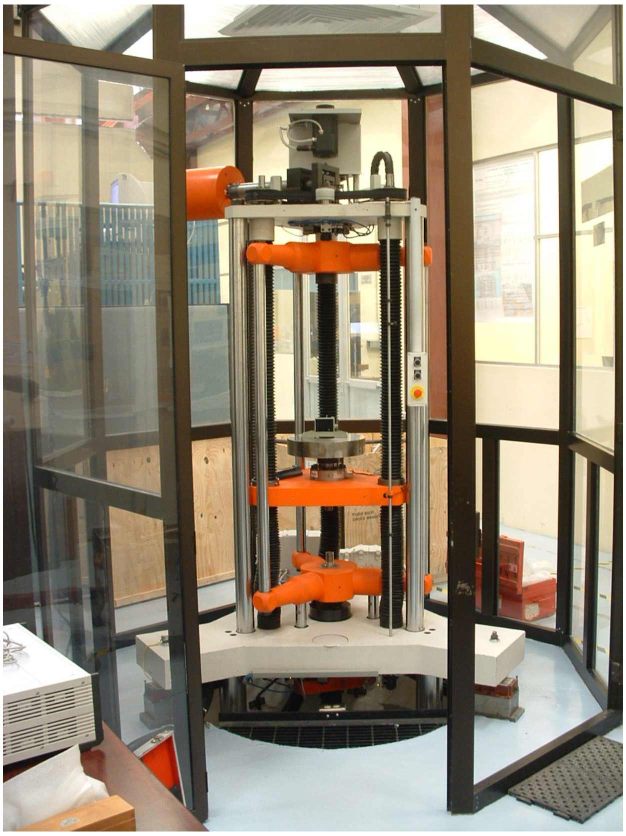

Figure 1. 150 kN CENAM force standard machine.

With a binary combination, only few weight pieces are necessary to obtain a high number of load levels. Eight pieces can generate 256 load levels.
In the CENAM 150 kN machine, the following load combinations were adopted (2x100; 200; 400; 800; 1600; 3200; 6400; 5x25600) N .

The adoption of the binary combination requires, additionally load to be kept constant on the dynamometer being calibrated during weight-piece substitution, so as to avoid undesirable effects of signal drift.
Load is kept constant, to within 5%, by a feedback system exploiting the deformation elasticity of the loading frame.

The great advantage of the two combined methods (binary with load maintenance) lies in the self-calibration of the weight pieces, which can be calibrated directly on the machine with uncertainty lower than 5×10^{-6}, by comparison with a previously calibrated piece.

A limit to calibration capabilities in deadweight machines is the weight of the loading frame. To overcome this difficulty, in the CENAM machine was adopted the solution proposed by Weiler and Shuster (PTB, 1986).

3. The 100 kN INRiM Six-Component Dynamometer

The INRIM six-component dynamometers were designed and constructed with the purpose of measuring, in addition to axial loads, also the five parasitic components. (Figure 2).

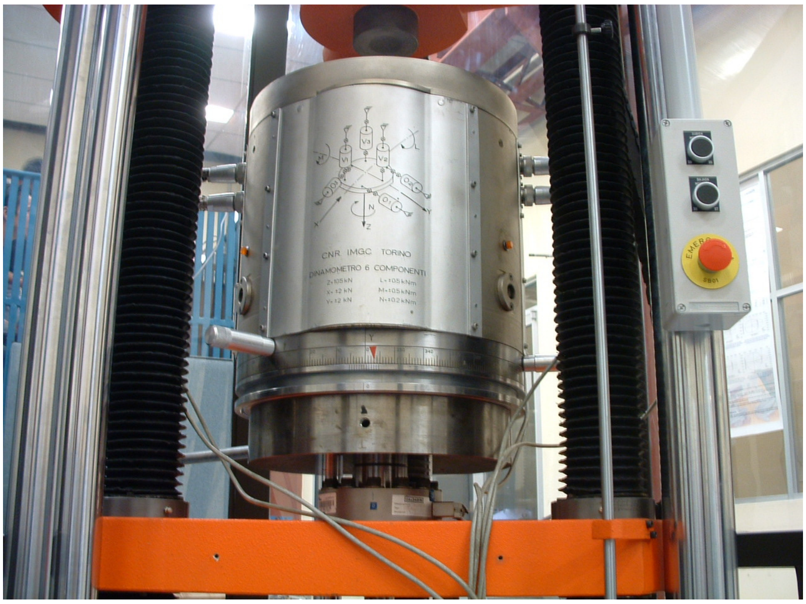

Figure 2. 100 kN INRiM six-component dynamometer.

The 100 kN INRiM six components dynamometer is made up of three vertical force transducers type Z4-HBM and three horizontal force transducers type Z6-HBM. The vertical force transducers measure, mainly, the vertical axial force, F_Z, and the two bending moments F_L and F_M. The horizontal force transducers measure, mainly, side components F_X and F_Y and the twisting moment F_N.

The measurement chain includes the following instrumentation:

a) A digital amplifier HBM MGC-plus with six channels: three with ML38 Bs for the Vertical load acquisition, and three with ML55Bs for the horizontal load acquisition
b) A computer to read the six load cells output signals and to compute, in real time, the parasitic components, by means of a Labview program.

The lower plate of the dynamometer, or fixed base plate, defines the horizontal reference plane and ensures the correct dynamometer positioning on the calibration system or on the standard machines under test. A stainless steel ball, of 50.8 mm diameter, was used as the load transfer device, with an associated soft and flat spacer, that was changed after each test.

The 100 kN six-component dynamometer is 430 mm high, with a diameter of 420 mm and a mass of about 200 kg (figure 1). Its measurement range is up 105 kN for axial loads, 2 kN for side components, 0.5 kN·m for bending moments and 0.2 kN·m for twisting moments.

On the basis of the evaluations and overall results obtained with the 100 kN 6-component dynamometer during eight years, the main performance parameters are:

- Axial load capacity: 100 kN (U= 3x10^{-5} with k=2)
- Side components F_X and F_Y capacity: 2 kN (U= 1x10^{-2} with k=2)
- Bending moments F_L and F_M 0.5 kN·m (U= 1.5x10^{-2} with k=2)
- Twisting moment F_N 0.2 kN·m (U= 1.5x10^{-2} with k=2)
- Axial load stability over 3 years better than 2x10^{-5}
- Temperature effect on rated output 0.02% fs/10 K.

The dynamometer was described in detail in previous papers [1-2]. The versatility characteristics of the dynamometer and the measurement method adopted make it possible to study and to measure dynamic phenomena of the machine-dynamometer system, which are investigated both as load-application transients and as free oscillations of the system under constant loads. 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 Purpose

The tests were designed to evaluate the influence on the performance of the 150 kN CENAM force standard machine of:

A. The value and direction of the parasitic components generated by the standard machine.
B. The influence of different weight combinations on component values. Changing the combination of weights used to generate a given 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.
C. The values of the dynamic components generated by the machine during both load-application transients and free oscillation of the weight-pieces.

5. Experimental Results and Analysis

The tests were carried out at four levels of load (20 kN, 40 kN, 60 kN and 80 kN), and four angular positions relative to the machine axes: 0°, 90°, 180°, 270°. The measurement temperature was (20.2 ± 0.5) °C.

The orientation of the dynamometer in the machine defines two orthogonal horizontal axes (X, Y), specific for each set of tests with a same orientation. The dynamometers measure the vertical force (Z), the two side forces (F_X, F_Y), the two bending moments around the horizontal axes (F_M, F_L), and the twisting moment around the vertical axis (F_N) (see figure 3).

At each orientation, three preload cycles of the maximum load were applied for a period of five minutes, followed by zero load application for another five minutes. Measurements were taken at incremental loads only.

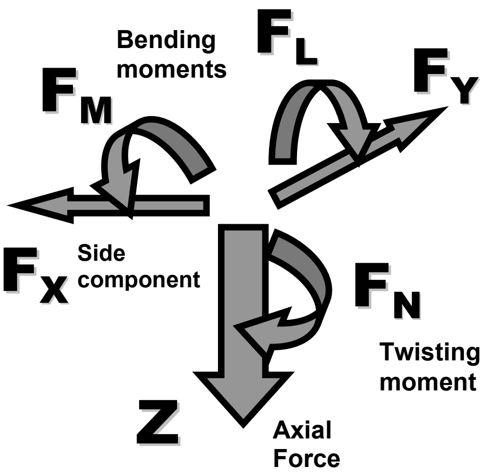

Figure 3. Diagram of the parasitic components orientation.

5.1 Parasitic Components In Static Conditions

a) Side components (F_X, F_Y)

With loads ranging from 20 kN to 80 kN, the average values of the component F_X, covering all the four angular positions of the dynamometer (Table I), varies from -6.00 N to 56.00 N. The average values range from 4.65 N at 20 kN to 45.13 N at 80 kN. The standard deviation is 8.43 N with Z = 20 kN, and 15.4 N at 80 kN.

Table I
Side components on Y direction (N)

Load	F_X					
	0°	90°	180°	270°	Average	STD
kN	N	N	N	N	N	N
20	2.09	13.00	9.50	-6.00	**4.65**	8.43
40	24.50	9.20	19.40	3.60	**14.18**	9.50
60	23.10	33.50	28.00	48.00	**33.15**	10.77
80	56.00	52.90	49.20	22.40	**45.13**	15.40

The average values of the component F_Y, covering all the dynamometer positions indicated in Table II, vary from 16.98 N at 20 kN to 28.95 N at 80 kN. The maximum standard deviation is 13.22 N with Z = 20 kN.

Table II
Side component on Y direction

Load	F_Y					
	0°	90°	180°	270°	Average	STD
kN	N	N	N	N	N	N
20	34.00	11.70	2.80	19.40	**16.98**	13.22
40	17.10	26.30	7.20	30.60	**20.30**	10.39
60	33.79	27.50	16.00	23.40	**25.17**	7.46
80	44.00	20.90	15.60	35.30	**28.95**	13.04

Side components are quite linear and both positive (figures 4 and 5), having considered the topographic orientation of the CENAM standard machine, this means that they are oriented in direction North-West.

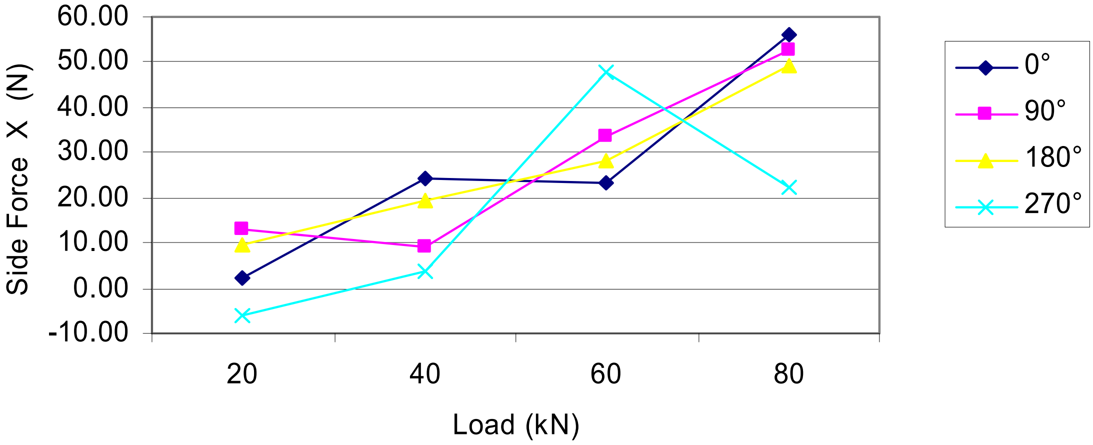

Figure 4. Side components F_X vs. axial load at different angular positions.

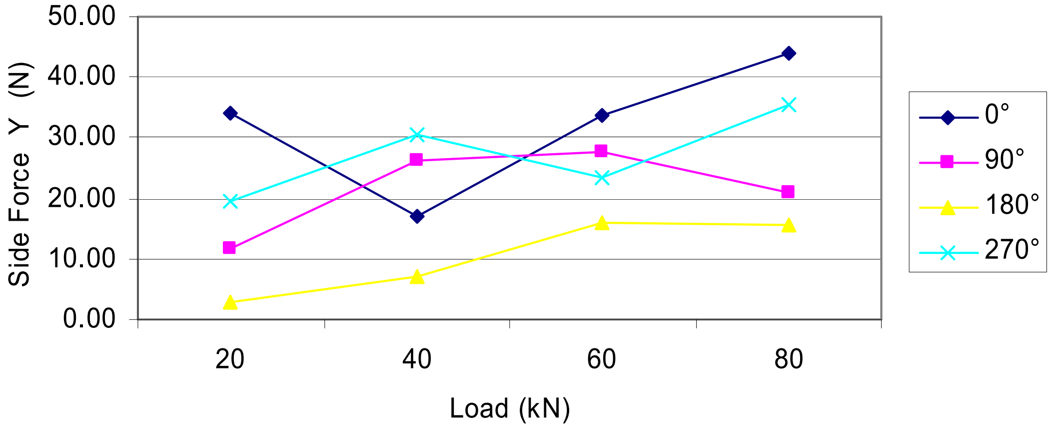

Figure 5. Side components F_y vs. axial load at different angular positions.

In figure 6 the average values of the side components at the four angular positions vs. axial load are summarized.

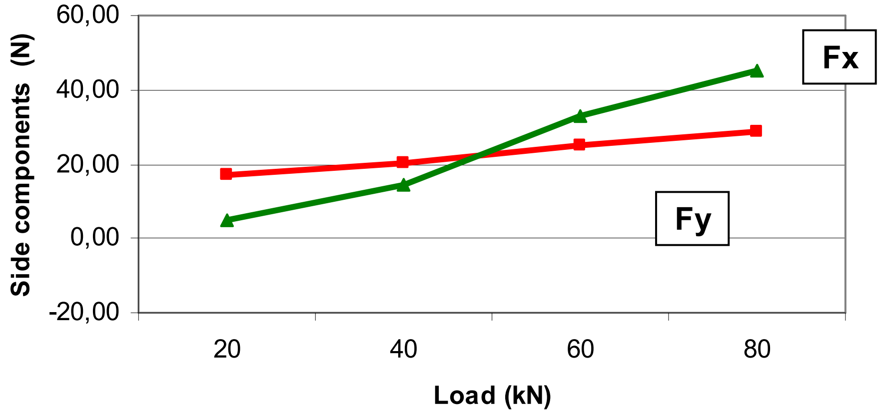

Figure 6. Averaged side components vs. axial load.

b) Bending moments F_L, F_M

As a rule, the average value of bending moment F_L resulted to be smaller than 7 N·m with Z = 80 kN; the average value of bending moment F_M was 6.63 N·m at the same load level (table III and table IV).

Table III
Values of bending moment F_L vs. axial load at different angular positions

Load	F_L					
	0°	90°	180°	270°	Average	STD
kN	N·m	N·m	N·m	N·m	N·m	N·m
20	2.64	-2.40	-5.00	5.30	**0.13**	4.68
40	-2.50	-5.20	8.00	-0.60	**-0.07**	5.70
60	5.80	11.00	-1.30	12.20	**6.93**	6.15
80	4.01	9.70	2.70	11.30	**6.93**	4.21

Table IV
Effects of bending moment F_M vs. axial load at different angular positions

Load	F_M					
	0°	90°	180°	270°	Average	STD
kN	N·m	N·m	N·m	N·m	N·m	N·m
20	-2.00	-3.80	-6.40	-7.10	**-4.83**	2.36
40	-3.10	-7.60	-4.50	-1.00	**-4.05**	2.77
60	-10.70	-1.70	-3.30	-5.70	**-5.35**	3.93
80	-8.60	-3.70	-8.00	-6.20	**-6.63**	2.20

Figure 7 shows the averages of the bending moments at the four angular positions vs. axial load.

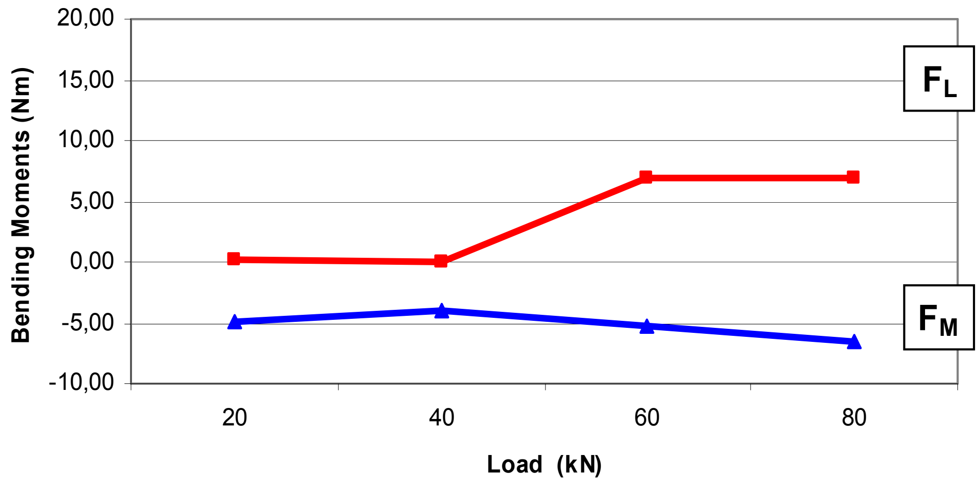

Figure 7. Average bending moments vs. axial load.

c) Twisting moment F_N

The values of twisting moment N resulted to be lower than 2.15 N·m, so that this moment can be considered negligible (table V).

Table V
Twisting moment F_N vs. axial load at different angular positions

Load	F_N					
	0°	90°	180°	270°	Average	STD
kN	N·m	N·m	N·m	N·m	N·m	N·m
20	1.40	2.27	1.50	1.85	**1.76**	0.39
40	2.01	2.20	2.00	2.40	**2.15**	0.19
60	2.60	1.80	2.20	2.00	**2.15**	0.34
80	1.41	1.80	1.97	1.60	**1.70**	0.24

Figure 8 shows the high repeatability of this component at the four angular position and its average values vs. axial loads.

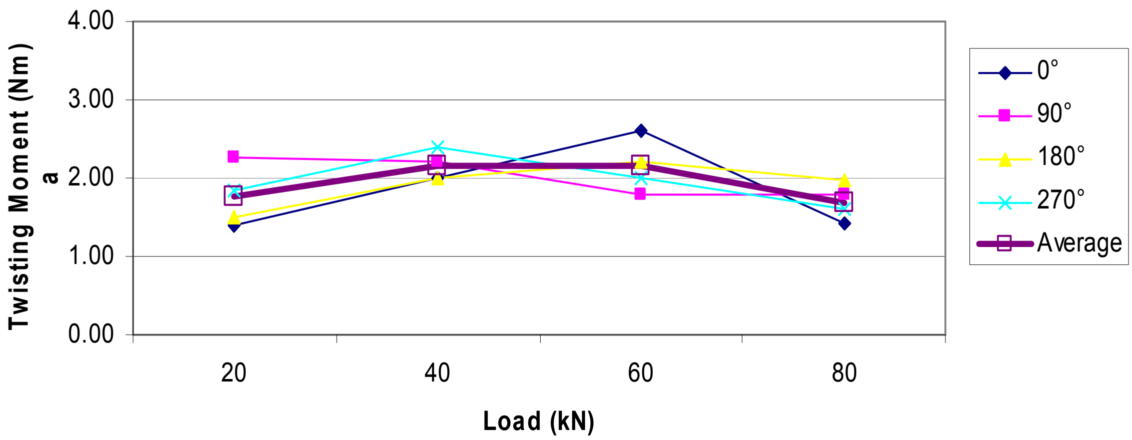

Figure 8. Twisting moments vs. axial load, at different angular positions.

d) Influence of different weight-piece combinations

The tests to evaluate the influence of the weight-piece oscillation on the parasitic components were carried out using two different series of masses (combination A and combination B), as shown in table VI.

Table VI
Different series of weight-pieces used to evaluate variation on parasitic components

	Weight combination A (N)	Weight combination B (N)
	100	12800
	100	
	200	
	400	
	800	
	1600	
	3200	
	6400	
	25600 (1st mass)	25600 (5th mass)
LOAD	38400	38400

No significant variation was detected for the side components vs. different weight pieces combinations. As an example, figure 9 shows the small variation of F_X at two different combinations.

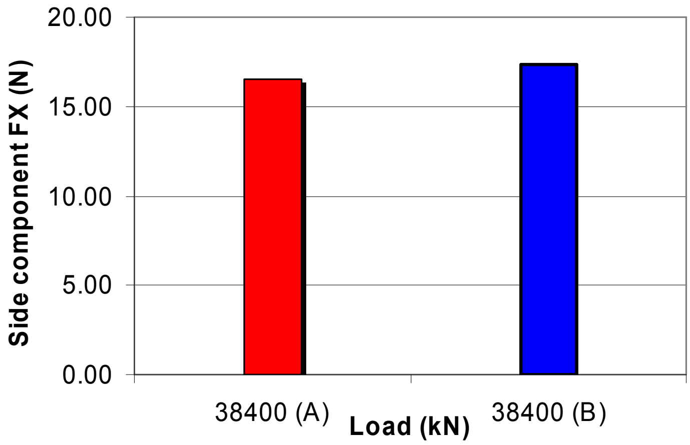

Figure 9. Side component F_X vs. different weight pieces combination.

5.2 Dynamic Components

Influence of weight-piece oscillations

The continuous recording of the signals from the three horizontal load cells (H_1, H_2, H_3) was analyzed during the reading time (60 s) in order to check, at any load level, the different amplitudes caused by weight piece oscillations.

Figure 10 shows the free oscillations of output signals of the horizontal load cells at 20 kN and 0° angular position and their mean values is constant. This means that, in this case, the weight pieces oscillate freely, so that no particular effects on the parasitic components were observed in the machine-dynamometer coupling, when changing load.

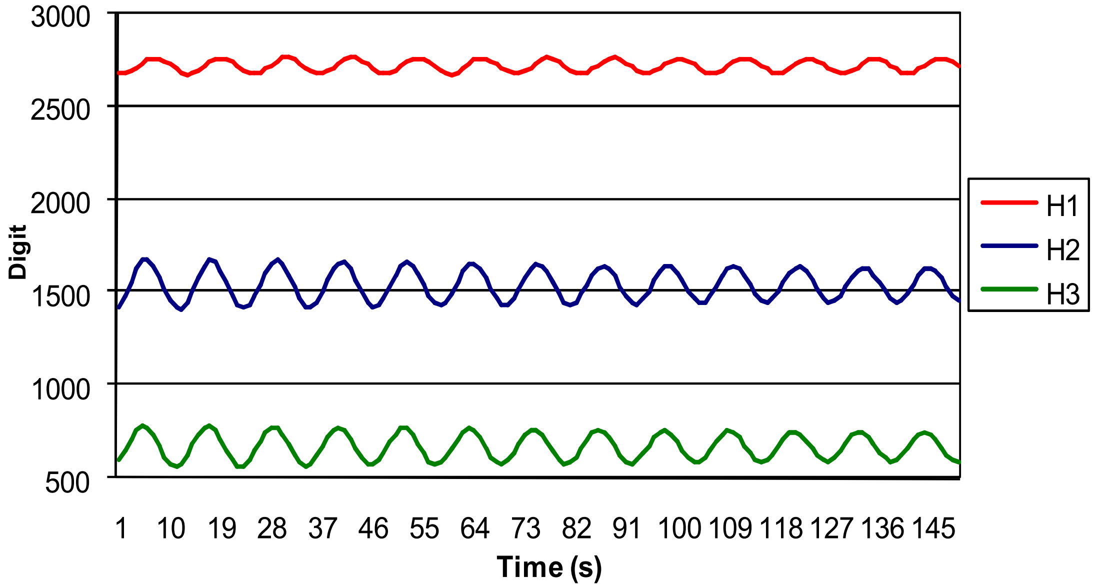

Figure 10. Continuous recording of free oscillation of weight-pieces. Horizontal channels at 20 kN.

Influence of the loading transient

Figures 11 and 12 illustrate a continuous recording of the signals from the three vertical and the three horizontal dynamometers, clearly show the peaks occurring in transients of weight-piece application on the carrier, which give rise to dynamic components in the machine-dynamometer interface.

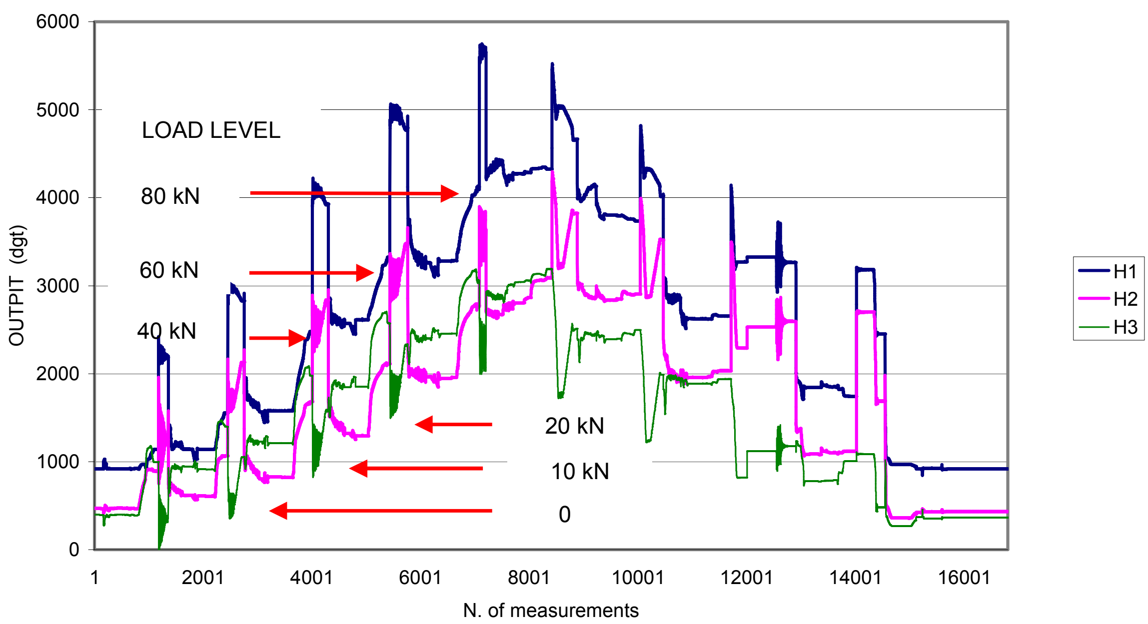

Figure 11. Continuous recording of the three horizontal channels during load application.

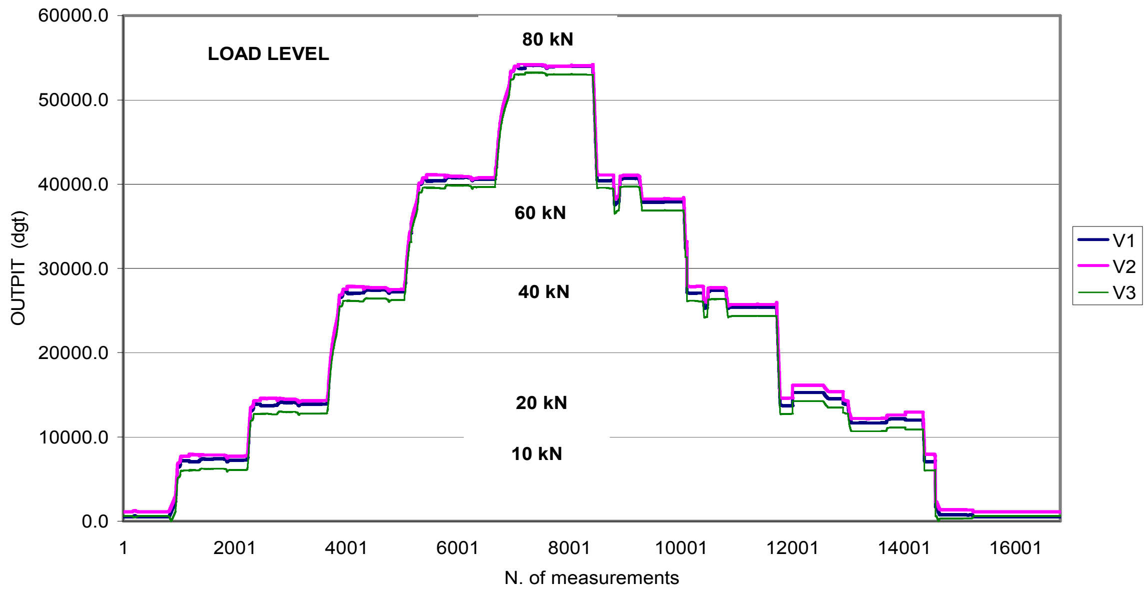

Figure 12. Continuous recording of the three vertical channels during load application.

In figure 13 the values of the static and dynamic side component F_Y, are compared at the same level of axial load.

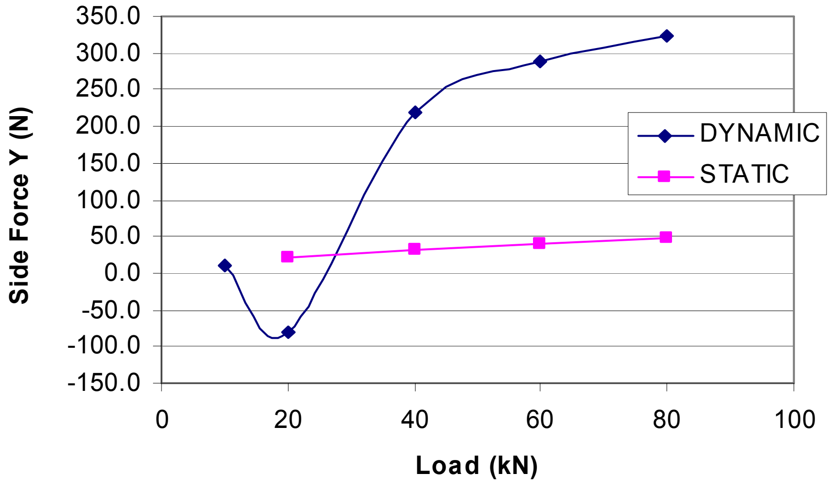

Figure 13. Dynamic and static components F_Y, vs. axial load.

6. Conclusions

The tests carried out on the CENAM 150 kN machine, as regards the measurement of parasitic components and the influence of several parameters on the values of such components, allow the following main conclusions to be drawn:

a. Significant variations on the static parasitic components are detected, due to the influence of dynamic components during load transients. The maximum value of side component (323.5 N) is recorded in $+F_Y$ direction. Special attention has to be paid when calibrating load cells with high sensitivity to transversal loads, by reducing, for example, the load application speed.

b. The variation of the side components at 38 400 N with two different stacks of weight pieces is always very small and its influence on the measured axial load value is less than $1x10^{-5}$.
c. Absolute values of Side components at 100 N and 1 000 N are small ($F_{X\ 100N} \leq 1$ N; $F_{X\ 1000N} \leq 12$ N; $F_{Y100N} \leq 5$ N; $F_{Y1000N} \leq 15$ N). They are coherent with the value calculated at upper loads; they indicate that those components mainly depend on how the machine has initially been settled.
d. Side components (F_X, F_Y) in the range from 100 N to 80 kN are quite small ($F_X \leq 45.13$ N; $F_Y \leq 28.95$ N) giving a correction of vertical force as follows: $\Delta Z/Z = X^2 / 2Z^2 \leq 2.5 \cdot 10^{-7}$ and $\Delta Z/Z = Y^2 / 2Z^2 \leq 1.5 \cdot 10^{-7}$ at 80 kN. It means that their influence on the nominal uncertainty of the 150 kN CENAM force standard machine is negligible.
e. Bending moments on the same range are FL ≤ 6.93 N·m, $F_M \leq -6.63$ N·m; and twisting moment $F_N \leq 1.7$ N·m. They are low and have no influence on the correction of vertical load.
f. Low repeatability of the values of side components F_X and F_Y vs. axial load (at 80 kN their relative standard deviation is respectively 34% and 45%), for each angular position, is an indication that the air bearing contact can strongly influence the values of the parasitic component generated by the standard deadweight machine.
g. The linearity of side components average values (F_X, F_Y) vs. axial load, as well as the insensitivity to the different weight-piece combinations, indicates that those components mainly depend on how the machine has initially been settled and that, consequently at least no distortions or rotations of the loading or main frames with variations of the applied load are detected.
h. Twisting moment N is usually lower than 2 N·m at all load levels, so that it can be safely neglected.

Acknowledgements

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